School of Architecture, Planning and Landscape

Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals Located in Semi-Arid Climates

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Title page

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Abstract

This thesis is an investigation into improving natural ventilation in low rise hospital wards in Northern Nigeria. The climate of this region is semi-arid, during the dry season, sub-Saharan fine dust (Harmattan dust) is blown into the region from the North East and during the wet season, Mosquitos are prevalent.

The energy infrastructure in the whole of Nigeria is under resourced; hence ventilation strategies' based on mechanical extraction are not possible. Five wards within low rise hospital buildings were studied; these were purpose designed hospital buildings, not converted buildings.

Questionnaire surveys of health care workers in the hospitals was conducted and revealed dissatisfaction with the buildings' ventilation and Indoor Air Quality. The questionnaires were then followed up by Tracer Gas measurements and during the period of measurement there was only one occasion when a ward achieved an air change rate of 6 ach^{-1}, the ASHREA Standard requirement for hospital buildings.

To investigate methods of improving natural ventilation in these wards, a CFD model was developed of a representative ward, the model was validated against the Tracer Gas measurements; with an acceptable agreement of ≤ 15%. Using the CFD model, achievable ventilation strategies within the context of the location, were investigated, and a combination of cross ventilation utilizing windows on the windward and leeward sides of the ward together with a roof ventilator on the leeward side proved the most successful. All openings were screened to prevent the entry of mosquitos.

This best case was further investigated with the wind direction at an oblique angle to the ward side. The oblique angle of wind attack reduced the air change rates but improved air circulation/mixing within the ward. With the exception when the wind direction was parallel to the ward side.

To reduce the ingress of Harmattan Dust, was problematic given the energy restrictions, a low energy solution of introducing screened plenums on both the windward and leeward sides of the building proved successful. Larger dust particles were detained within the windward plenum and the smaller dust particles were exhausted into the leeward plenum. With the mosquito screens located on the large surface area of the plenum, the window screens were removed resulting in higher air change rates.

Thus, it is recommended that, openings should be provided on the windward and leeward walls and on the roof toward the leeward side for efficient ventilation and airflow circulation at the occupancy level. The longer sides of the wards should be oriented toward the North-South to capture the North-East trade winds and South-West monsoon winds with oblique angle of attack. Plenums should be incorporated to the windward and leeward facades and Insect screen should be installed on the plenums instead of the wards' openings to increase ventilation rates while excluding mosquitoes and decreasing dust particle concentration in the hospital wards. Openings should be at the middle of the windward and leeward walls and on the roof toward the leeward to avoid airflow short-circuiting. It is recommended to use insect screen with the porosity of 0.2 and when the outdoor local wind speed is ≤ 1.26 m/s (2 m/s: airport value), the ventilation should be supplemented with fan.

Related Published Works

- Mohammed A. M., Steve J. M. D. and Hamza N. (2013). *Simulation of Natural Ventilation in Hospitals of Semi-Arid Climates for Harmattan Dust and Mosquitoes: A Conundrum.* A Paper Presented at the Building Simulation Conference 2013, France.

- Mohammed A. M., Steve J. M. D. and Hamza N. (2013). *Natural Ventilation in Hospitals of Semi-Arid Climates: A Case for Excluding Mosquitoes and Harmattan Dust.* A Paper presented at the Future build conference 2013, Bath UK.

- Mohammed A. M., Steve J. M. D. and Hamza N. (2013). *Natural ventilation in hospital wards of semi-arid climates: a case for acceptable indoor air quality and patients' health.* Proceedings of the 34th AIVC - 3rd TightVent - 2nd Cool Roofs' - 1st venticool Conference , 25-26 September, Athens 2013

- Setaih K, Mohammed A, Hamza N, Dudek S, Townshend T. (2013). *Crafting and Assessing Urban Environments Using Computational Fluid Dynamics. In: Digital Crafting, the 7th international conference of the Arab Society for Computer Aided Architectural Design (ASCAAD).* 2013, Jeddah, Saudi Arabia.

Dedication

This Thesis is dedicated to my Parents and Family

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Table of Contents

TITLE PAGE .... **II**

ABSTRACT .... **III**

RELATED PUBLISHED WORKS .... **IV**

DEDICATION .... **V**

ACKNOWLEDGEMENTS .... **VI**

TABLE OF CONTENTS .... **VII**

LIST OF FIGURES .... **XIII**

LIST OF TABLES .... **XXI**

LIST OF SYMBOLS, ACRONYMS AND ABBREVIATIONS .... **XXVIII**

1. CHAPTER ONE: INTRODUCTION **2**

1.1 BACKGROUND OF THE STUDY 2
1.2 STATEMENT OF PROBLEM 4
1.3 AIMS AND OBJECTIVES 5
1.3.1 Aims *5*
1.3.2 Objectives *5*
1.4 NATURE OF STUDY 6
1.5 IMPORTANCE OF STUDY 6
1.6 REASONS/RATIONALE OF THE STUDY 6
1.6.1 Scope *7*
1.7 CONTEXT OF STUDY 7
1.8 THE GENERAL RESEARCH CONCEPT 7
1.9 THESIS STRUCTURE 8

2. CHAPTER TWO: STUDY AREA **12**

2.1 INTRODUCTION 12
2.2 ARID AND SEMI-ARID CLIMATES 12
2.3 NIGERIAN CLIMATE 14
2.3.1 Study Area (Maiduguri) *18*
2.4 SUSPENDED PARTICULATE MATTERS (SPM) 22
2.4.1 Introduction to Harmattan Dust *23*
2.4.2 Effect of Harmattan Dust on Air Quality *24*
2.4.3 Health Consequences of Harmattan Dust *25*
2.4.4 Harmattan Dust Particle Size *26*
2.4.5 Element Composition of Harmattan Dust *28*
2.5 MOSQUITOES 29
2.5.1 Mosquito Prevention *30*
2.5.2 Sizes of Mosquito *30*
2.5.3 Types of Mosquito *30*
2.5.4 Malaria *32*
2.6 CHAPTER CONCLUSION 33

3 CHAPTER THREE: LITERATURE REVIEW 36

3.1 INTRODUCTION 36
3.2 ENERGY CONCERN IN NIGERIA 36
3.3 THE HOSPITAL MULTI-BED WARDS 37
3.3.1 Multi-Bed hospital wards types 38
3.4 VENTILATION IN BUILDINGS 43
3.4.1 Mechanical Ventilation in Buildings 44
3.4.2 Natural Ventilation in Buildings 45
3.4.3 Driven Forces for Natural Ventilations 53
3.5 NATURAL VENTILATION AND INDOOR AIR QUALITY STUDIES IN HOSPITAL WARDS 56
3.5.1 Openings in Hospital Buildings 60
3.5.2 Wire Mesh Screens 60
3.5.3 Indoor Ventilation Conditions Assessment Criteria 62
3.5.4 Ventilation Guidelines, Codes and Standards in Hospital Wards 62
3.5.5 Ventilation performance prediction and modelling approaches 63
3.6 INDOOR AIR QUALITY (IAQ) IN BUILDINGS 67
3.6.1 Indoor Air Pollution and control 68
3.6.2 Health Consequences of Indoor Air Pollution 69
3.6.3 Indoor Air Quality and velocity Models 69
3.6.4 Building-related illness (BRI) 71
3.6.5 Nosocomial infection (hospital-associated infection) 72
3.7 INDOOR AIR CHEMICAL CONTAMINANTS IN HOSPITALS 73
3.7.1 Particulates 74
3.7.2 Gases 75
3.7.3 Biological agents and Pathogens 81
3.7.4 Sources of Indoor Air Contaminants 82
3.8 BUILDING INDOOR ENVIRONMENTAL PARAMETERS 84
3.8.1 Ventilation rates in buildings 84
3.8.2 Air temperature 84
3.8.3 The radiant temperature 85
3.8.4 Relative humidity 85
3.8.5 Indoor Air Velocity 86
3.8.6 Adaptive Comfort based on Thermal Neutrality 88
3.9 THE EFFECTS OF ENERGY EFFICIENCY ON VENTILATION IN HOSPITAL MULTI-BED WARDS 89
3.9.1 Energy Efficiency and Ventilation 89
3.10 CHAPTER CONCLUSION 90

4 CHAPTER FOUR: RESEARCH METHODOLOGY 94

4.1 INTRODUCTION 94
4.2 DATA COLLECTION METHODS 95
4.2.1 Case study research design 97
4.3 PSYCHO-SOCIAL PERCEPTION 98
4.3.1 Self-Administered Questionnaire 98

4.3.2 *Walkthrough Evaluation* *98*
4.3.3 *Building Drawings and Images Analysis* *99*
4.4 PHYSICAL (FULL-SCALE) MEASUREMENTS 99
4.4.1 *Air Change Rates (ACR) Measurement using Tracer Gas Techniques* *100*
4.4.2 *Indoor Temperature and Humidity Measurement* *101*
4.4.3 *Outdoor Temperature, Wind Speed and Direction Measurement* *101*
4.5 QUANTITATIVE RESEARCH METHOD 102
4.6 DATA ANALYSIS METHODS 102
4.6.1 *Full-scale measurement (Tracer gas) result analysis* *103*
4.6.2 *Questionnaire survey result analysis* *103*
4.7 METHODOLOGY FOR ACHIEVING ACCEPTABLE INDOOR AIR QUALITY IN HOSPITAL WARDS 104
4.8 CHAPTER CONCLUSION 104

5 CHAPTER FIVE: PHYSICAL, ENVIRONMENTAL AND SOCIAL ASSESSMENT OF THE EXISTING HOSPITALS WARDS 107

5.1 INTRODUCTION 107
5.2 THE PHYSICAL PROPERTIES OF THE EXISTING HOSPITAL WARDS 107
5.2.1 *Selected Hospital Building Parameters* *108*
5.2.2 *Hospital Multi-Bed Wards Parameters* *109*
5.2.3 *The Characteristics of the Multi-bed Wards Window Openings* *118*
5.2.4 *The Furniture Characteristics of the Multi-bed Wards* *120*
5.2.5 *The Building Components of the Multi-bed Hospital Wards* *120*
5.2.6 *The Ventilation Parameters of the Studied Multi-bed Wards* *122*
5.3 ENVIRONMENTAL PROPERTIES OF THE EXISTING HOSPITAL WARDS 122
5.4 QUESTIONNAIRE SURVEY RESULT ANALYSIS 124
5.4.1 *Introduction* *124*
5.4.2 *Indoor Air Quality (IAQ) Consideration* *125*
5.4.3 *Dust problems in the Wards* *133*
5.4.4 *Mosquito Problem in the Wards* *138*
5.4.5 *Thermal comfort in the Wards* *142*
5.4.6 *Ventilation in the Wards* *145*
5.4.7 *Indoor Air Quality and Patients Health* *146*
5.5 CHAPTER CONCLUSION 147

6 CHAPTER SIX: MEASUREMENT OF ENVIRONMENTAL CONDITION AND VENTILATION RATES USING TRACER GAS TECHNIQUES 150

6.1 INTRODUCTION 150
6.2 MEASUREMENT OF VENTILATION RATES USING TRACER GAS TECHNIQUE 150
6.3 TRACER GAS MEASUREMENT PROCEDURES 154
6.3.1 *Measurement Equipment* *154*
6.3.2 *Data Logger Channels* *155*
6.3.3 *Transmitters* *155*
6.3.4 *Measurement of Ventilation Rates Using Tracer gas Techniques* *157*
6.3.5 *Measurement Procedure* *158*
6.3.6 *Carbon Dioxide (CO_2) as Tracer Gas* *160*

6.3.7 Tracer gas injection and Mixing *161*
6.3.8 Tracer gas sampling *161*
6.3.9 The Tracer Gas Concentration Analysis and Estimation of Air Change Rates 162
6.4 FULL-SCALE MEASUREMENT RESULTS AND DISCUSSION 163
6.4.1 Measurement of Air Change Rates *163*
6.4.2 Air Temperature Measurements *166*
6.4.3 Relative Humidity Measurements *169*
6.5 CHAPTER CONCLUSION 178

7 CHAPTER SEVEN: THE PROCESS OF CFD SIMULATION AND SOFTWARE VALIDATION 180

7.1 INTRODUCTION 180
7.2 VENTILATION PERFORMANCE PREDICTION USING COMPUTATIONAL FLUID DYNAMICS (CFD) 180
7.2.1 Model Geometry Creation *182*
7.2.2 Computational Mesh Creation *183*
7.2.3 Solution boundaries *183*
7.3 COMPUTATIONAL DOMAIN 184
7.4 ATMOSPHERIC BOUNDARY LAYER (ABL) 186
7.4.1 Horizontal homogeneity *190*
7.4.2 Wall Functions *194*
7.5 TURBULENCE MODEL -REYNOLDS-AVERAGED NAVIER-STOKES (RANS) EQUATIONS 195
7.6 BOUNDARY CONDITIONS 196
7.7 POROUS MEDIA BOUNDARY CONDITION 198
7.8 THE SELECTED HOSPITAL WARDS BUILDING MATERIALS AND INDOOR AIR PROPERTIES 199
7.8.1 Building Envelope (Wall) *199*
7.8.2 Concrete Slab and sand *200*
7.8.3 Indoor Air Properties *200*
7.9 MODEL VALIDATION AND CALIBRATION STUDIES 200
7.10 THE CFD VALIDATION RESULTS 201
7.10.1 Acceptable Error limits between CFD simulation and Full-scale Measurements *206*
7.10.2 Grid Independency Test *207*
7.11 SIMULATION CONVERGENCE 208
7.12 CHAPTER CONCLUSION 209

8 CHAPTER EIGHT: CFD SIMULATION RESULTS 212

8.1 INTRODUCTION 212
8.2 COMPUTATIONAL FLUID DYNAMIC (CFD) SIMULATION IN BUILDINGS 212
8.3 NATURAL VENTILATION IN MULTI-BED HOSPITAL WARD 213
8.3.1 Air Change rates (ACR) and Volumetric Airflow Rates *214*
8.4 PERCENTAGE DISSATISFIED WITH AIR QUALITY 240
8.5 LOCAL INDOOR VELOCITY AND TURBULENT INTENSITY 243

8.5.1 Local indoor Air velocity *243*
8.5.2 Local Indoor Turbulent Intensity *249*
8.6 LOCAL DRAUGHT RISK 251
8.7 BUILDING ORIENTATION AND NATURAL VENTILATION 253
8.7.1 Volumetric flow rates and orientations *255*
8.7.2 Air Change Rates and Orientation *261*
8.7.3 Average Indoor Air Velocity and Orientation *264*
8.7.4 Average Turbulence Intensity and Orientation *266*
8.8 OPENINGS INSECT SCREEN AND NATURAL VENTILATION 266
8.8.1 Volumetric flow rates and screen porosity *267*
8.8.2 Air Change Rates (ACR) and screen porosity *269*
8.8.3 Average Indoor Air Velocity and screen porosity *270*
8.8.4 Average Indoor Air Turbulent Intensity and screen porosity *271*
8.9 OUTDOOR WIND SPEED AND NATURAL VENTILATION 272
8.9.1 Volumetric airflow rates and outdoor wind speed *272*
8.9.2 Air Change rates (ACR) and outdoor wind speed *275*
8.9.3 Average Indoor Air Velocity and outdoor wind speed *276*
8.9.4 Average Indoor Turbulent Intensity and outdoor wind speed *277*
8.10 MONTHLY EVALUATION OF NATURAL VENTILATION IN HOSPITAL WARDS OF SEMI-ARID CLIMATES 278
8.11 CHAPTER CONCLUSION 282

9 CHAPTER NINE: POLLUTANT DISPERSION IN HOSPITAL WARDS . 286

9.1 INTRODUCTION 286
9.2 INDOOR POLLUTANT DISPERSION PREDICTION IN HOSPITAL WARDS 287
9.3 DISCRETE PHASE MODEL (DPM) 289
9.4 DPM BOUNDARY CONDITIONS 291
9.4.1 Particles injection and properties *291*
9.4.2 Turbulence in particle dispersion *292*
9.4.3 Building Surface DPM boundary conditions *292*
9.4.4 DPM Tracking parameters *293*
9.5 THE EFFECT OF SCREEN POROSITY ON DUST PARTICLES DEPOSITION IN HOSPITAL WARDS 294
9.6 THE EFFECT OF OUTDOOR WIND SPEED ON DUST PARTICLES DEPOSITION IN HOSPITAL WARDS 302
9.7 THE EFFECT OF PLENUM ON DUST PARTICLES CONCENTRATION AND DEPOSITION IN HOSPITAL WARDS 310
9.8 CHAPTER CONCLUSION 335

10 CHAPTER TEN: GUIDANCE FOR ARCHITECTS 338

10.1 INTRODUCTION 338
10.2 SITE PLANNING AND ORIENTATION 338
10.3 PHYSICAL SIZE OF THE BUILDING 342
10.4 ARRANGEMENT OF FENESTRATIONS 342
10.5 LOCATION OF VENTILATORS AND BAFFLES ON THE ROOF 342
10.6 THE RATIO OF OPENING SIZES TO WARD FLOOR AREA 343

10.7 INSECT SCREEN MESH ... 344
10.8 OUTDOOR PREVAILING WIND SPEED ... 345
10.9 PLENUM INTEGRATION AND POSITIONS ... 345
10.10 CHAPTER CONCLUSION ... 346

11 CHAPTER ELEVEN: CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORKS ... 348

11.1 INTRODUCTION ... 348
11.2 CONCLUSIONS ... 348
11.2.1 The occupants' psychosocial perception of the existing hospital wards 348
11.2.2 The measurement of ventilation rates in the existing hospital wards ... 349
11.2.3 The opening position and ventilation rates in hospital wards ... 349
11.2.4 The influence of building orientation, wind speed and Insect screen porosity on ventilation rates ... 349
11.2.5 The influence of monthly average weather condition on ventilation rates, indoor air velocity and temperature ... 350
11.2.6 The influence of insect screen, wind speed, and plenum on dust particle concentration indoors ... 351
11.3 LIMITATIONS ... 352
11.4 RECOMMENDATIONS FOR FUTURE WORKS ... 353
11.4.1 Full-scale measurement ... 353
11.4.2 CFD simulation ... 354
11.4.3 Natural ventilation ... 354
11.4.4 Indoor air quality ... 354
11.4.5 Thermal Comfort ... 355
11.5 CLOSING REMARKS ... 355

12 APPENDICES ... 358

12.1 APPENDIX 1: QUESTIONNAIRE SURVEY ... 358
12.2 APPENDIX 2: WALKTHROUGH EVALUATION CHECKLIST ... 362
12.3 APPENDIX 3: PARTICLE TRACKING DATA ... 364
12.3.1 Insect Screen Porosity and Dust Particles Concentration ... 364
12.3.2 Outdoor Prevailing Wind Speeds and Dust Particles Concentration Indoors 371
12.3.3 Effect of Plenums on Dust Particles Concentration Indoors ... 376
12.3.4 Effect of Plenums and Screen Porosity on Dust Particles Concentration Indoors 378

13 REFERENCES ... 382

List of Figures

Figure 1.1: The General Research Concept 10
Figure 2.1 Aridity Zones in Africa 14
Figure 2.2: Nigerian Map showing North-East (NE) Trade wind and South-West (SW) Monsoon wind 15
Figure 2.3 Climatic Classification of Nigeria According to Koppen (Olaniran, 1986) .. 16
Figure 2.4 The climatic regions for bioclimatic design in Nigeria according to Nick Hollo. (Ogunsote, and Prucnal-Ogunsote, 2002) 17
Figure 2.5: The proposed climatic zones for architectural design in Nigeria (Ogunsote and Prucnal-Ogunsote, (2002) 18
Figure 2.6: Map of Nigeria showing the location of Maiduguri and other state capitals 19
Figure 2.7: Wind Rose showing the dominant wind direction in Maiduguri, the study area 21
Figure 2.8: Distribution of Harmattan Dust Particles in West Africa (Ogunseitan, 2007) 24
Figure 2.9: Harmattan dust storms from the Sahara desert as captured by NASA's MODIS satellite (Kaufman, et al. 2005) 24
Figure 2.10: The effect of Harmattan dust on air quality and visibility 25
Figure 2.11: Relationship of Harmattan dust particle size to distance downwind from the source area, January to March 1979 (Source: Mctainsh, 1982) 27
Figure 2.12 Mosquito Life Cycle (MetaPathogen, 2014) 30
Figure 2.13: Typical Mosquito Insect 32
Figure 2.14 Control of Malaria in Africa 32
Figure 3.1: Bay Ward Arrangement (Yau et al 2011) 39
Figure 3.2: Nightingale Wards Arrangement (Yau et al. 2011) 39
Figure 3.3: Racetrack ward type, High Wycombe hospital, Buckinghamshire, UK, source: James and Tatton-Brown 1986 (Nazarian et al. 2011). 40
Figure 3.4: Nuffield or duplex ward type, Larkfield hospital, UK, source: James and Tatton-Brown 1986 (Nazarian et al. 2011) 41
Figure 3.5: Cruciform cluster ward type, Weston general hospital, UK, source: James and Tatton-Brown 1986 42
Figure 3.3.6: Circular nursing unit design with one centralized nursing station (Morelli, 2007) 43
Figure 3.7: Wind-driven natural ventilation in the single-side corridor type hospital with wind entering the ward (Atkinson, 2009) 48
Figure 3.8: Cross ventilation (CIBSE, 1997) 49
Figure 3.9: Central Corridor Ventilation 49
Figure 3.10: Combined wind and buoyancy-driven natural ventilation in the courtyard type (outer corridor) hospital (Atkinson, 2009) 50
Figure 3.11: Combined wind and buoyancy-driven natural ventilation in the courtyard type (inner corridor) hospital (Atkinson, 2009) 51
Figure 3.12: Operating principle of a wind tower (Khan et al. 2008) 52
Figure 3.13: Buoyancy-driven (including solar chimney) natural ventilation in the solar chimney type of hospital (Atkinson, 2009) 53
Figure 3.14: Wind pressure field around building (CIBSE, 1997) 54

Figure 3.15: Stack-driven flows in atrium 55
Figure 3.16: Dissatisfaction caused by a standard person at different ventilation rates (Olsen, 2004) 70
Figure 3.17: Total Average Ambience Temperature of the Study Area in Relation to Comfort Temperature Zone 89
Figure 4.1: The General Research Methodology 95
Figure 4.2: Data Collection Methods 95
Figure 4.3: The application of data collection methods on the case study hospitals 96
Figure 4.4 Framework for Ventilation and Indoor Air Quality measurement 97
Figure 4.5: Data Analysis and Simulation Method 102
Figure 4.6: Methodological Framework for Natural Ventilation simulation in Multi-Bed Wards of Semi-Arid Climates 104
Figure 5.1: University of Maiduguri Teaching Hospital (UMTH) 112
Figure 5.2: State Specialist Hospital Maiduguri (SSHM) 113
Figure 5.3: Federal Neuro Psychiatric Hospital Maiduguri (FNPHM) 114
Figure 5.4: Umar Shehu Ultra-Modern Hospital Maiduguri (USUHM) 115
Figure 5.5: Nursing Home Hospital Maiduguri (NHHM) 116
Figure 5.6: The Difference between Measured Indoor and Outdoor Temperatures 123
Figure 5.7: Indoor Air Quality Problem Consideration in Wards 126
Figure 5.8: Experience of Smell and Odour in the Wards 128
Figure 5.9: Availability of Contaminant Sources in the Wards 130
Figure 5.10: Presence of Dust Problem in the Wards 134
Figure 5.11: Noticeable Dust Particles in the Wards 136
Figure 5.12: Seasonality of Dust Problem in the Wards 137
Figure 5.13: Season with Highest Dust problem 138
Figure 5.14: Mosquito Problem in the Hospital Wards 139
Figure 5.15: Seasonality of Mosquito Problem 141
Figure 5.16: Extend of Mosquito Problem per Season 142
Figure 5.17: Thermal Comfort Satisfaction Level 143
Figure 5.18: Draughtiness in the Wards 144
Figure 5.19: Humidity in the Wards 145
Figure 5.20: Nature of the Airflow in the Wards 146
Figure 5.21: Indoor Air Quality and Patient Health Deterioration 147
Figure 6.1: The interior view of the measured hospital wards showing Fans, instruments and CO_2 bottles 153
Figure 6.2: Telemetry of Eltek data loggers/receivers and transmitters (Source: Eltek, 2014) 154
Figure 6.3: Squirrel 1000 Series Data Logger (Source: Eltek, 2014) 155
Figure 6.4: Gen-II Transmitters type GD-47 156
Figure 6.5: Gen-II Transmitters type GD-10 157
Figure 6.6: Procedures for conducting concentration decay tracer gas measurement 158
Figure 6.7: Corridor Covered with polythene Sheets 159
Figure 6.8: Infiltration rates and air change rates in closed and opened windows respectively 166

Figure 6.9: Air temperature of all the cases measured in (a) closed and (b) opened window situations 168
Figure 6.10: The difference in temperature between closed and opened window wards 169
Figure 6.11: Relative Humidity of all the cases measured in closed and opened window situation 170
Figure 6.12: The difference in relative humidity between closed and opened window wards 171
Figure 7.1: The CFD Simulation Process 182
Figure 7.2: Computational domain with building models for CFD simulation of ABL showing inlet flow, approach flow and incident flow 185
Figure 7.3: Subdivision of the Atmospheric Boundary, with conceptual illustration of vertical distribution of horizontal velocity and shear stress within the boundary layer (Zhang, 2009) 187
Figure 7.4: Vertical profiles of Mean wind speed at the inlet, outlet and the building positions of the computational domain showing homogeneity of the ABL profile 192
Figure 7.5: Vertical profiles of turbulent kinetic energy at the inlet, outlet and the building positions of the computational domain showing homogeneity of the ABL profile 192
Figure 7.6: Vertical profiles of turbulent dissipation rate at the inlet, outlet and the building positions of the computational domain showing homogeneity of the ABL profile 193
Figure 7.7: Vertical profiles of turbulent intensity at the inlet, outlet and the building positions of the computational domain showing homogeneity of the ABL profile 193
Figure 7.8: Graphical representation of fitting the mean-velocity ABL log-law inlet profile to the wall function for mean velocity in the centre point P of the wall-adjacent cell (Blocken et al. 2007) 195
Figure 7.9: Inlet velocity magnitude profile 197
Figure 7.10: Inlet Turbulence Kinetic Energy Profile 198
Figure 7.11: Inlet Turbulent Dissipation rate Profile 198
Figure 7.12: The Validation Results Comparing Air Flow Rates of Full-Scale Measurement and CFD Simulation 205
Figure 7.13: The Validation Results Comparing Air Change Rates of Full-Scale Measurement and CFD Simulation 206
Figure 7.14: The Volumetric Flow rates of three different Mesh alternatives 208
Figure 7.15: Scaled Residuals showing convergence history 209
Figure 8.1: Vertical section of case 1 showing airflow circulation and distribution 215
Figure 8.2: Vertical section of case 2 showing airflow circulation and distribution 216
Figure 8.3: Vertical section of case 3 showing airflow circulation and distribution 217
Figure 8.4: Vertical section of case 4 showing airflow circulation and distribution 217
Figure 8.5 : Vertical section of case 5 showing airflow circulation and distribution 218
Figure 8.6: Vertical section of case 6 showing airflow circulation and distribution 219
Figure 8.7: Vertical section of case 7 showing airflow circulation and distribution 220
Figure 8.8: Vertical section of case 8 showing airflow circulation and distribution 221
Figure 8.9: Vertical section of case 9 showing airflow circulation and distribution 222

Figure 8.10: Vertical section of case 10 showing airflow circulation and distribution 223
Figure 8.11: Vertical section of case 11 showing airflow circulation and distribution 223
Figure 8.12: Vertical section of case 12 showing airflow circulation and distribution 224
Figure 8.13: Vertical section of case 13 showing airflow circulation and distribution 225
Figure 8.14: Vertical section of case 14 showing airflow circulation and distribution 226
Figure 8.15: Vertical section of case 15 showing airflow circulation and distribution 227
Figure 8.16: Vertical section of case 16 showing airflow circulation and distribution 228
Figure 8.17: Vertical section of case 17 showing airflow circulation and distribution 229
Figure 8.18: Air change rates of different simulated cases compared to the base-case (Case-1) 230
Figure 8.19: Dissatisfaction caused by a standard person at different ventilation rates (Olesen, 2004) 241
Figure 8.20: Air change rates per standard person for different occupancy levels 241
Figure 8.21: The measuring points for local indoor air parameters 243
Figure 8.22: Local indoor air speed at 1.0 m above floor level in Case-1 244
Figure 8.23: Local indoor air speed at 1.0 m above floor level in Case-16 245
Figure 8.24: Local indoor air speed at 0.6 m above floor level in Case-1 245
Figure 8.25: Local indoor air speed at 0.6 m above floor level in Case-16 246
Figure 8.26: The comparative analysis of local indoor air speed at 1.0 m height at the windward sides of Cases 1 and 16 246
Figure 8.27: The comparative analysis of local indoor air speed at 1.0 m height at the centre of Cases 1 and 16 247
Figure 8.28: The comparative analysis of local indoor air speed at 1.0 m height at the leeward sides of Cases 1 and 16 247
Figure 8.29: The comparative analysis of local indoor air speed at 0.6 m height at the windward sides of Cases 1 and 16 248
Figure 8.30: The comparative analysis of local indoor air speed at 0.6 m height at the centre of Cases 1 and 16 248
Figure 8.31: The comparative analysis of local indoor air speed at 0.6 m height at the leeward sides of Cases 1 and 16 248
Figure 8.32: Local indoor turbulent intensity at 1.0 m height in Case 1 250
Figure 8.33: Local indoor turbulent intensity at 1.0 m height in Case 16 250
Figure 8.34: Local indoor turbulent intensity at 0.6 m height in Case 1 251
Figure 8.35: Local indoor turbulent intensity at 0.6 m height in Case 16 251
Figure 8.36: The comparative analysis of draught risk at 1.0 m height in the windward positions of case 1 and 16 252
Figure 8.37: The comparative analysis of draught risk at 0.6 m height in the windward positions of case 1 and 16 253
Figure 8.38: Different ward Orientations Studied 255
Figure 8.39: Volumetric flow rates of different ward orientations for cases 1, 9 and 16 261
Figure 8.40: Air change rates of different ward orientations for the base-case (Case-1) 262
Figure 8.41: Air change rates of different ward orientations for (Case-9) 263
Figure 8.42: Air change rates of different ward orientations for the (Case-16) 263

Figure 8.43: Air change rates of different ward orientations for cases 1, 9 and 16 264
Figure 8.44: Indoor Average Air Velocity of different ward orientations for cases 1, 9 and 16 265
Figure 8.45: Indoor Average Turbulence Intensity of different ward orientations for cases 1, 9 and 16........ 266
Figure 8.46: Volumetric airflow rates for different Porosities........ 269
Figure 8.47: Volumetric flow rates gradient for different Porosities........ 269
Figure 8.48: Air change rates for different Porosities........ 270
Figure 8.49: Average indoor air velocity for different Porosities........ 271
Figure 8.50: Average indoor air velocity gradient for different Porosities........ 271
Figure 8.51: Average indoor turbulence intensity for different Porosities 272
Figure 8.52: Volumetric Airflow Rates (m3/s) for different Velocities (Cases 1 and 16) 275
Figure 8.53: Air Change Rates (ach^{-1}) for different Velocities (Cases 1 and 16)........ 276
Figure 8.54: Average indoor air Velocity for different Velocities (Cases 1 and 16).... 277
Figure 8.55: The Trend of Average indoor air Velocity for different Velocities (Cases 1 and 16)........ 277
Figure 8.56: Average indoor Turbulent Intensity (%) for different Velocities (Cases 1 and 16)........ 278
Figure 8.57: Monthly Airflow Rates in the simulated hospital wards 279
Figure 8.58: Monthly Air Change Rates in the simulated hospital wards 279
Figure 8.59: Monthly average indoor air velocity in the simulated hospital wards...... 280
Figure 8.60: Monthly average indoor turbulent intensity in the simulated hospital wards 281
Figure 8.61: Monthly average indoor air temperature in the simulated hospital wards 281
Figure 9.1: Concentration characteristics of dust particles for different insect screen porosities (1μm-10μm)........ 294
Figure 9.2: Concentration characteristics of dust particles for different insect screen porosities (1μm-100μm)........ 295
Figure 9.3: Concentration characteristics of dust particles for different particle sizes (1μm-100μm) 295
Figure 9.4: Dust particles prevention characteristics of different insect screen porosities (1μm-10μm) 296
Figure 9.5: Dust particles prevention characteristics of different insect screen porosities (1μm-100μm) 296
Figure 9.6: The effect of screen porosity and particle size on particle deposition (1μm-10μm) 297
Figure 9.7: The effect of screen porosity on particle deposition for different particle sizes (1μm-100μm) 298
Figure 9.8: The effect of particle size on particle deposition for different screen porosity (1μm-100μm) 299
Figure 9.9: The effect of screen porosity and particle size on particle suspension (1μm-10μm) 300
Figure 9.10: The effect of screen porosity on particle suspension for different particle size (1μm-100μm)........ 300

Figure 9.11: The effect of particle size on particle suspension for different screen porosity (1μm-100μm) 301
Figure 9.12: The effect of outdoor wind speed on dust particle concentration of different particle sizes (1μm-10μm) 302
Figure 9.13: The effect of outdoor wind speed on dust particle concentration of different particle sizes (1μm-100μm) 303
Figure 9.14: The effect of particle sizes on dust particle concentration of different outdoor wind speeds (1μm-100μm) 303
Figure 9.15: The effect of outdoor wind speed on dust particle prevention (escaped particles) of different particle sizes (1μm-10μm) 304
Figure 9.16: The effect of outdoor wind speed on dust particle prevention (escaped particles) of different particle sizes (1μm-100μm) 305
Figure 9.17: The effect of particle sizes on dust particle prevention (escaped particles) of different outdoor wind speed (1μm-100μm) 305
Figure 9.18: The effect of outdoor wind speed on dust particle deposition of different particle sizes (1μm-10μm) 306
Figure 9.19: The effect of outdoor wind speed on dust particle deposition of different particle sizes (1μm-100μm) 306
Figure 9.20: The effect of particle sizes on dust particle deposition of different outdoor wind speeds (1μm-100μm) 307
Figure 9.21: The effect of outdoor wind speed on dust particle suspension of different particle sizes (1μm-10μm) 308
Figure 9.22: The effect of outdoor wind speed on dust particle suspension of different particle sizes (1μm-100μm) 308
Figure 9.23: The effect of particle sizes on dust particle suspension of different outdoor wind speed (1μm-100μm) 309
Figure 9.24: The influence of plenum on different sizes of dust particle concentration (1μm-10μm) 314
Figure 9.25: The influence of plenum on different sizes of dust particle concentration (1μm-10μm) 315
Figure 9.26: The influence of plenum on different sizes of dust particle concentration (1μm-100μm) 315
Figure 9.27: The influence of plenum on different sizes of dust particle concentration (1μm-100μm) 316
Figure 9.28: The influence of plenum on preventing different sizes of dust particle (1μm-10μm) 317
Figure 9.29: The influence of plenum on removing dust particle of different sizes (1μm-10μm) 317
Figure 9.30: The influence of plenum on preventing different sizes of dust particle (1μm-100μm) 318
Figure 9.31: The influence of plenum on removing dust particle of different sizes (1μm-100μm) 318
Figure 9.32: Quantity of Particles Deposited in the Windward Plenums 319
Figure 9.33: Quantity of Particles Deposited in the Windward Plenums 320

Figure 9.34: The influence of plenum on different sizes of dust particle deposition (1μm-10μm) 320
Figure 9.35: The influence of plenum on different sizes of dust particle deposition (1μm-10μm) 321
Figure 9.36: The influence of plenum on different sizes of dust particle deposition (1μm-100μm) 321
Figure 9.37: The influence of plenum on different sizes of dust particle deposition (1μm-100μm) 322
Figure 9.38: The influence of plenum on different sizes of dust particle suspension (1μm-10μm) 323
Figure 9.39: The influence of plenum on different sizes of dust particle suspension (1μm-10μm) 323
Figure 9.40: The influence of plenum on different sizes of dust particle suspension (1μm-100μm) 324
Figure 9.41: The influence of plenum on different sizes of dust particle suspension (1μm-100μm) 324
Figure 9.42: The effect of Plenum on Air Change Rates in Cases 19 and 20........ 327
Figure 9.43: The effect of Plenum on Indoor Air Velocity in Cases 19 and 20 327
Figure 9.44: The variation in particle concentration between particles of different sizes in cases 19 and 20 328
Figure 9.45: The variation in percentage of particle concentration between particles of different sizes in cases 19 and 20 328
Figure 9.46: The variation in percentage of particle concentration between particles of different sizes in cases 19........ 329
Figure 9.47: The variation in percentage of particle concentration between particles of different sizes in cases 20........ 329
Figure 9.48: The variation in particle deposition between particles of different sizes in cases 19 and 20........ 330
Figure 9.49: The variation in particle deposition between particles of different sizes in cases 19 and 20........ 330
Figure 9.50: The effect of plenum on different sizes on dust particles deposition 331
Figure 9.51: The effect of plenum on different sizes on dust particles deposition 331
Figure 9.52: The variation in particle suspension between particles of different sizes in cases 19 and 20........ 332
Figure 9.53: The variation in percentage of particle suspension between particles of different sizes in cases 19 and 20 333
Figure 9.54: The variation in infiltration prevention (escaped) between particles of different sizes in cases 19 and 20 334
Figure 9.55: The variation in infiltration prevention (escaped) between particles of different sizes in cases 19 and 20 334
Figure 10.1: The recommended ward orientation in relation to wind direction 339
Figure 10.2: The site plan of USUHM........ 339
Figure 10.3: The site plan of UMTH 340
Figure 10.4: The site plan of FNPHM 340
Figure 10.5: The site plan of NHHM........ 341

Figure 10.6: The site plan of SSHM 341
Figure 10.7: The position of the ventilators and Plenums 343
Figure 10.8: The position of insect screen mesh on the Plenum....................................344
Figure 10.9: The size of the Plenum 345

List of Tables

Table 2-1 Mean Temperature, wind and solar radiation data for Maiduguri 20
Table 2-2 Monthly variations of wind characteristics for Maiduguri location (wind speed data of 37 years, 1971–2007 periods measured at 10m) 21
Table 2-3: Particles size characteristics of dust 28
Table 2-4 Mosquito larva species in a sampling of artificial and natural sources in Mid-Western Nigeria (Okogun et al. 2005) 31
Table 3-1 Potential applicability of natural ventilation solutions in ideal conditions (consensus of a WHO systematic review) 46
Table 3-2 Natural Ventilation and Indoor Air Quality Related Studies 59
Table 3-3: Characteristics of different mesh types 61
Table 3-4 Comparison of the various guidelines governing the ventilation of general and intensive care ward spaces in the United Kingdom and the United States 63
Table 3-5 Diseases and disease syndromes associated with exposure to bacteria and fungi 73
Table 3-6 Potential Indoor Source of Formaldehyde 78
Table 3-7 Acute health effects from formaldehyde exposure 78
Table 3-8 Sources of common volatile organic compounds in indoor air 79
Table 3-9 Low TVOCs Recommended Emission Limits for Building Materials and Furnishings 79
Table 3-10 Sources of Airborne Microbial pollutants 81
Table 3-11 Common indoor allergic agents 82
Table 3-12 Indoor Air Contaminants and Sources 83
Table 3-13 Major indoor pollutants and emission sources 83
Table 3-14: Subjective reaction to air movement (Szokolay, 2008) 87
Table 3-15: Subjective response to air motion 87
Table 4-1 Different Tracer Gas Methods 100
Table 5-1: The Building Parameters of the Selected Hospitals in the Study Area 109
Table 5-2: The Building Parameters of the Selected Multi-Bed Wards 111
Table 5-3: The images of the hospital wards investigated 117
Table 5-4: Multi-Bed Ward Openings Characteristics 119
Table 5-5: Window Area in Relation to the Hospital Ward's Floor Area 120
Table 5-6: Multi-Bed Ward Furniture Characteristics 120
Table 5-7: various components of the multi-bed wards and their characteristics 121
Table 5-8: Multi-Bed Ward Ventilation Parameters 122
Table 5-9: Randomly Measured Temperature and Relative Humidity of Hospitals wards in Maiduguri 123
Table 5-10: The Questionnaire response rates 125
Table 5-11: Indoor Air Quality Problem Consideration in Wards 126
Table 5-12: Frequency of responses for Reason IAQ Considerations in different Hospitals in Maiduguri 127
Table 5-13: Experience of Smell and Odour in the Wards 128
Table 5-14: Reasons for Smell and Odours in the Hospital Multi-Bed Wards 129
Table 5-15: Availability of Contaminant Sources in the Wards 130

Table 5-16: Sources of Contaminants in Hospital Multi-Bed Wards in the Study Area 131
Table 5-17: The Respondents Views about Indoor Air Quality in the Multi-Bed Wards in the Study Area...133
Table 5-18: Presence of Dust Problem in the Wards 134
Table 5-19: Possible Sources of Dust in Hospital Multi-Bed Wards 135
Table 5-20: Noticeable Dust Particles in the Wards 136
Table 5-21: Seasonality of Dust Problem in the Wards...137
Table 5-22: Season with Highest Dust problem 137
Table 5-23: Mosquito Problem in the Hospital Wards 139
Table 5-24: Sources of Entrances of Mosquito in the Multi-Bed Wards...............140
Table 5-25: Seasonality of Mosquito Problem 141
Table 5-26: Extend of Mosquito Problem per Season 141
Table 5-27: Thermal Comfort Satisfaction Level 142
Table 5-28: Draughtiness in the Wards..143
Table 5-29: Humidity in the Wards 144
Table 5-30: Nature of the Airflow in the Wards 146
Table 5-31: Indoor Air Quality and Patient Health Deterioration 147
Table 6-1: The measured hospital wards and their prevailing wind directions (angel of attack)...152
Table 6-2: Squirrel Data logger Channels Employed 155
Table 6-3: Sequence of events in the tracer gas measurement process..................159
Table 6-4 properties of some typical tracer gases 160
Table 6-5: Infiltration Rates and other Climatic Parameters at measurement period for closed window in wards 164
Table 6-6: Air Change Rates and other Climatic Parameters at measurement period for opened window in wards...165
Table 6-7: The difference in air temperature between closed and opened window wards 168
Table 6-8: The difference in relative humidity between closed and opened window wards 170
Table 6-9: The logarithmic CO_2 concentration decay curve for all the cases studied ..172
Table 6-10: The CO2 concentration (ppm) decay curve for all the cases studied showing data points used..175
Table 6-11: The Air Change Rates and Indoor Air Temperature of the measured hospital wards 178
Table 7-1: Surface roughness lengths 187
Table 7-2: Davenport classification of effective terrain roughness (Wieringa et al, 2001) 187
Table 7-3: Terrain coefficients for wind speeds 189
Table 7-4: The corrected velocities at the building positions (city) for different cases validated 190
Table 7-5: The corrected velocities at the building positions (city) for Different Velocities investigated 190

Table 7-6: The corrected velocities at the building positions (city) for the 12 months investigated 190
Table 7-7: Properties of Concrete Hollow Block........ 199
Table 7-8: Properties of Concrete slab and Sand........ 200
Table 7-9: Properties of Air 200
Table 7-10: Volumetric airflow rates of individual openings and air change rates of cases 1 to 9 202
Table 7-11: Summary of boundary conditions used for the simulations 203
Table 7-12: Contours of Velocity Magnitudes for the 9 Cases Validated 204
Table 7-13: The Validation of the Measured Volumetric Flow Rates with CFD Simulation 205
Table 7-14: The Validation of the Measured Air Change Rates with CFD Simulation206
Table 7-15 Mesh Properties 208
Table 7-16: The Volumetric Flow rates of three different Mesh sizes 208
Table 8-1: Horizontal sections and 3D streamline of Case 1 showing airflow distribution 215
Table 8-2: Horizontal sections and 3D streamline of Case 2 showing airflow distribution 216
Table 8-3: Horizontal sections and 3D streamline of Case 3 showing airflow distribution 217
Table 8-4: Horizontal sections and 3D streamline of Case 4 showing airflow distribution 218
Table 8-5: Horizontal sections and 3D streamline of Case 5 showing airflow distribution 219
Table 8-6: Horizontal sections and 3D streamline of Case 6 showing airflow distribution 219
Table 8-7: Horizontal sections and 3D streamline of Case 7 showing airflow distribution 220
Table 8-8: Horizontal sections and 3D streamline of Case 8 showing airflow distribution 221
Table 8-9: Horizontal sections and 3D streamline of Case 9 showing airflow distribution 222
Table 8-10: Horizontal sections and 3D streamline of Case 10 showing airflow distribution 223
Table 8-11: Horizontal sections and 3D streamline of Case 11 showing airflow distribution 224
Table 8-12: Horizontal sections and 3D streamline of Case 12 showing airflow distribution 225
Table 8-13: Horizontal sections and 3D streamline of Case 13 showing airflow distribution 225
Table 8-14: Horizontal sections and 3D streamline of Case 14 showing airflow distribution 226
Table 8-15: Horizontal sections and 3D streamline of Case 15 showing airflow distribution 227

Table 8-16: Horizontal sections and 3D streamline of Case 16 showing airflow distribution 228
Table 8-17: Horizontal sections and 3D streamline of Case 17 showing airflow distribution 229
Table 8-18: Indoor Airflow rates characteristics various ventilation strategies in the multi-bed wards........ 232
Table 8-19: Volumetric flow rates of the various openings strategies in the multi-bed wards 234
Table 8-20: Contours showing velocity magnitudes at 1.0 meters (occupancy level) above floor level........ 235
Table 8-21: Contours showing velocity magnitudes at 0.6 meters (occupancy level) above floor level........ 236
Table 8-22: Contours showing vertical section of velocity magnitudes at the centre of the ward (through the window)........ 237
Table 8-23: 3D streamlines showing velocity magnitudes of different opening cases. 238
Table 8-24: Air change rates per standard person for different occupancy levels and their corresponding percentage of dissatisfactions (PD)........ 242
Table 8-25: Volumetric flow rates of different ward orientations for Cases 1, 9 and 16 256
Table 8-26: Indoor air distribution of different ward orientations at 1.0 metres above floor level 257
Table 8-27: Indoor air distribution of different ward orientations at 0.6 metres above floor level 258
Table 8-28: Vertical indoor air distribution of different ward orientations at the centre of the ward........ 259
Table 8-29: 3D streamline showing Indoor air distribution of different ward orientations 260
Table 8-30: Volumetric flow rates of different ward orientations for cases 1, 9 and 16 261
Table 8-31: Air change rates of different ward orientations for cases 1, 9 and 16 264
Table 8-32: Indoor Average Air Velocity of different ward orientations for cases 1, 9 and 16........ 265
Table 8-33: Indoor Average Turbulence Intensity of different ward orientations for cases 1, 9 and 16........ 266
Table 8-34: Volumetric flow rates for different Porosities (Cases 1 and 16) 268
Table 8-35: Total volumetric airflow rates for different porosities (m^3/s) (Cases 1 and 16) 269
Table 8-36: Air Change Rates (ACR) of different Porosities (ach^{-1}) (Cases 1 and 16) 270
Table 8-37: Average indoor air velocities for different screen porosities (m/s) (Cases 1 and 16)........ 270
Table 8-38: Average indoor turbulent intensity for different porosities (%) (Cases 1 and16)........ 272
Table 8-39: Volumetric airflow rates for different velocities of cases 1 and 16........... 274
Table 8-40: Volumetric Airflow Rates (m3/s) for different Velocities (Cases 1 and 16) 275

Table 8-41: Air Change Rates (ach^{-1}) for different Velocities (Cases 1 and 16)..........276
Table 8-42: Average indoor air Velocity for different Velocities (Cases 1 and 16).....277
Table 8-43: Average indoor Turbulent Intensity (%) for different Velocities (Cases 1 and 16).....278
Table 8-44: The monthly volumetric flow rates and air change rates (Cases 1 and 16) 279
Table 8-45: The monthly average indoor air velocity and turbulent intensity (Cases 1 and 16).....280
Table 8-46: The summary of the simulated case studies showing air change rates and short-circuiting effects 284
Table 9-1: The Volumetric flow rates of individual openings and total volumetric flow rates of cases 16, 18 and 19.....310
Table 9-2; Indoor air flow characteristics of ventilation strategies with and without plenums 312
Table 9-3: Contours showing airflow pattern (Velocity magnitude) and 3D streamlines of cases 16, 18 and 19. 313
Table 9-4: The Volumetric flow rates of individual openings and total volumetric flow rates of different porosities of Case 19 325
Table 9-5: The Volumetric flow rates of individual openings and total volumetric flow rates of different porosities of Case 20 325
Table 9-6: Indoor air flow characteristics of case 19 with different screen porosities .326
Table 9-7: Indoor air flow characteristics of case 20 with different screen porosities .326
Table 9-8: Indoor air characteristics of different ventilation strategies with and without plenums 336
Table 10-1: Window Area in Relation to the Hospital Ward's Floor Area.....343
Table 10-2: Air change rates of different ward orientations for cases 16.....344
Table 10-3: Design Guidance for Architects 346
Table 12-1: Tracked, escaped and trapped characteristics of 1µm dust particles for different insect screen porosities.....364
Table 12-2: Tracked, escaped and trapped characteristics of 2.5µm dust particles for different insect screen porosities.....364
Table 12-3: Tracked, escaped and trapped characteristics of 5.0µm dust particles for different insect screen porosities.....365
Table 12-4: Tracked, escaped and trapped characteristics of 10.0µm dust particles for different insect screen porosities.....365
Table 12-5: Tracked, escaped and trapped characteristics of 20.0µm dust particles for different insect screen porosities.....366
Table 12-6: Tracked, escaped and trapped characteristics of 30.0µm dust particles for different insect screen porosities.....366
Table 12-7: Tracked, escaped and trapped characteristics of 40.0µm dust particles for different insect screen porosities.....367
Table 12-8: Tracked, escaped and trapped characteristics of 50.0µm dust particles for different insect screen porosities.....367
Table 12-9: Tracked, escaped and trapped characteristics of 60.0µm dust particles for different insect screen porosities.....368

Table 12-10: Tracked, escaped and trapped characteristics of 70.0μm dust particles for different insect screen porosities 368
Table 12-11: Tracked, escaped and trapped characteristics of 80.0μm dust particles for different insect screen porosities 369
Table 12-12: Tracked, escaped and trapped characteristics of 90.0μm dust particles for different insect screen porosities 369
Table 12-13: Tracked, escaped and trapped characteristics of 100.0μm dust particles for different insect screen porosities 370
Table 12-14: Tracked, escaped and trapped characteristics of 1μm dust particles for different outdoor wind speeds 371
Table 12-15: Tracked, escaped and trapped characteristics of 2.5μm dust particles for different outdoor wind speeds 371
Table 12-16: Tracked, escaped and trapped characteristics of 5.0μm dust particles for different outdoor wind speeds 371
Table 12-17: Tracked, escaped and trapped characteristics of 10.0μm dust particles for different outdoor wind speeds 372
Table 12-18: Tracked, escaped and trapped characteristics of 20.0μm dust particles for different outdoor wind speeds 372
Table 12-19: Tracked, escaped and trapped characteristics of 30.0μm dust particles for different outdoor wind speeds 372
Table 12-20: Tracked, escaped and trapped characteristics of 40.0μm dust particles for different outdoor wind speeds 373
Table 12-21: Tracked, escaped and trapped characteristics of 50.0μm dust particles for different outdoor wind speeds 373
Table 12-22: Tracked, escaped and trapped characteristics of 60.0μm dust particles for different outdoor wind speeds 373
Table 12-23: Tracked, escaped and trapped characteristics of 70.0μm dust particles for different outdoor wind speeds 374
Table 12-24: Tracked, escaped and trapped characteristics of 80.0μm dust particles for different outdoor wind speeds 374
Table 12-25: Tracked, escaped and trapped characteristics of 90.0μm dust particles for different outdoor wind speeds 374
Table 12-26: Tracked, escaped and trapped characteristics of 100.0μm dust particles for different outdoor wind speeds 375
Table 12-27: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 16 376
Table 12-28: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 18 376
Table 12-29: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 19 377
Table 12-30: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 20 377
Table 12-31: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 19 with insect screen porosity of P-0.1 378

Table 12-32: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 19 with insect screen porosity of P-0.2 378
Table 12-33: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 19 with insect screen porosity of P-0.3 379
Table 12-34: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 20 with insect screen porosity of P-0.1 379
Table 12-35: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 20 with insect screen porosity of P-0.2 380
Table 12-36: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 20 with insect screen porosity of P-0.3 380

List of Symbols, Acronyms and Abbreviations

Acronyms and Abbreviations

Acronym/Symbols	Description
A	Opening area (m^2)
a	The thermal diffusivity of the fluid.
ABL	Atmospheric Boundary Layer
AC	Air Conditions/ Alternating Current
ach^{-1}	Air Change per Hour
ACR	Air Change Rate (ach^{-1})
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
C	Tracer Gas Concentration in Rooms
C	Centre
C_2	Pressure jump coefficient
CAD	Computer Aided Design
C_c	Cunningham correction factor
CFD	Computational Fluid Dynamics
CH_2O	Formaldehyde
$C_5H_8O_2$	Glutaraldehyde
$C_{int}t_0$	Internal concentration of tracer gas in enclosure at start
C_{ext}	External concentration of tracer gas in room
$C_{int}t_1$	Internal concentration of tracer gas in enclosure at end
CO	Carbon monoxide
CO_2	Carbon Dioxide
C_s	Roughness constant
C_μ	0.09 (the model constant of the standard k-ε model)
CPU	Central Processing Unit

Cv	Convection (including respiration)
EIA	Energy Information Administration
CIBSE	Chartered Institution of Building Service Engineers
DNS	Direct Numerical Simulation
d_p	Particle diameter
DPM	Discrete Phase Model
DRW	Discrete Random Walk
EPA	Environmental Protection Agency
Ev	Evaporation (including respiration)
F	Additional acceleration term
$F_D(u - u_p)$	Drag force per unit particle mass
FNPHM	Federal Neuro-Psychiatric Hospital Maiduguri
g	Gravitational acceleration (m/s^2)
$g\ \rho_p - \rho/\ \rho_p$	Gravity force
H	Building Height (m)
h	Opening height (m)
U_H	Wind velocity at the building height H (m/s)
HAI	Healthcare associated infections
HCW	Health Care Workers
HVAC	Heating Ventilating and Air Conditioning
HTM	Health Technical Memorandum
k	Turbulence kinetic energy
K	Screen permeability
k–ε	k epsilon turbulence model
k_s	Sand-grain roughness height (m)
LCC	Life Cycle cost
LPD	Lagrangian Particle Dispersion
IAQ	Indoor Air Quality

IEA	International Energy Agency
IMC	International Mechanical Code
ISO	International Standard Organisation
L	Leeward
LES	Large Eddy Simulation
ln	Natural logarithm
L/S	Litre per second
M	Metabolic heat production
MDRO	Multi drug Resistant Organism
MPSM	Modified Passive Scalar Model
MRSA	Methicillin-Resistant Staphylococcus Aureus
MRT	Mean Radiant Temperature
m/s	Metre per second
m^3/s	Cubic metres per second
MW	Mega Watts
NHHM	Nursing Home Hospital Maiduguri
N	Air Change Rate
N/A	Not applicable
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
O_3	Ozone
P	Points
p	The instantaneous static pressure (N/m^2)
PD	Percentage Dissatisfied
PM	Particulate Matters
PM_{10}	Particles if size <10µm
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied

PPM	Parts Per Million
PSM	Passive Scalar Model
Q_{tot}	Total volumetric flow rate (m^3/s)
Q_w	Volumetric flow rates due to wind effect (m^3/s)
Q_s	Volumetric flow rates due to stack effect (m^3/s)
Q(t)	Air supply into a room [m^3/s]
R^2	Regression coefficient
RANS	Reynolds-Averaged Navier-Stokes
RC	Telemetry Receiver Channel
Rd	Net radiation exchange
RH	Relative Humidity
RSP	Respirable Suspended Particulates
SARS	Severe Acute Respiratory Syndrome
S/N	Serial Number
SSHM	State Specialist Hospital Maiduguri
SO_2	Sulphur dioxide
SPM	Suspended Particulate Matter
T	Temperature (K)
T_0	The fluid temperature at a reference location (K)
T_{avg}	Average of inside and outside temperature (K).
T_{oav}	Average ambience temperature (K)
TVOC	Total Volatile Organic Compounds
T_n	Neutrality temperature (°C)
t	Time [s]
t	Air temperature (°C)
T_u	turbulence intensity (%)
t_n	Surface temperature of surface n, °C
t_0	Time at start (seconds)

t_1	Time at end (seconds)
U	Vertical velocity profile
U_{10}	Inlet wind speed in computational domain at 10m height (m/s)
U_{pot}	Potential wind speed (m/s)
U_{city}	Wind speed for city terrain (m/s)
U_{meteo}	Wind speed at meteorological station (m/s)
U_{ref}	Reference wind speed at reference height z
u	Airflow velocity (m/s)
u	The instantaneous x velocity components (m/s)
u_p	Particle velocity (m/s)
u*	Friction velocity (m/s)
u^*_{city}	Friction velocity for city terrain (m/s)
u^*_{meteo}	Friction velocity at meteorological station (m/s)
UDF	User Defined File
UMTH	University of Maiduguri Teaching Hospital
USUHM	Umaru Shehu Ultra-Modern Hospital Maiduguri
v	The air velocity (m/s)
v	The instantaneous y velocity components (m/s)
v_z	Wind speed at the building height (m/s)
v_m	Wind speed measures in open country at a height of 10 (m/s)
VOC	Volatile Organic Compounds
VR	The room's volume [m^3]
W	Windward/ Window
WHO	World Health Organisation
WSR	Wireless Sensor Receiver system
W_Screen	Window Screen
Y	Inertial factor
y_p	A distance from the centre point P of the wall-adjacent cell to the wall (bottom of domain) (m)

z	Height above ground level/Building height (m)
z_0	Aerodynamic roughness length (m)
$z_{0, city}$	Aerodynamic roughness length for the city terrain (m)
$z_{0, meteo}$	Aerodynamic roughness length for meteorological terrain (m)
z_{ref}	Reference height 3.3m
3D	Three dimensional
ΔT	Inside-outside temperature difference (K)
ρ	Density Fluid density (kg/m^3)
ρ_p	Particle density (kg/m^3)
μ	kinematic viscosity/Fluid viscosity
μm	Micrometre
β_T	The expansion coefficient due to temperature change
τ	Time (s)
ε	Turbulence dissipation rate
ƙ	0.42(the von Karman constant)
λ	Molecular mean free path
$\lambda(t)$	Ventilation rate or air change rate [h^{-1}]

Chapter One

Introduction

Chapter Structure

1.1 Background of the Study

1.2 Statement of Problem

1.3 Research Questions

1.4 Aims and Objectives

1.5 Nature of Study

1.6 Importance of Study

1.7 Reasons/Rationale of the Study

1.8 Context of Study

1.9 The General Research Concept

1.10 Thesis Structure

1. Chapter One: Introduction

1.1 Background of the Study

The study “Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals Located in Semi-Arid Climates” was initiated to provide acceptable indoor air quality in the hospital wards of the study area (semi-arid climates). Indoor Air Quality (IAQ) in hospital multi-bed wards is more essential compared to any other facility because of the nature of people it accommodates who are immunosuppressed and immune-compromised due to certain illnesses. However, the provision of acceptable indoor air quality requires an effective ventilation system that can remove all contaminants in the indoor space while preventing outdoor ones from entering. Indoor air quality in the context of this study stands for the ability of the natural ventilation system to provide the acceptable ventilation rates of at least 6 ach^{-1} recommended by ASHRAE, while eliminating or reducing the penetration of outdoor unwanted substances/contaminants including Harmattan dust and mosquitoes. Thus, enhancing the ventilation rates increases the removal of other indoor contaminants. Moreover, owing to the recent trend in design that gives more consideration to sustainable and energy efficient buildings to cut down carbon emission and global warming together with protracted energy shortage in the study area. There is a need to adopt a non-energy intensive ventilation strategy in providing acceptable indoor air quality.

A hospital is a place people visit seeking medical treatments to recover from their illnesses. These visitors usually range from children to adults, sick and healthy, able and disabled. Among them are often those individuals who are immunosuppressed and immunocompromised due to certain illnesses, which makes them highly vulnerable to be infected with nosocomial (Healthcare Acquired Illnesses) infections, of which some are life-threatening diseases. However, the major concern of this study is hospital multi-bed wards design which happens to be one of the most important spaces due to the nature of its diverse indoor environment and how indoor quality is maintained.

Furthermore, most indoor air associated infections in hospitals are believed to be product of poor architectural designs, building material selection, ventilation system design, and ambient climatic situation. A simple airborne dispersion of some nosocomial pathogens to hospital’s interior space can trigger extensive indoor contamination and contributes to the spread of infection in the facility. In addition, if hospitals happen to be a place where life-threatening infections could be acquired, then the aim of the visit has been defeated and this situation would create great concern for all visitors. Thus, using indoor air quality control measures, prevalent problems of infections that could affect patients in hospitals will be minimize or totally eliminated.

According to Pepper and Carrington (2009), indoor air pollution denote the studies related to emission, accumulation, and assessment of pollutants commonly attributed to poor ventilation and air exchange in buildings. The health consequences of indoor air pollutants could be experienced shortly after exposure or, maybe, years later. Immediate effects include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue, whereas Long-term effects include some respiratory diseases, heart disease, and cancer, etc. Symptoms of some diseases may emerge shortly after exposure to indoor air contaminants, including asthma, hypersensitivity pneumonitis, and humidifier fever (U.S. Environmental Protection Agency-EPA, 2010c).

However, due to the strict climatic condition in the tropics (semi-arid) characterized with overheating as a result of solar gain, hot and dusty air and mosquitoes, the need for the design of sustainable and energy efficient hospitals cannot be over-emphasized. Several studies have shown that extra energy is required to maintain acceptable indoor air quality. Hence, sustainable and energy efficient ventilation systems are required for the removal of various indoor air pollutants in hospital wards. As ventilation systems are designed to stop contaminants from entering a space and at the same time remove contaminants from interior sources within the space (Pepper and Carrington, 2009). The major concern of this study is contaminants with outdoor sources such as mosquitoes and Harmattan dust. Therefore, the performance and condition of ventilation in hospitals have great impact on the perceived indoor air quality (Hellagren, U. et al, 2011).

Energy utilization in buildings is a key issue having a direct impact on the indoor air quality and thermal comfort of a building. However, energy conservation is important for the growth of developing countries especially with protracted power and energy shortages. The simplest approach is to use mechanical systems to improve air quality, but these systems have an energy penalty that developing countries cannot sustain. Hence, design teams have to reconcile energy demand, indoor air quality and pollutant source control (Guenther, 2010). Wong et al. (2008) in their studies found a non-linear relationship between indoor air quality acceptability and energy consumption, meaning extra energy is needed to maintain a higher indoor air quality acceptability.

Consequently, to pursue energy conservation in hospitals without taking the quality of indoor air into consideration puts occupants at unnecessary health risk. On the contrary, the major concern is to pursue good indoor air quality without considering the efficient use of energy that may unnecessarily increase energy costs and emissions of greenhouse gases, thereby contributing to outdoor air pollution and possibly even global warming (Air Quality Sciences, Inc. 2006). According to ASHRAE Position Document (2011) IAQ and building energy performance are significantly connected and these connections must be considered from the very beginning stages and throughout the processes of design, retrofit and renovation. However, in the study area (Nigeria), the electricity demand exceeds the supply and even the supply remains unreliable (Sambo, 2008). The available power supply in Nigeria is less than 41% of the total installed capacity (Emovon et al. 2011). Thus, energy intensive ventilation systems are not applicable in the study area.

Therefore, the major concern is to provide sustainable and clean indoor air in hospital wards with less energy and without compromising occupants' health. The World Commission on Environment and Development has defined "sustainability" as meeting the needs of the present without compromising the ability of future generations to meet their own needs (Kim and Rigdon, 1998). Thus, this study will focus on investigating how different concepts of sustainable natural ventilation strategies in semi-arid climates can affect indoor air quality in hospital wards in the presence of challenging Harmattan dust and mosquitoes. In this study, natural ventilation was selected due to its low/zero energy requirements.

Hence this research aims to provide acceptable indoor air quality using ventilation in hospital wards of the study area. Selected case studies have been investigated to ascertain the actual situation in the context of semi-arid climate of northern Nigeria with the aim of providing strategies for clean and healthy indoor air quality in hospitals. Based on the outcome of the existing hospital wards' ventilation, which fall short of the ASHRAE's standard requirement of 6 ach^{-1}, Computational Fluid Dynamics (CFD) simulations of various natural ventilation strategies have been conducted.

1.2 Statement of Problem

The study "Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals Located in Semi-Arid Climates" was informed by the problems of infections associated with indoor air pollutants in hospitals and contribution of outdoor sources of indoor air pollutants such as mosquitoes and Harmattan dust. Owing to the nature of these hospital wards, which accommodates the most vulnerable group of people often immunosuppressed and immunocompromised due to certain illnesses, there is a high opportunity for infectious pathogens and other healthcare acquired illnesses to spread rapidly. Furthermore, these infectious pathogens were spread often as a result of poor ventilations and presence of contaminant source within and around the hospital wards. The recent emergence of new pathogens like Severe Acute Respiratory Syndrome (SARS), Swine Flu influenza and presence of tuberculosis has also aggravated the research on efficient indoor air in hospitals. Moreover, the harsh weather conditions associated with the semi-arid climates, characterized with overheating as a result of direct solar gain, hot and dusty air blowing from the north east and mosquitoes have contributed immensely to the complication of the indoor air quality and ventilation problems. These circumstances have further made the indoor air quality more complex to predict and study. Hence, holistic approach is required for the investigation of natural ventilation strategies that can suite the situation in semi-arid climates of Nigeria.

1.3 Aims and Objectives

1.3.1 Aims

The major aim of the studies is to *'study the possibility of natural ventilation strategies in achieving acceptable indoor air quality in hospital wards of semi-arid climates with the presence of Harmattan dust and mosquitoes'*.

1.3.2 Objectives

The objectives of this study are as follows:

1. To investigate the nature of existing ventilation systems used in hospital wards of semi-arid climates.

2. To determine the effects of the identified ventilation strategies on indoor-air pollution in hospital wards of semi-arid climates.

3. To examine and analyse the performance of the existing ventilation strategies in relation to indoor air quality?

4. To explore the potentials of using natural ventilation strategies for achieving acceptable indoor air quality with the presence of Harmattan dust and Mosquitoes

5. To provide guidance for Architects

1.4 Nature of Study

The study "Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals Located in Semi-Arid Climates" is characterized by quantitative method of data collection on the selected case study hospital wards, the base-case model and the different CFD simulation cases and analysis of data to provide a sustainable design solution to the problems of indoor air quality, and natural ventilation in hospital multi-beds wards. In addition the study also investigates the consequences of mosquito and Harmattan dust in providing effective natural ventilation to achieve acceptable IAQ, ventilation and healthy environment.

1.5 Importance of Study

The study is an attempt to solve the key health and comfort problem related to IAQ and ventilation in hospital multi-beds wards. The outcome of this study will help in providing hospital multi-bed wards, with acceptable indoor air quality and free from mosquitoes and Harmattan dust. Moreover, the adoption and implementation of natural ventilation strategies in hospital wards will conserve energy, and consequently reduce the running cost of hospitals. The eradication or reduction in the effect of mosquitoes and Harmattan dust will prevent hospital ward occupants' from related diseases such as malaria and respiratory illnesses. Furthermore, the improvement of the ventilation rate will help in removing indoor air contaminant and subsequently provide the required fresh air.

1.6 Reasons/Rationale of the Study

The study "Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals Located in Semi-Arid Climates" was informed by the need for the design of healthy and energy efficient hospital wards in the semi-arid climates. Hospital wards, being home to vulnerable people who are often immunosuppressed and immunocompromised, requires good IAQ and ventilation compared to any other type of facility. However, several studies have been conducted on indoor air quality and ventilation in hospitals, which are mostly in temperate climates. Yau, et al (2011) reviewed the literature on the ventilation of multiple-bed hospitals in the tropics and concluded that, apparent knowledge gap exist for ventilation studies in the tropic compared with temperate climates. Thus, this study is intended to bridge or reduce the existing knowledge gap by providing hospital wards with efficient ventilation and acceptable indoor air quality.

1.6.1 Scope

The study will focus on natural ventilation strategies and their consequences on indoor air quality in hospital multi-beds wards in semi-arid climates. The case study hospital wards were selected in the semi-arid climatic region of North-East Nigeria (Maiduguri). Moreover, the study also concentrates on outdoor sources of indoor air pollutants including mosquitoes and Harmattan dust.

1.7 Context of Study

The study will investigate some existing multi-bed wards in hospitals of semi-arid climate (Maiduguri), with the objective of acquiring the exact nature of indoor air quality and ventilation and their effects on patients' health, staffs and visitors. This information is being exploited to consolidate the research problem and subsequently used as an input for CFD simulation for the provision of sustainable natural ventilation strategies in hospital multi-beds wards of semi-arid climates.

1.8 The General Research Concept

The conceptual framework of this research is explained in six stages. The first stage of the research is the identification of the problem, which was initiated through literature review of previous studies. The literature review facilitated the identification of the knowledge gap in ventilation and indoor air quality studies in hospital wards between the temperate and the tropical (semi-arid) climates. Various factors affecting natural ventilation design in relation to indoor air quality have been identified.

The second stage of this study is the selection of suitable research methodologies to be employed to answer the research questions. In selecting these methodologies, importance issues such as reliability, practicality, availability, cost effectiveness and easiness in implementation has been considered. The various methodologies used in this research have been discussed in detail and presented in chapter 4.

The third stage of this research is the investigation of the hospital wards occupants' psychosocial perception about the condition of indoor air quality and other indoor environmental factors that affects indoor air quality and ventilation in buildings. The inquiry about the psychosocial perception is conducted by administering questionnaire survey to medical doctors, nurses and other healthcare workers who are the most frequent users of the hospital wards. Likewise, the fourth stage of the study is the confirmation of the result obtained through the psychosocial perception using full-scale measurement. This is because the result from the questionnaire survey is a mere social perception of the occupants' which is not enough to establish the existence of problems and therefore, needs to be confirmed using experimental methods. Hence, it is difficult to confirm an environmental problem such as indoor air quality and ventilation through subjective social perception of people. The tracer gas decay method using CO_2 was used in assessing the indoor air quality of some existing hospital wards in the study area.

The fifth stage of this research is the selection of building performance prediction software (CFD) to enable in-depth investigation of different ventilation strategies and validation of the simulation models. State-of-the-art CFD simulation software Fluent 13.0 was used to validate the hospital ward models using the results obtained from the full-scale measurement through comparing the measured and the simulated ventilation rates, and the difference between the two is within the acceptable error limit. Finally, the sixth stage of this study is the evaluation of different ventilation strategies with the aim of providing acceptable indoor air quality, while reducing the effects of Harmattan dust and mosquitoes. These assessments will enable the selection of the best ventilation alternative for the hospital wards of the study area. The general description of the research concept is illustrated in figure 1.1.

Ventilation effectiveness in the context of this study refers to the ability of the ventilation air to circulate and cover the entire volume of the hospital ward especially at the occupant's level. This is evaluated qualitatively by visualising/assessing the contours of airflow vertically and horizontally in the room. Thus, the higher the area covered by ventilation air, the greater its effectiveness and the higher its ability to remove contaminants indoors.

1.9 Thesis Structure

In this research, chapter one (1) is the introduction of the entire study, providing the general overview of the study. Chapter two (2) introduces the characteristics of the study area. Chapter three (3) is the literature review, which discusses indoor air quality and ventilation and various factors affecting ventilation design in hospital wards. Chapter four (4) of the study presents the general research methodology adopted in satisfying the research objectives. Moreover, chapter five (5) of this study presents results of the physical, environmental, and social assessment of the existing hospital wards. Chapter six (6) discusses and presents the methods and results of the ventilation rates measurements using tracer gas decay methods. Likewise, chapter seven (7) describes the methods used in conducting the CFD simulation and the results of the CFD validation. Chapter eight (8) of the research presents the CFD simulation results on the effects of openings positions, screen porosity, outdoor wind speed and building orientation on ventilation rates. Furthermore, chapter nine (9) of this study presents the results of the CFD simulation on pollutants dispersion including the influence of screen porosity, outdoor wind speed, plenums and particle sizes on indoor particle concentration, deposition and suspension. Chapter ten (10) presents the guidance for Architects. Finally, chapter eleven (11) is conclusions, limitations and recommendations for future research.

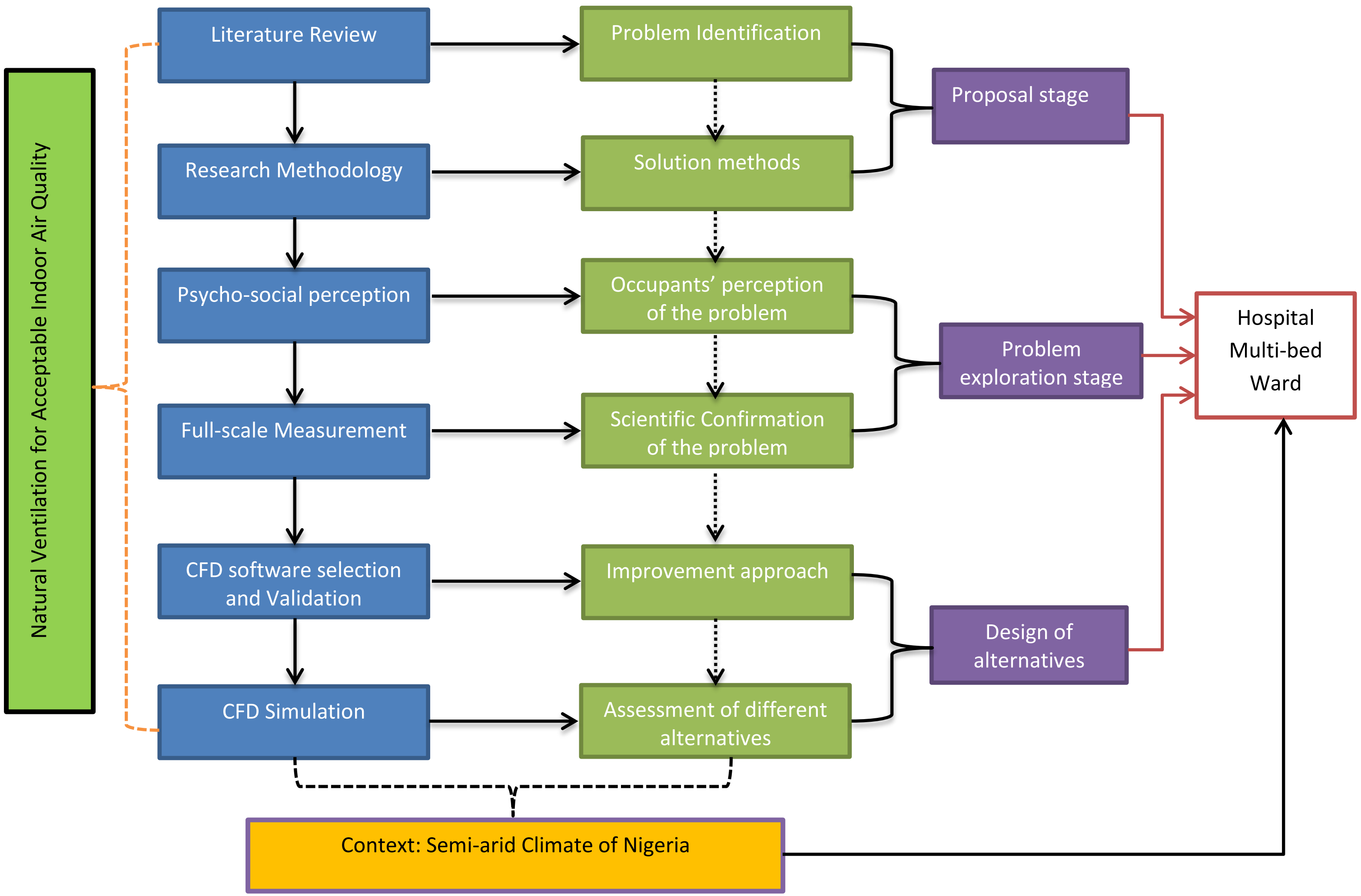


Figure 1.1: The General Research Concept

Chapter Two

Study Area, Semi-arid, Harmattan Dust and Mosquito

Chapter Structure

2.1 Introduction

2.2 Arid and Semi-Arid Climates

2.3 Nigerian Climate

2.4 Suspended Particulate Matters (SPM)

2.5 Mosquitoes

2.6 Chapter Conclusion

2. Chapter Two: Study Area

2.1 Introduction

The introduction of the study area (Semi-arid climate of Nigeria) is necessary to provide the required information about the various factors to be considered while designing ventilation system in the study area. The geographic location of the building is among the most important considerations in the design of natural ventilation systems that will eventually determine the seasonal differences in the outdoor environmental factors, such as air temperature, solar radiation, wind, humidity and outdoor air quality (Awbi, 1994). The previous chapter (Chapter 1) introduces the background of the entire thesis and described the research problem and objectives. This chapter introduces the environmental characteristics of the study area (Maiduguri) and various factors affecting ventilation and indoor air quality including mosquitoes, Harmattan dust and temperature.

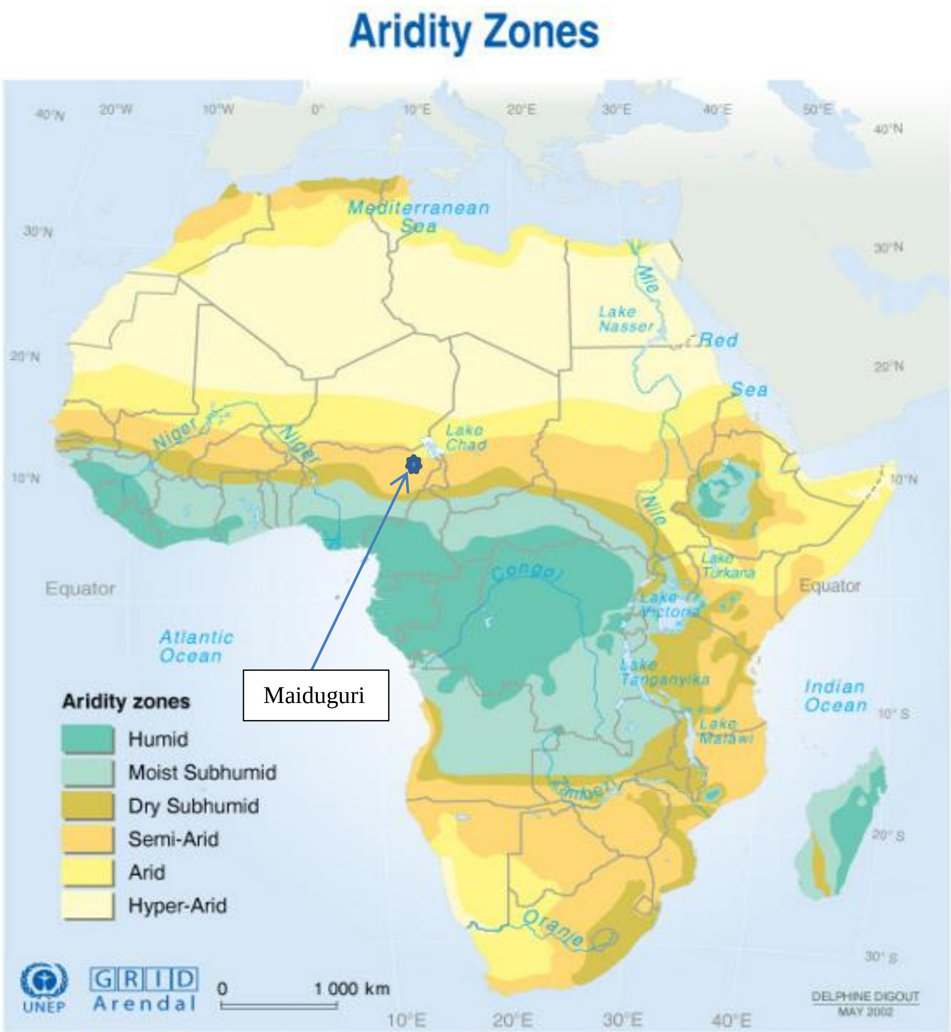
In order to achieve comfortable indoor air quality with the presence of mosquitoes and Harmattan dust in healthcare facilities, the climatic elements and type have to be considered at the design stage. In this chapter, section 2.2 discusses the characteristics of arid and semi-arid climates; section 2.3 introduces the climate condition of Nigerian and the study area Maiduguri; section 2.4 presents the characteristics of suspended particulate matters and Harmattan dust; and section 2.5 discusses the characteristics of mosquito insects and the effect of malaria in the study area.

2.2 Arid and Semi-Arid Climates

Aridity generally occurs due to persistence anticyclonic circumstances of an environment, as a result of the presence of dry and descending air, akin to the case in the areas lying under the anticyclones of the subtropics. The climatic pattern in arid zones are distinguished by relatively “cool” dry season, subsequently a relatively “hot” dry season, and finally by a “moderate” rainy season. They are characterized by extreme heat and inadequate, variable precipitation with occurrence of contrasts in climate. These climatic contrasts develop from differences in temperature, the season in which rain falls, and in the degree of aridity (FAO, 1989).

The characteristics of arid zones in the warmer climates like that of Nigeria consist of low and erratic precipitation, diurnal fluctuations in air and soil temperatures, strong winds, bright sunny days, and low humidity, while dew point is believed to be contributing considerably to the availability of moisture in certain seasons (Ben Salem, 1980). Furthermore, owing to the considerable variation in diurnal temperature in these zones, quite frequently during the “cool” dry season, daytime temperatures peak between 35^{o}C and 45^{o}C and fall to 10^{o}C to 15^{o}C at night. However, during the “hot” dry season, daytime temperatures climax approaches 45^{o}C, but, falling to 15^{o}C at night, while the temperature ranges from 35^{o}C, in the day time, to 20^{o}C at night, during the rainy season. Moreover, due to the shortage of vegetation that can decrease air movements, arid regions are generally windy (FAO, 1989).

According to WMO, (2001) forty per cent of population in Africa resides in arid, semi-arid, and dry sub-humid areas. Semi-arid climates referred to mainly non Polar Regions that are generally characterized with low annual rainfall (from 250 to 500 mm) and comprises of short grasses or shrub vegetation (Meteorology and Climate, 2007). According to FAO, (1989) semi-arid zone covers 12.2 per cent of the total area of the world. Figure 2.1 shows the various divisions of aridity in Africa.



Source: World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

Figure 2.1 Aridity Zones in Africa

2.3 Nigerian Climate

Nigeria's Climate like most of West Africa is characterized by strong latitudinal zones, gradually becoming drier as one moves north from the coast. According to Olaniran, (1986) the Nigerian regional climatology can be distinguished by three aspects, including the air mass residential time, the wind regime and characteristics of rainfall. Although, the major climatic variable remains rainfall, but there is a noticeable alternation of wet and dry seasons in most areas. Two air masses control rainfall including moist south-westerly monsoon wind, which is a moving maritime air coming from the Atlantic Ocean and dry continental north easterly trade wind coming south from the African landmass (Metz, 1991) as illustrated in figure 2.2. In the far north, rainfall generally commences between June and July, while the peak rainy season occurs in month of August when air from the Atlantic covers the entire country. However, the inland regions, particularly in the northeast, have greater extremes in temperatures reaching as high as 44° C prior to the rainy season and drop as low as 6° C during an incursion of cool air from the north between December and February (Metz, 1991).

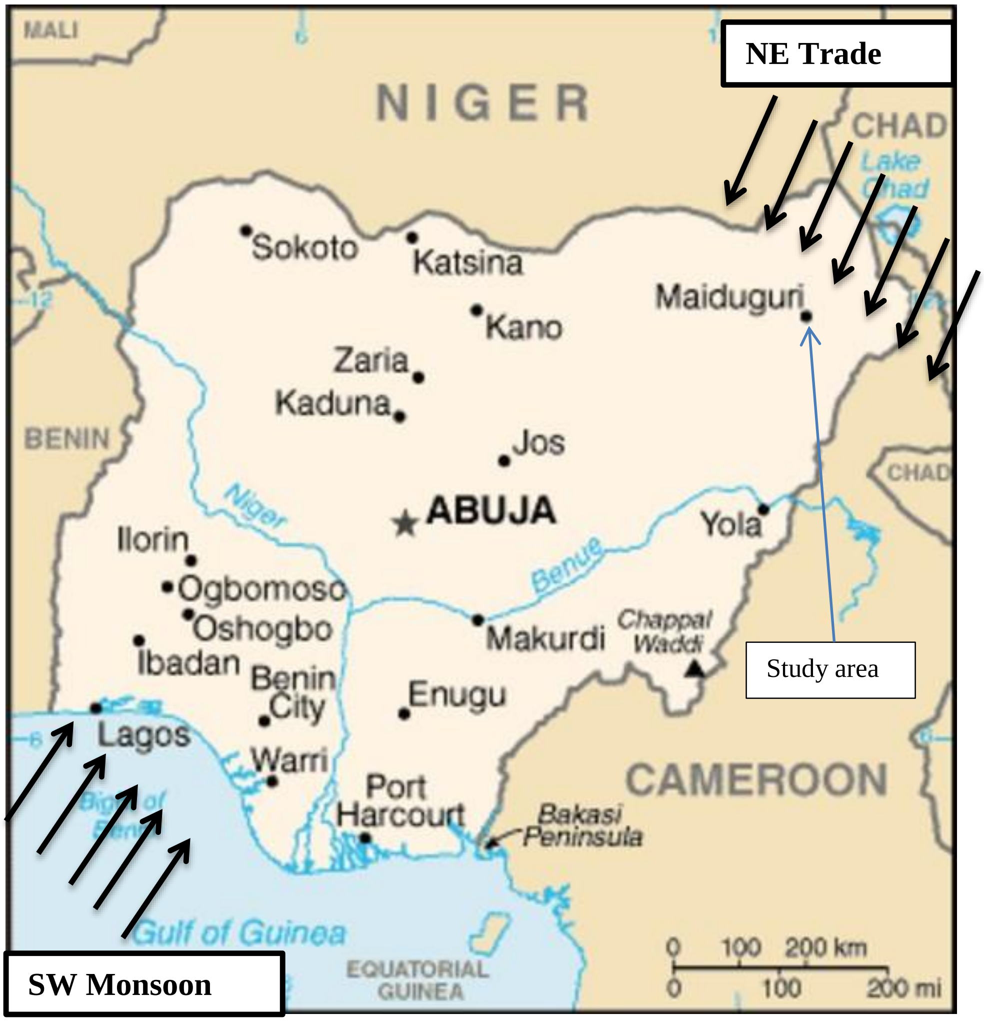


Figure 2.2: Nigerian Map showing North-East (NE) Trade wind and South-West (SW) Monsoon wind

Moreover, the period of clear skies, moderate temperatures, and lower humidity is usually experienced from September through November, as a result of the Northeast trade winds for most of the country. However, the North-east trade wind gust strongly from December to February, transporting huge amount of fine dust from the Sahara desert locally referred to as Harmattan dust. The Harmattan dust normally emerges as a dense fog, covering everything in the environment with a layer of fine particles. It is more regular in the North but it effects cover the whole country apart from a narrow strip along the southwest coast (Metz, 1991).

Owing to the complex nature of the environment, it is difficult to accurately determine the boundaries of climatic zones for the architectural design purpose. Olaniran, (1986) presented the Koppen classification of Nigerian climates. The Koppen classification categorised the Nigerian climate into five (5) categories including Tropical Monsoon (Am), Tropical wet and dry marked by two rainfall peaks (Aw”), Tropical wet and dry marked by a single rainfall peaks (Aw), Semi-arid (Bs), and Desert (Bw) as illustrated in Figure 2.3. However, Koppen classification system which is mostly recognized for the global assessment of climatic zones has a major limitation that, it relies solely on rainfall and temperature and as such, relationship to building design for thermal comfort is less (Evans, 1980). This is consistent with the findings of Olgyay (1963), which said the Koppen “classifications are not directly applicable to housing”. This is owing to the absence of a significant thermal comfort factor of humidity in the classification (Ogunsote and Prucnal-Ogunsote, 2002).

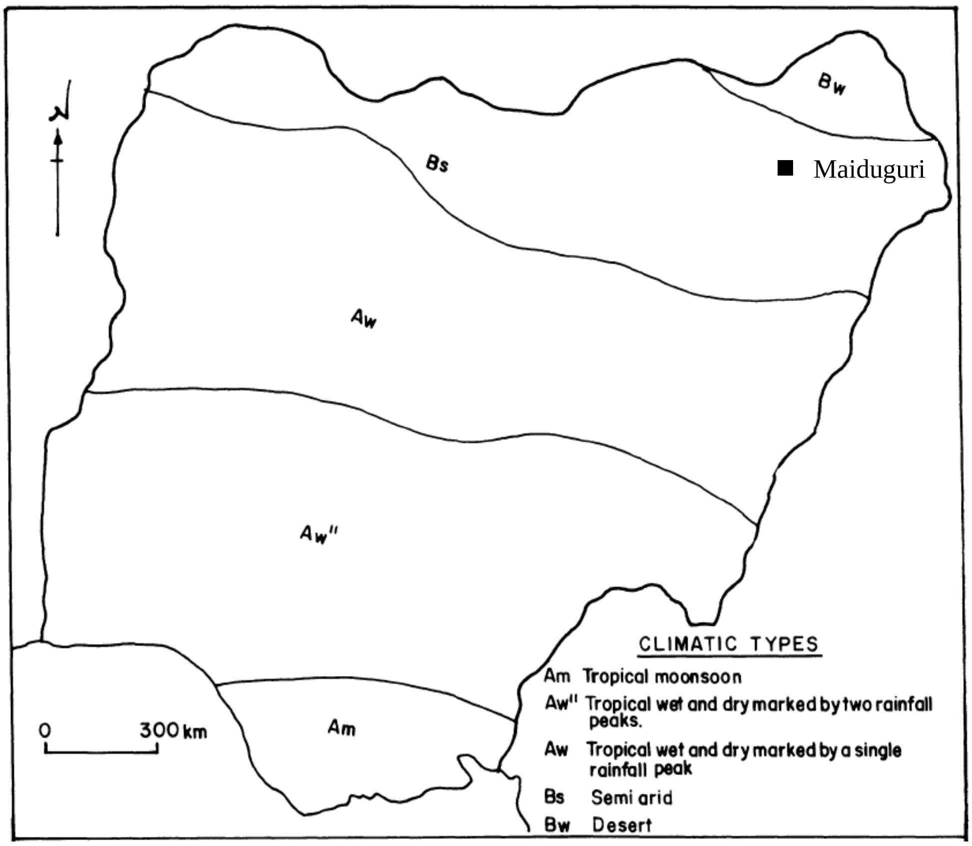


Figure 2.3 Climatic Classification of Nigeria According to Koppen (Olaniran, 1986)

However, the Nick Hollo classification was presented by Ogunsote and Prucnal-Ogunsote, (2002) which proposed four major design zones and later expanded by identifying sub-regions within the major zone. These sub-regions are divided into six including the Coastal Zone (IV), the Forest Zone (IIIa), the Transitional Zone (III), the Savannah Zone (II), the Highland Zone (IIa) and the Semi-Desert Zone (II), as illustrated in Figures 2.4. Although, this method is attractive and largely depends on descriptions and imagery, but due to the general and unspecific nature of the method, it is difficult to be used in locations identified by the most basic climatic data (Ogunsote and Prucnal-Ogunsote, (2002)

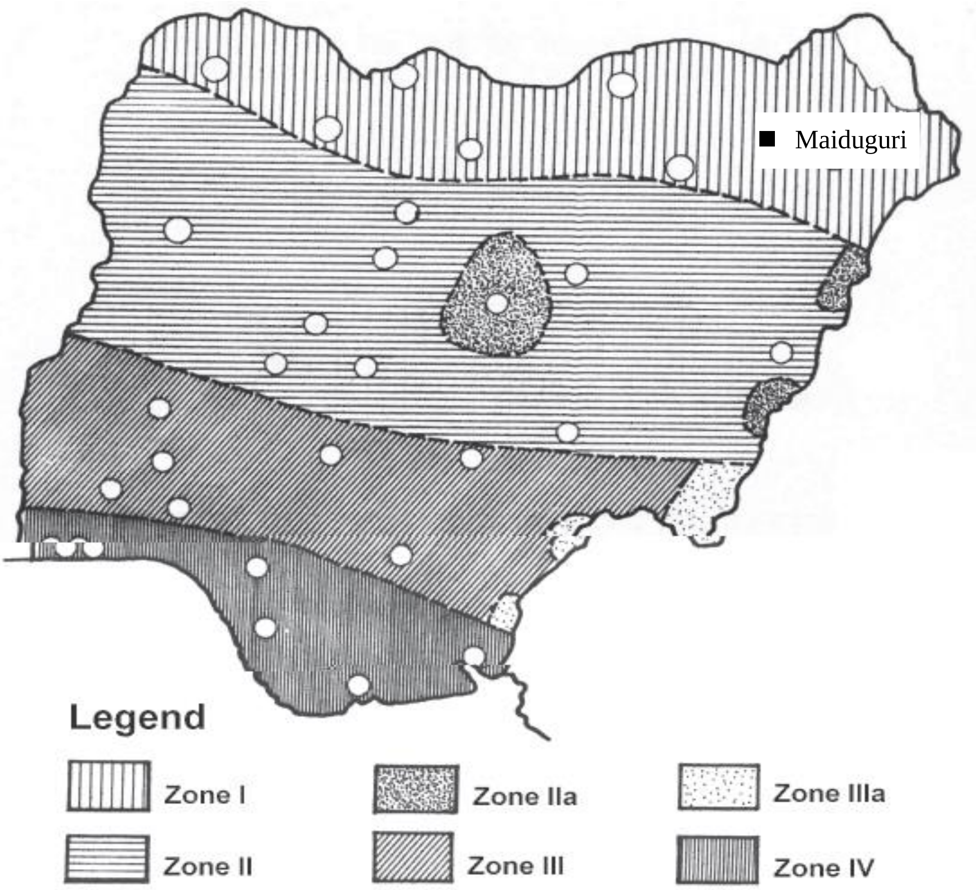


Figure 2.4 The climatic regions for bioclimatic design in Nigeria according to Nick Hollo. (Ogunsote, and Prucnal-Ogunsote, 2002)

Owing to the shortcomings of both Koppen and Nick Hollo climate classifications, Ogunsote and Prucnal-Ogunsote, (2002) have proposed another classification for architectural designs in Nigeria. The classification has nine different design zones in including the Coastal Zone, the Forest Zone, the Transitional Zone (a), the Transitional Zone(b),the highland zone, the Savannah Zone (a), Savannah Zone (b), the Semi-Desert Zone (a), and the Semi-Desert Zone (b), as illustrated in Figure 2.5. Compared to the Koppen and Nick Hollo climate classifications, this method succeeded in providing reference bioclimatic design for most major cities in Nigeria. As such, the method provides more specific data by identifying the locations lying in the different climatic design zones as shown in Figure 2.5. However, boundaries are not established due to the limitation on the availability of data (Ogunsote and Prucnal-Ogunsote, 2002). The study area Maiduguri (MAI) lies in the Savannah zone (a).

Figure 2.5: The proposed climatic zones for architectural design in Nigeria (Ogunsote and Prucnal-Ogunsote, (2002)

2.3.1 Study Area (Maiduguri)

Maiduguri (called Yerwa by locals) was the capital and the largest city of the former north-eastern state of Nigeria and present capital of Borno state. It lies in an open country about 144 km to the southern part of the Lake Chad. It is situated in the area occupied by the former Borno Empire, which dates back to 17th century. Lord Lugard, the first British governor general of Nigeria chose Maiduguri in 1808 as the administrative headquarters of the new Borno province. It has long been the dominant city in the North Eastern region of Nigeria, and it's located close to the republic of Chad, Niger and Cameroon at latitude 11˚51" N and longitude 13˚ 05" E and it stands some 354m above sea level, (Max Lock group 1976) which gives it an increasing international importance as a commercial, transportation, educational, religion and administrational hub. Figure 2.6 shows the position of Maiduguri and other state capitals in Nigeria.

Figure 2.6: Map of Nigeria showing the location of Maiduguri and other state capitals

Maiduguri lies on a relatively flat terrain, which is part of a larger undulating plain surface that slopes gently toward Lake Chad. The Borno plains are covered by superficial deposit of sand and clay. The area is drained largely by the river Alau otherwise referred to as river Ngadda, and receives a tributary known as Ngaddabul from the south west (Max Lock group 1976). The climate of Borno state has diversified over time and geographical coverage. Maiduguri is clearly in the semi-arid region of Nigerian climatic zone, in which the year is divided into two distinct seasons a short rainy season and a long protracted dry season. Consequently, the harsh climate due to the protracted dry season has an over-riding influence on the range of social and economic activities and inhabitants.

2.3.1.1 Rainfall

The rainfall in Maiduguri is seasonal and is characterised by a single maximum, with the average annual rainfall of 670.56 mm. It usually rains between May and September attaining a peak in the month of August. Thunderstorms or short sharp shower and much rain occurrence records between 2.54 mm and 6.35 mm characterised the rainfall of Maiduguri, with extensive losses sustained through evaporation, evapotranspiration and run off (Mintar, 1984). According Arku, et al. (2012), Maiduguri is known for its dryness, with semi-arid climate, savannah or tropical grasslands vegetation, light annual rainfall of about 300-500 mm.

2.3.1.2 Temperature

In dry season the temperature in Maiduguri is extremes with wide diurnal and annual ranges dry hot air, with the hottest months of April, May and June. The maximum temperature in Maiduguri can exceed 40°C but the daily average can fall to the level of 22°C to 35°C with the start of the rainy season (Arku, et al. 2012). The coldest night of the year are experienced in the months of December, January and February (Harmattan). Table 2.1 show the mean temperature, wind and solar radiation data for Maiduguri.

Table 2-1 Mean Temperature, wind and solar radiation data for Maiduguri

*Month	*Temperature, oC		*Relative Humidity, %
	Min.	Max	
Jan	12.60	31.90	18.67
Feb	15.30	34.60	14.25
Mar	19.70	37.80	11.50
Apr	23.90	40.10	21.38
May	25.50	39.40	35.00
Jun	24.50	36.40	49.50
Jul	22.90	33.20	63.52
Aug	22.30	32.00	72.17
Sept	22.40	33.70	64.30
Oct	20.70	36.40	45.67
Nov	16.00	34.20	22.08
Dec	13.10	32.30	19.58

Source (Arku, et al. 2012).

2.3.1.3 Wind

There are two dominant trade winds that influence the climate of Maiduguri, including, the North-East trade winds from the Sahara, between November to April and South-West monsoon wind from the coastal area between the months of May to September. North-East trade wind is dry, hot and dusty with thick haze of diamantiferous dust from Sahara. They are destructive with an average speed of 5.14 m/s (Max Lock group, 1976). The mean wind speed in Maiduguri ranges from 4.49 to 6.10 m/s with synoptical readings obtained from two periods of 9:00 and 15:00 h showing higher wind speeds in the morning hours compared to the evening. The seasonal trend of wind speed in Maiduguri illustrates that wind speed is higher in the dry periods of the year compared to the rainy season as illustrated in table 2.2 (Ohunakin, 2011). Wind rose showing the dominant wind direction in a year in the study area is illustrated in figure 2.7.

Table 2-2 Monthly variations of wind characteristics for Maiduguri location (wind speed data of 37 years, 1971–2007 periods measured at 10m)

Month	Mean wind speed (10 m)
January	4.94
February	5.90
March	6.10
April	5.80
May	5.81
June	6.06
July	5.66
August	4.62
September	4.49
October	4.55
November	5.10
December	4.68

Source: Ohunakin O. S. (2011)

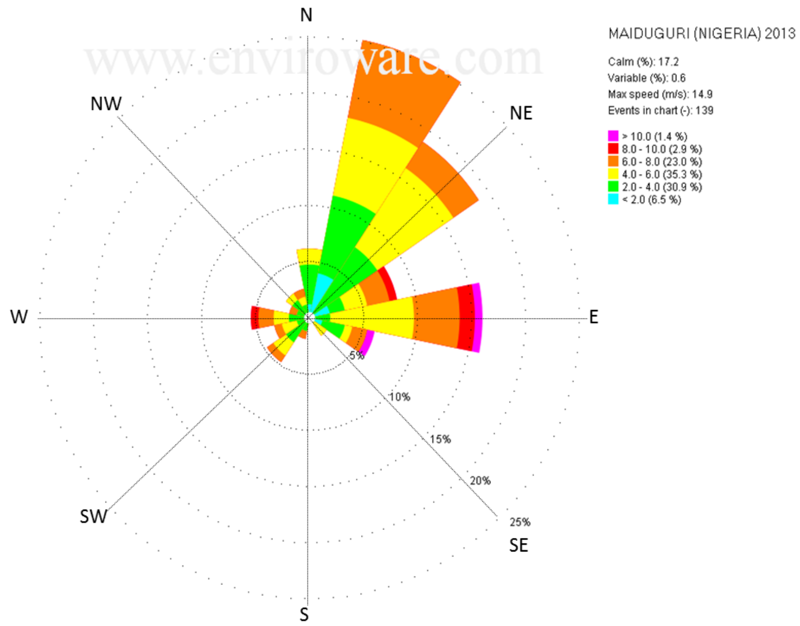


Figure 2.7: Wind Rose showing the dominant wind direction in Maiduguri, the study area

2.3.1.4 Vegetation

Maiduguri falls within the savannah desert woodland zones, which are characterised by a relatively light tree growth with a more-or-less continuous cover of grass. It is specifically located in the Sudan savannah belt. Common trees in Maiduguri metropolitan area are Neem trees (70-80%), baobabs, Date palms acacia, Cactus and some thorny species (Max Lock group, 1976). The Neem trees have an average height of 12 to 18 m with evergreen foliage. The grass cover could not survive in the harsh weather and the intensity of solar radiation without sufficient water.

2.3.1.5 Relative Humidity

Although, the average relative humidity is estimated at about 49% in the Maiduguri metropolis, the city and its surrounding area are fragile and highly susceptible to drought with extreme relative humidity of 13% in dry seasons and up to 80% in rainy seasons (Kindersley, 1999). Thus, since rainy season only last for about three months in the study area, the effect of relative humidity on building design is negligible.

2.3.1.6 Population

The estimated population of Maiduguri was 600 in 1851. The Max Lock group (1976) house hold survey of 1973 gave a population of 200,167 and projected growth of 7-10%, which is huge increment to the 1851 estimation. Moreover, according to the 1991 National population Census figures, the population of Maiduguri, which is made up of predominately Kanuri, Shuwa Arab ethnic groups including the minorities is about 2, 997,448 (FRN, 2007).

2.4 Suspended Particulate Matters (SPM)

Suspended particulate matters (SPM) are finely divided solids or liquids that may be dispersed through the air from combustion processes, industrial activities or natural sources (OECD, 1997).

A suspended particulate matter (SPM) integrates diverse airborne particulates with sizes ranging from less than 0.1 μm to not more than 10 μm, mainly originating from dust storms, forest fires, bush and wood burning, volcanic eruptions, coal burning, waste incinerations, industrial activities and traffic exhausts (Ogugbuaja and Barsisa 2001). It remains the most apparent air contaminants of the urban and rural ambient environment in Nigerian (Akeredolu, 1989). The presence of SPMs in indoor spaces has serious health consequences once inhaled and about 75% of it will remain in the body (Ogugbuaja and Barsisa 2001).

2.4.1 Introduction to Harmattan Dust

Dusts are fine particles with particles diameter ranging from 0.1 to 1,000µm. in the study area, the major source of dust is the Harmattan dust. But, domestically dusts are often formed due to operations such as pulverizing, crushing, grinding, drilling, detonation, and polishing (Cheremisinoff, 2002). They are transported by the wind and their movement speed and directions depends on the speed and direction of the wind in an environment.

Harmattan is a fugitive dust believed to be originating from the Faya Largeau area in the Chad basin and transported by dry North-East trade wind that usually blows across Nigeria between November and March annually, diminishing southwards. This period is usually associated with cool, dry Harmattan climate, dusty and cloudy atmosphere, and poor visibility, often necessitating cleaning of homes and work places numerous times a day (Adepetu *et al.* 1988). These consequences are higher in the Nigerian semi-arid climatic zone being situated in the Northern boarders of the country, adjacent to the origin of the Harmattan dust. According to Akeredolu (1989), Harmattan dust haze remains the largest anthropogenic source of particulate matter that is associated with increasing cases of chest congestions and respiratory diseases in Nigeria. Such illnesses often result in high body temperatures during dustier Harmattan periods including nasal congestion, cough, muscular aches and pains, painful watery eyes (or Apollo disease), which are believed to be caused by toxic effect of the dust (Adepetu *et al.* 1988). Figure 2.8 illustrates the distribution of Harmattan dust in West Africa and figure 2.9 shows Harmattan dust storms from the Sahara desert as captured by NASA's MODIS satellite.

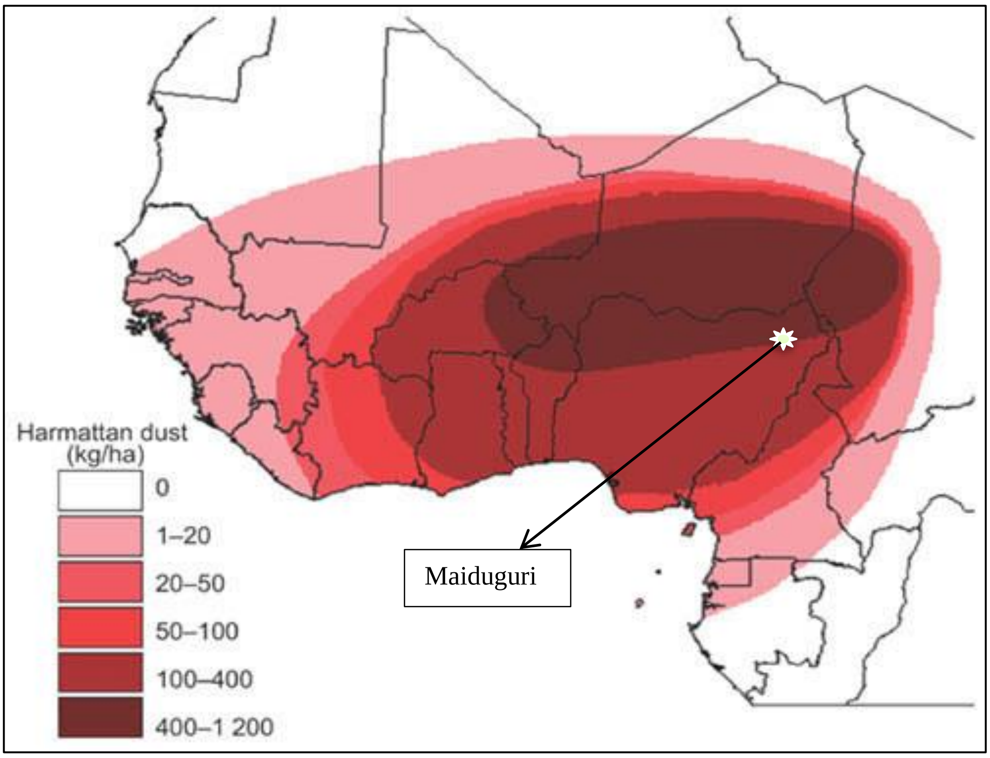


Figure 2.8: Distribution of Harmattan Dust Particles in West Africa (Ogunseitan, 2007)

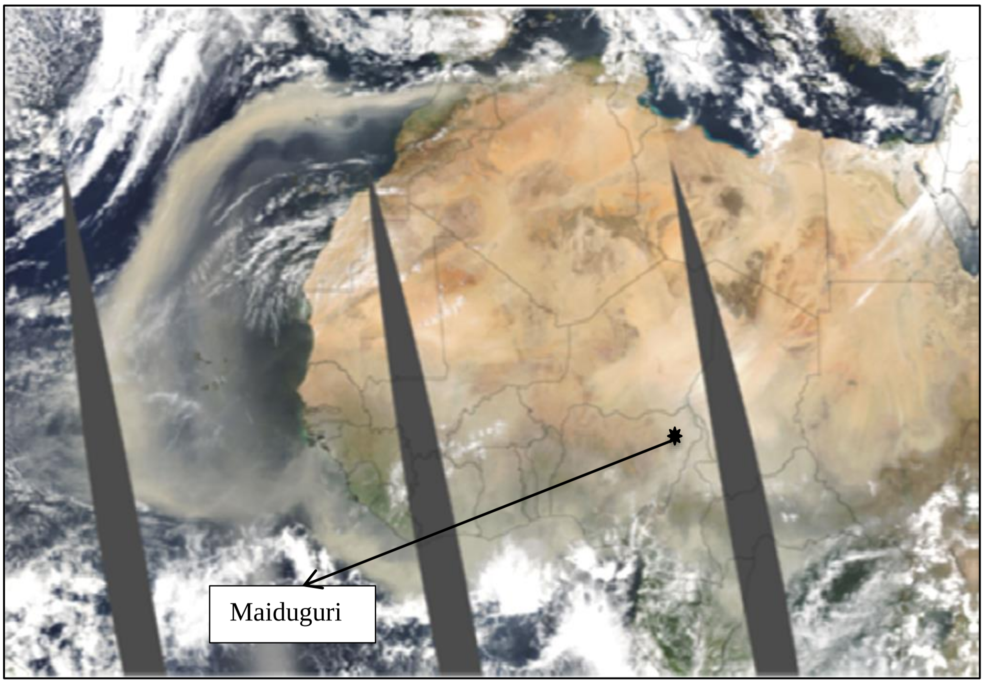


Figure 2.9: Harmattan dust storms from the Sahara desert as captured by NASA's MODIS satellite (Kaufman, et al. 2005)

2.4.2 Effect of Harmattan Dust on Air Quality

Dust particles usually originate naturally from the desert or partially from human sources due to bush fires and other human activities and have great effect on air quality. Saharan dust which is the source of dust particles to North-eastern Nigeria, is largely constituent of clay minerals, quartz, calcium and magnesium carbonates, whereas particles of anthropogenic origin appeared to be largely composed of carbon containing particles, sulphates and nitrates (De Longueville et al. 2010). The fine particulate matter of typically 0.5 – 10 μm originating from the Sahara desert blowing southward, restricting vision and creates breathing difficulties for people. This dry dusty wind begins in the month of November and ends around March every year. Furthermore, it causes different types of inconveniences in domestic areas since the dust layers covers everything both outdoors and indoors (Ogunseitan, 2007). The images in Figure 2.10 show the effect of Harmattan dust on air quality and visibility.

Figure 2.10: The effect of Harmattan dust on air quality and visibility

2.4.3 Health Consequences of Harmattan Dust

The respiration of airborne dust particles in form of particulate matter of less than 2.5 μm in size is known as a health hazard, particularly at ambient concentrations as reported for many West African countries (Ogunseitan, 2007). These airborne dust particles usually affect human health, as a result of their impact on local and regional air qualities (Anuforom, 2007). The health consequences of Particulate Matters (PM) is significantly related to its size and weight once inhaled, PM_{10} (particle size of <10μm) penetrate deep into the lungs and remain there, contributing to respiratory illness, lung damage, and even premature death in sensitive individuals (U.S. Environmental Protection Agency-EPA, 2004). Moreover, the human nose usually filters out Harmattan dusts with particles size of about 10μm and larger. The dusts of these sizes are normally trapped by the hairs and/or mucus in the nose. Dust with sizes ranging from 4μm and 10μm can penetrate into the nose and reach the bronchi tubes. This size and smaller is especially dangerous for people who have asthma, while Harmattan dusts with size less than 4μm can travel beyond the bronchi and enter into lungs themselves (Jimoh, 2012). Therefore, the major concern remains with small fine size air particles (0.1–3 μm), which are usually accumulated in the respiratory system upon inhalation (Ogugbuaja and Barsisa, 2001). These particles demonstrate 60–80% deposition efficiency into the human biological system (Schroeder, 1971).

Moreover, the relationship between dust particles concentration and its effect on human health has already been established in the literature, particularly linking cardiovascular and respiratory diseases to dust outbreaks (Kwon et al. 2002; Chen et al. 2004; Meng and Lu, 2007). Another study by Yoo, et al. (2008), established that children with mild asthma reported more respiratory symptoms during dust days, often requiring the use of bronchodilator compared to clean days. Furthermore, Harmattan winds experienced during dry season in North Eastern Nigeria are believed to be responsible for an increase in positive ions and other gases in the air triggering migraine head pain. When an interview was conducted among margarine sufferers in this region, 46% and 38% of the respondents mostly experienced migraine attack during warmest months and Harmattan season respectively (Timothy, et al. 2011). The Environmental Protection Agency (EPA) in United State of America issued final guidelines on 29th March, 2007 for regions to clean up their air that, the presence of fine particles or "$PM_{2.5}$" in the air can ignite heart and lung diseases and have been connected to premature death and a range of severe health complications including heart attacks, chronic bronchitis and asthma attacks (Ogunseitan, 2007).

2.4.4 Harmattan Dust Particle Size

The particles size obtainable from Harmattan dust varies with location, depending on the proximity of the collection centre from the origin in the Sahara desert. These particles are very fine opalescent which are so small that they can remain airborne for a significant interval of time (Kalu, 1979). Moreover, the distance covered by dust particles is largely dependents on the particles size. Dust particles that can be transported a few kilometres to lower than 100km is generally ranges from 0.005mm (5μm) to 0.05mm (50μm). However, dust particles that have the potential of covering longer distance are usually less than 0.02mm (20μm) in diameter (Gillette, 1979). These materials (particles) could stay suspended in the troposphere, often at high levels, as an aerosol for several days, at times beyond one week. This type of dust has been noted to have sizes ranging from 0.002mm (2μm) to 0.01mm (10μm) (Middleton, 1986).

The amount of Harmattan dust collected in Nigeria also varies significantly from year to year with particle-size becoming finer towards the south with an increasing amount of organic matter. Previous empirical findings have indicated that, generally mean sizes of Harmattan dust particles are bigger in the Northern parts of Nigeria, being closer to the dust source area in the Sahara, and the size diminishes southwards as the particles moves further from its source (McTainsh and Walker, 1982; Adedokun et al., 1989; Oluwafemi, 1988; Utah et al., 2005). After discharging from their source, dust particles are vulnerable to turbulent fluctuations and their suspension periods depend largely on their sizes. Thus generally, dust particles of 20 - 70 μm diameter are within the short-term suspension range while particles with diameter <20 μm are within the long-term suspension range. The long-term suspended dust could remain in the air for weeks reaching thousands of kilometres (Kok et al. 2012). Moreover, the relationship of Harmattan dust particle size to distance downwind from the source area is illustrated in figure 2.11. The figure compared dust particle sizes in relation to distance from the source for the three major cities in northern Nigeria including Maiduguri the study area, Kano and Sokoto. The results in figure 2.11 confirmed that the dust particle sizes in relation to distance from the source are higher in the study area Maiduguri compared to the other two cities. The map of Nigeria showing the locations of Maiduguri, Kano and Sokoto is presented in figures 2.5 and 2.6.

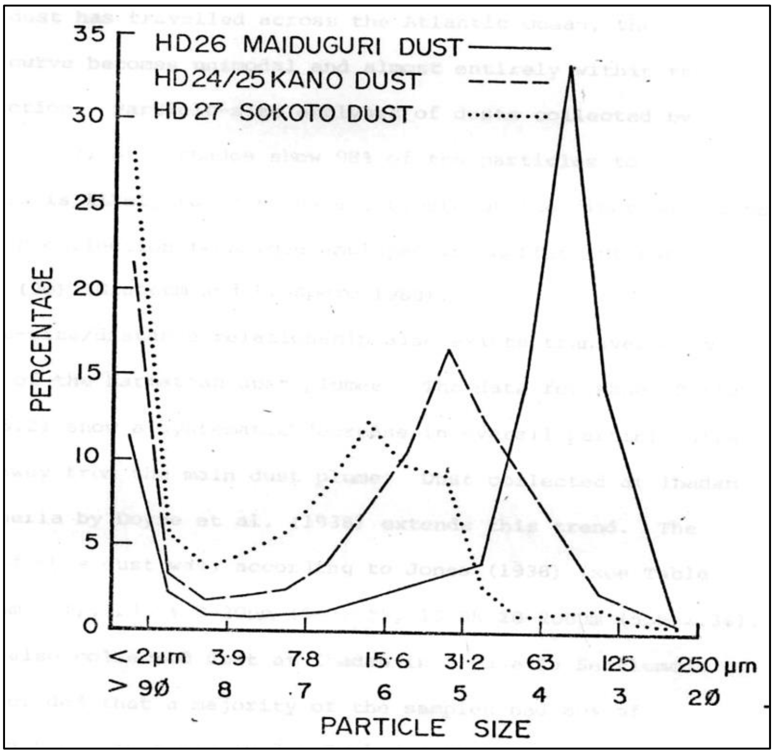


Figure 2.11: Relationship of Harmattan dust particle size to distance downwind from the source area, January to March 1979 (Source: Mctainsh, 1982)

However, the Research conducted by Awadzi and Breuning-Madsen (2007) found dust median diameter of slightly above 15 µm and 5 µm with organic carbon content of 5% and 10-15% in the north and south respectively. The mean sizes of Harmattan dust samples collected in Nigeria for two Harmattan seasons are 2.7µm and 4.4 µm, respectively (Chineke and Chiemeka, 2009). According to Efe (2008) in their studies of seventeen (17) Nigeria cities, Maiduguri recorded the highest concentration of ambient PM_{10} in both urban environments and their surrounding rural landscape. The study also affirms that the higher concentration of PM_{10} is obtainable in the Northern cities compared to the south. The particle size characterises obtainable in some West Africa countries including the study area is presented in table 2-3.

Table 2-3: Particles size characteristics of dust

S/N	Dust diameter	Location	Months	Year	Reference
1	1.57±0.54 µm (average)	Kumasi, Ghana	January-February	1997-2009	Sunnu, 2012
2	2.7µm and 4.4 µm (Mean)	Uturu, South Eastern Nigeria	October-February	2001-2005	Chineke and Chiemeka 2009
3	15 µm and 5 µm (Median)	Bawku, Tamale, Kade and Kpong in Ghana			Awadzi and Breuning-Madsen, (2007)
5	8.9 µm (mean)	Kano, Northern Western Nigeria	-		Kalu (1979)
6	3.2 µm (mean)	Ile-Ife South Western, Nigeria	January-February	1983-1985	(Adedokun et al. 1989)
9	0.0743mm (74.3 µm) (Median (grain size)	Maiduguri, North Eastern Nigeria	-	-	Cooke et al. (1993)
10	2 to 50 µm (Range)	Damaturu, North-eastern Nigeria			Mohammed (2013b)
11	68 µm (median diameter	Maiduguri, Nigeria	-	1976-1979	McTainsh and Walker, (1982)

2.4.5 Element Composition of Harmattan Dust

The characteristics of the dust source is the major factor influencing dust mineralogy and elemental composition, while the transport distance covered and the deposition process are the secondary influential factors. The deposits from Harmattan dust are dominated by minerals including quarts and feldspar, while kaolinite was the dominant clay mineral, followed by smectite and then illite (McTainsh et al. 2013). However, Mctainsh and Walker (1982) established inconsistency between dusts collected at different times. Thus, the concentration of dust particles differs from time to time depending on the various factors such as wind speeds and direction at the time of the measurement. According to the studies conducted by Adepetu et al. (1988), about the elemental composition of Harmattan dust in Nigeria, by using neutron activation analysis to determine the concentrations of 29 elements, with iron (Fe), aluminium (Al), and potassium (k) being among the highest at 61, 431and 15 mg g-1, respectively.

2.5 Mosquitoes

Mosquitoes are cold-blooded insects that survive only if the surrounding temperature is as warm as their body. Depending on various species, for mosquito to develop the malaria parasite, it requires a temperature that is above 14–16^{o}C. Therefore, the warmer the ambient temperature, the faster the parasite can develop inside the mosquito, and the possibility of transferring back the parasite into a warm-blooded host during the mosquito's next blood meal before it dies will be high (WHO, 2011). The average lifespan of a Mosquito is from 2 weeks to 6 months (National Geographic, 2013). Figure 2.12 illustrate typical stages in life cycle of mosquito. The life cycle of a mosquito involve four discrete and different stages including; Egg, Larva, pupa, and adult, which can be simply identified by their specific appearance.

In the first stage, the mosquitoes lay their eggs one at a time and these eggs float on the surface of the water and most eggs usually hatch into larvae within 48 hours. The second stage is the larva (larvae - plural) which stay inside the water and move towards the surface to breathe. The larva shed their skin four times, while they grow bigger after every moulting. Most larvae have siphon tubes which help them in breathing and hanging from the surface of the water and they feed on micro-organisms and other organic matters obtainable in the water. Subsequently, the larva transforms into a pupa on the fourth moult. The third stage is the Pupa, also known as non-feeding stage is a resting stage, in which the mosquito changes to adult. The complete development process of the adult requires about two days, and once the development is complete, the pupal skin splits and the mosquito becomes adult. The fourth and final stage of mosquito development is the adulthood. In this stage, the newly emerged adult relaxes on the surface of the water for a short period to dry up and strengthen all its parts, which enables their wings to spread out and dry appropriately before they can fly (Alameda County Mosquito Abatement, 2014).

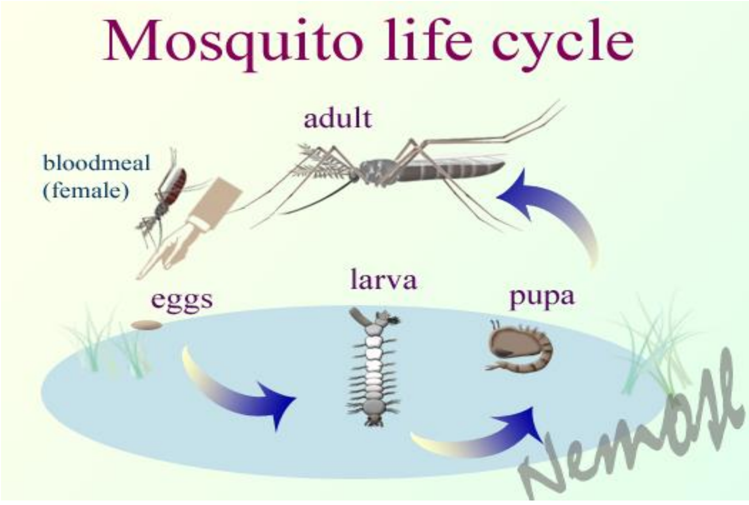


Figure 2.12 Mosquito Life Cycle (MetaPathogen, 2014)

2.5.1 Mosquito Prevention

In the tropics where the case of mosquito insects are prevalent, the most common method used in preventing mosquito from entering into a building is by sealing all openings with insect screen meshing. However, in rural areas, smoke is generated with half-dry fire woods to drive mosquitoes away from communities. But this method has its own consequences of creating air pollution. There are other commonly used mosquito prevention strategies such as insecticide, chemical repellents and non-chemical control system. The non-chemical control system includes source control, water management, exclusion, public education, personal protection and biological control.

2.5.2 Sizes of Mosquito

The mosquito size differs from one place the other depending on the environment where they are found. Generally, the average size of a mosquito according to the National Geographic (2013) is 0.3 to 2 cm, while their average weight is 2.5 mg. thus, to prevent mosquitoes from building through filtration, the mesh size should be less than the size of mosquitoes.

2.5.3 Types of Mosquito

There are only three species out of more than 3,000 species of mosquitoes that are largely responsible for the spread of human infections including; Anopheles, Culex and Aedes. The Anopheles mosquitoes are the only species known to be transmitting malaria, and they also spreads filariasis (elephantiasis) and encephalitis. The Culex mosquitoes transmit encephalitis, filariasis, and the West Nile virus, while, the Aedes mosquitoes, of which the voracious Asian tiger is a member transmit yellow fever, dengue, and encephalitis (National Geographic, 2013). The Anopheles mosquito is divided into many species but the most prominent ones include Anopheles gambiae s. l., Anopheles funestus, and Anopheles nili. The Anopheles nili is the most common efficient vector of Plasmodium parasites in the humid savannahs and in the forest areas of sub-Saharan Africa. It is the nominal taxon of a group of closely related species including An. Nili sensu stricto, Anopheles somalicus, Anopheles carnevalei and Anopheles ovengensis. Study by Okogun et al. (2005) identified 17 mosquito species belonging to three genera (Anopheles, Culex and Aedes) that are potential vectors of four human diseases, as illustrated in table 2.4, while figure 2.13 shows a typical mosquito insect.

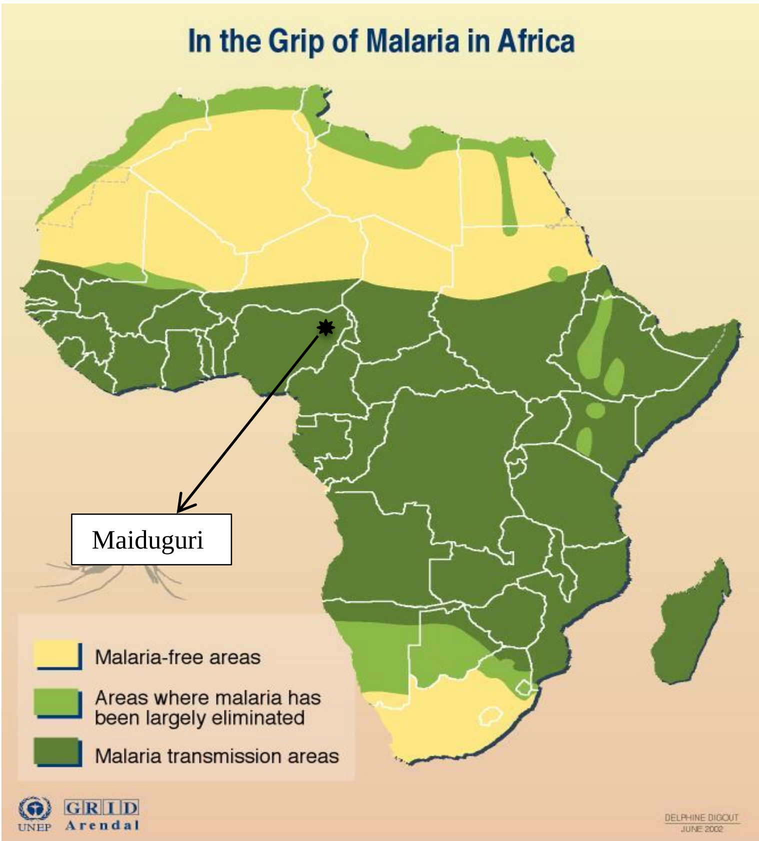
Table 2-4 Mosquito larva species in a sampling of artificial and natural sources in Mid-Western Nigeria (Okogun et al. 2005)

S. No.	Mosquito larva species	Natural sources (Receptacle types)	No.	Artificial sources (Container types)	No.	Total (General)	% in study area
1.	*An. pseudopunctipennis*	Pools, tree holes, leaves stalk and bamboo stumps	28	Plastic drums/containers, metal cans, clay pots and bamboo sticks	110	138	11.2
2.	*An. gambiae*	Pools, shells and tree holes	159	-do-	126	285	23.1
3.	*An. funestus*	Rock holes and leaves stalk	14	-do-	20	34	2.8
4.	*Ae. aegypti*	Pools, plants, shells and tree holes	41	Pools, rock holes, plants and animal shell, plastics, metals and earthenware containers	150	191	15.5
5.	*Ae. albopictus*	Leaves stalk, plant and animal shells	34	Automobile tyres and tubes	17	51	4.1
6.	*Ae. simpsoni*	Tree holes and leaves stalk	26	—	-	26	2.1
7.	*Ae. palpalis*	Plants and animal shells	16	Pools, puddles and metal cans	28	44	3.6
8.	*Ae. africanus*	Tree holes and plant shells	13	—	-	13	1.1
9.	*Ae. vittatus*	—	—	Plant and animal shells, pools and puddles	27	27	2.2
10.	*Ae. unlingeatus*	—	—	Pools, metals, plastics and bamboo sticks	18	18	1.5
11.	*Ae. luteocephalus*	Tree holes and leaves stalk	36	—	—	36	2.9
12.	*Cx. (p) fatigans*	Pools and plant shells	56	Pools, metals, plastics and earthenware containers	98	154	12.5
13.	*Cx. (p) quinquefasciatus*	—	—	Domestic runoffs, pools, metals and plastic containers	62	62	5.0
14.	*Cx. (p) pipiens*	Pools and leaves stalk	41	Metal cans, plastic cups, bamboo sticks	20	61	4.9
15.	*Cx. decens*	Leaves stalk and plant shells	34	Earthenware, metal and plastic containers	38	72	5.5
16.	*Cx. albovitrolus*	—	—	Earthenware, metal and plastic containers	15	15	1.2
17.	*Cx. perfuscus*	—	—	Pools and metal cans	8	8	0.6
	Total					1235	100

Figure 2.13: Typical Mosquito Insect

2.5.4 Malaria

Malaria is the most parasitic infectious disease in the world, is transmitted by mosquitoes which breed in fresh or rarely salty water. It symptoms include fever, headache, chills, muscle aches, tiredness, nausea and vomiting, diarrhoea, and jaundice. Convulsions, coma, severe anaemia and kidney failure can also occur. The severity and range of symptoms depend on the specific type of malaria. In certain types, the infection can remain inactive for up to five years and then recur. In areas with intense malaria transmission, people can develop protective immunity after repeated infections. Without prompt and effective treatment, malaria can evolve into a severe cerebral form followed by death. Malaria is among the five leading causes of death in under-5-year-old children in Africa (WHO, 2001). Figure 2.14 shows the control of Malaria in Africa.



Sources: A. Platt McGinn, *Malaria, Mosquitoes, and DDT*, World.Watch, Vol.15. No.3, May-June 2002.

Figure 2.14 Control of Malaria in Africa

2.6 Chapter Conclusion

This chapter introduced the environmental characteristics of the study area's semi-arid climate of Nigeria, including climatic condition, and other climatic factors that distinguished the zone from other part of the world. The semi-arid climates referred to mainly non Polar Regions that are generally characterised with low annual rainfall and comprises of short grasses or shrubs vegetation. The study area Maiduguri is located at the semi-arid zone of Nigeria which is situated at the far northern part of the country.

The chapter provides detailed information in relation to climatic condition of the study area, which is divided into three seasons including dry season, wet season and Harmattan season. The dry season is the period without rainfall which includes the months of October, November, December, January, February, March and April. Similarly the wet season is the periods that have rainfall which falls within the months of May, June, July, August and September. Equally, the Harmattan season is the cold sand dusty season which usually falls within the dry season months of December, January and February. Moreover, the individual climatic characteristics of the study area including mosquitos, Harmattan dust, temperatures, humidity and wind speeds have been presented.

The mean monthly wind speed in the study area ranges from 4.49 m/s (minimum) in September to 6.10 m/s (maximum) in March. The dominant wind direction in the study area is North-East (7-8 months in the dry season) and South-West (4-5 months in the wet/rainy season). The average monthly air temperature in the study area ranges from 22.3^{o}C (minimum) in January to 32.5^{o}C (maximum) in May. The wind speed, direction and temperature data will be used as a boundary condition for the CFD simulation.

The study established that Harmattan dust of sizes less than 10 μm are dangerous to health causing respiratory illnesses because they can easily travel beyond the bronchi and enter into the lung. The median size of the Harmattan dust obtainable in the study area is about 68 μm. The dust sizes are important consideration in the simulation of the dust particle dispersion. During the wet season the mosquito is most active as the rain fall encourages the breeding cycle, however due to poor drainage and sanitation there is open water throughout the year, giving rise to mosquito's present in the region for the whole year. Mosquito is an insect that transmits Malaria fever, which is one of the most infectious diseases in the world. The sizes of Mosquitoes range from 0.3 to 2cm. in this study, the

Mosquito size is considered in the simulation and subsequent recommendation of insect screen mesh size/porosity.

The climatic data obtained including wind speed, wind direction, Mosquitoes and Harmattan dust sizes will be used as an input for both the analysis of the full-scale measurement and the CFD simulation. This is because, to create a virtual environment with the same climatic condition with the reality, climatic data is required. The full-scale measurement is presented in chapter 6 and the CFD simulation is presented in chapters 7, 8 and 9.

Chapter Three

Literature Review

Chapter Structure

3.1 Introduction

3.2 Energy Concern in Nigeria

3.3 The Hospital Multi-bed Wards

3.4 Ventilation in Buildings

3.5 Natural ventilation and indoor air quality in Hospital Wards

3.6 Indoor Air Quality (IAQ) in Buildings

3.7 Indoor Air Chemical Contaminants in Hospitals

3.8 Building Indoor Environmental Parameters

3.9 The Effects of Energy Efficiency on Ventilation in Hospital multi-bed wards

3.10 Chapter Conclusion

3 Chapter Three: Literature Review

3.1 Introduction

The previous chapter (Chapter 2) introduces the characteristics of the study area semi-arid, including Harmattan dust and Mosquito has been discussed and presented. This chapter (chapter 3) presents the general literature review about ventilation and indoor air quality. The chapter also examined literature on various factors influencing ventilation and indoor air quality in hospitals. These factors include; the effect of indoor air quality on health, hospital wards designs and energy requirements.

This chapter is divided into various sections. Section 3.2 discusses the energy concern in Nigeria and section 3.3 introduces various characteristics of hospital multi-bed wards. Section 3.4 discusses the ventilation in buildings, while section 3.5 introduces previous studies on natural ventilation and indoor air quality in buildings. Section 3.6 introduces the effects of indoor air quality in hospital buildings; and section 3.7 discusses some chemical contaminants in hospitals. Section 3.8 of the chapter presents different aspects of indoor environmental parameters in buildings, while section 3.9 discusses the effect of energy efficiency on ventilation in hospital wards and section 3.10 presents the chapter conclusion.

3.2 Energy Concern in Nigeria

A considerable amount of literature has been published on the sustainability in hospitals design. Hospitals being large public structures with a significant impact on the environment, occupants (patients, staffs and visitors) and economy of the immediate neighbourhood, they have high demand on energy and water and produce large amounts of waste. Hence, the level of concerns for sustainable design is higher compared to other types of facilities (Robert, 2011).

In Nigeria, the electricity demand exceeds the supply, and even the supply remains unreliable (Sambo, 2008). The total grid installed capacity produced by Nigerian power stations was 8,876 MW with only 3,653 MW available as at December 2009, meaning the available power supply is less than 41% of the total installed capacity (Emovon, et al. 2011). Moreover, According to the 2009 International Energy Agency (IEA) records, the electrification rate for the whole country was about 45% to 50%, thus, depriving approximately 76 million people access to electricity (EIA, 2012). According to a World

Bank report, the yearly (2007–2008) average power outages experienced in Nigeria was 46 days, and an outage last for about 6 hours on average. In addition to problems such as insufficient maintenance, inadequate feedstock and insufficient transmission network, high population growth combined with underinvestment in the electricity sector have also resulted in increased power demand without any substantial growth in production (EIA, 2012).

3.3 The Hospital multi-bed wards

Due to its wide range of functional units and services, hospitals remain the most complex types of buildings. Robert (2011) categorized the ideal basic forms of hospitals based on functionality as; bed related inpatient functions, outpatient-related functions, diagnostic and treatment functions, administrative functions, services functions and research and teaching functions. But the major concern of this study is the bed related inpatient functions (wards), which is one of the most complex sections of the hospital ward. The various building attributes of hospital design including; efficiency and cost effectiveness, flexibility and expandability, therapeutic environment, cleanliness and sanitation, accessibility, controlled circulation, aesthetics, security and safety, and sustainability (Robert, 2011).

The planning of any open ward facilities are based on three principles including ample visibility of the patients at all times, cross ventilation, and economy in construction and maintenance. This allows easy supervision of the sick patient (Gainsborough and Gainsborough 1964). However, owing to the increased concern and awareness about disease spread and transmission in hospital wards, the control and management of infection and infectious pathogens in hospital wards not only involves the employment of the principles of asepsis and hygiene but also wards' design, equipment and ventilation considerations (Rao, 2004).

Moreover, on average, around 50% of rooms in a general hospital are wards spaces (Welsh Health Estate (2009). In developing countries and in regions with limited-resource, the application of open multi-bed wards dominates the hospital environment. However, the possibility of infection is higher in open ward and the spread of infectious organisms within the space take place within a short period of time. However, some of the most obvious disadvantages of the open ward system include noise, lack of privacy and complexity in controlling climatic conditions to suit all patients (Gainsborough and Gainsborough 1964).

3.3.1 Multi-Bed hospital wards types

Hospital multi-beds wards are categorized into different types depending on the shape and layouts. Apart from their influence on contaminant control, the wards layouts also affect the time spent by nurses in performing different activities (Ampt et al. 2008). Various researchers have presented the classification of hospital wards. James and Tatton-Brown (1986) as cited in Alalouch and Aspinall (2007) have classified different types of hospital wards into seven categories: nightingale, corridor or continental, duplex or Nuffield, racetrack or double corridor, courtyard, cruciform and radial ward. Furthermore, recently, Yau, et al. (2011) described four types of hospital ward designs that are frequently being utilised throughout the world including; bay wards, nightingale wards, racetrack wards and hub and spoke units. Hospital wards arrangements such as Bay and Nightingale are obtainable in the study area, but the rest are not commonly used in the study area, but relevant in the temperate climates of Europe. They are presented to provide readers with the idea of global hospital ward design trends.

3.3.1.1 Bay wards

A bay ward is one of the various types of hospital wards design layouts. In Bay wards, the space is divided into various cubicle rooms, each housing several beds with central nurses' station (Yau, et al. 2011) and peripheral rooms accommodating small numbers of beds. Bay wards are more flexible compared to Nightingale wards and can enhance patient-nurse interaction. With better recruitment and state-of-the-art facilities, Bay wards provide satisfactory environments for patients and staff (Hurst, 2008). However, one of the major shortfalls of Bay wards is the restriction of direct view from a centrally positioned nursing station and bed locations (Morelli, 2007). Typical Bay ward arrangement is illustrated in figure 3.1.

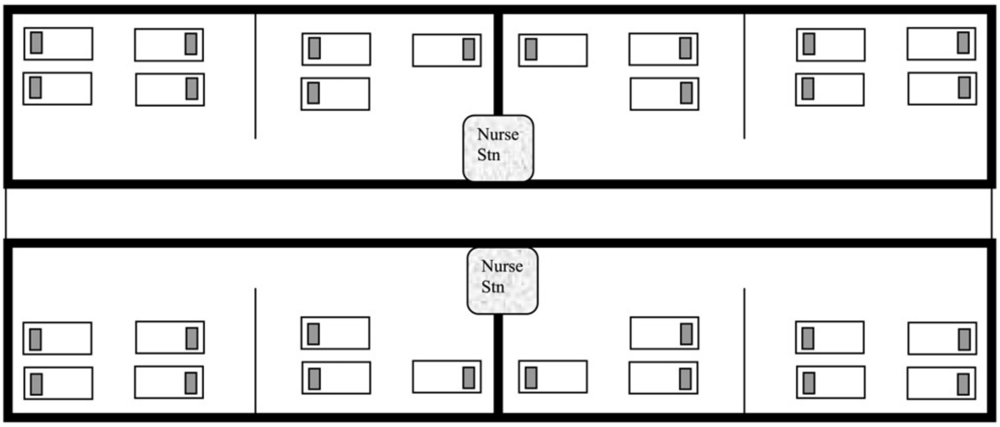


Figure 3.1: Bay Ward Arrangement (Yau et al 2011)

3.3.1.2 Nightingale wards

The nightingale wards are a type of multi-bed arrangement in which the beds are position along the perimeter of the space, with the nurses' station situated at the centre or end (Yau, et al. 2011) from which visibility and hearing are maximised (Hurst, 2008). Owing to recent ideas of decreasing cross infections in hospitals and patients' concern about privacy and dignity, the nightingale arrangement was modified to what is now referred to as Corridor/ Continental ward (Pattison and Robertson, 1996). To address these concerns, in the Corridor design, patients are placed by one or both sides of a corridor with four to six beds per apartment (Nazarian et al. 2011). The typical Nightingale ward arrangement is illustrated in figure 3.2.

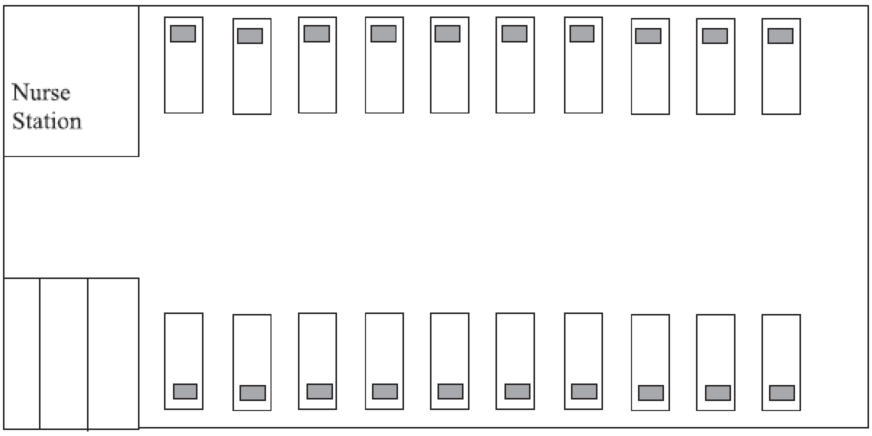


Figure 3.2: Nightingale Wards Arrangement (Yau et al. 2011)

3.3.1.3 Racetrack wards

Racetrack wards are rectilinear with offices and utility rooms occupying the central ward area while bays are positioned off a corridor that encircles the ward's central block (Stichler, 2001). In racetrack ward arrangement which is also referred to as double corridor, the nursing area and other support areas are located between two corridors (Nazarian et al. 2011) as illustrated in figure 3.3. This type of ward arrangement is acknowledged to minimise the walking distances and time spent of nurses (Rashid, 2006; Ampt, et al. 2008).

However, the clear disadvantage of the Racetrack ward arrangement is its long corridors without natural light and view (Nazarian et al. 2011). According to Barefoot (1992) *"the racetrack ward is a failure; one should avoid too long corridors without windows. The reassurance of relating to outside orientation is vital. It can be done with corridor breaks giving pleasant views of the outside"*. However, the establishment of Courtyard wards remain the most regularly used measure of mitigating this deficit (Nazarian et al. 2011). Thus, another modification of racetrack arrangement is the courtyard ward, which has courtyard located at the centre of the building for ventilation (Catrambone et al. 2009). This type of arrangement has courtyards of different sizes provided at the central areas to provide natural lighting and ventilation (Nazarian et al. 2011).

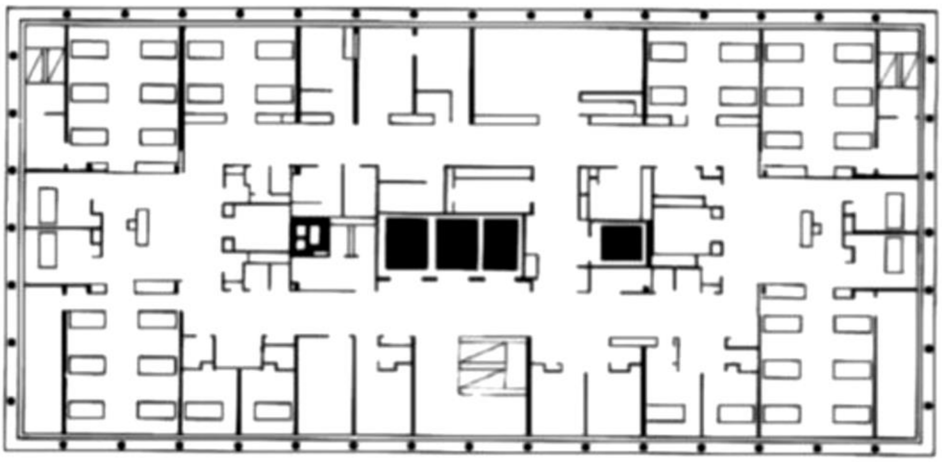


Figure 3.3: Racetrack ward type, High Wycombe hospital, Buckinghamshire, UK, source: James and Tatton-Brown 1986 (Nazarian et al. 2011).

3.3.1.4 Duplex or Nuffield

The Duplex ward arrangement also referred to as Nuffield is ward category belonging to the 1950s (Nazarian et al. 2011). It is an amalgamation of two Corridor wards, each with its own station, while sharing common support space located between the two wards (Catrambone et al., 2009). In this arrangement the beds are in small group with common facilities, but owing to the increasing awareness about cross infection in hospital wards together with the desire to avoid disrupting other patients, separate rooms were established in each ward for performing treatments and clinical procedure (Smith, 1966). The typical Nuffield ward arrangement is shown in figure 3.4.

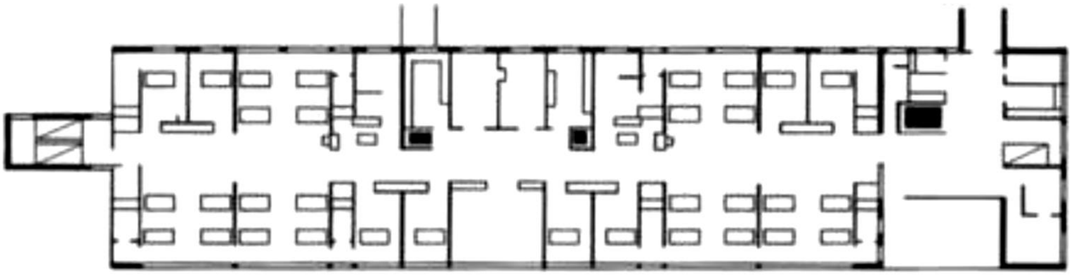


Figure 3.4: Nuffield or duplex ward type, Larkfield hospital, UK, source: James and Tatton-Brown 1986 (Nazarian et al. 2011)

3.3.1.5 Cluster wards

In cluster ward arrangement, the geometry functions as a generator and *"The combination of orthogonal and diagonal axes can generate close packing plan forms for single room layouts"* (HBN 4 Volume 2, 1998). This geometric arrangement apart from permitting more external wall surface for improved natural ventilation and lighting, however, it also solves the problem associated with deep plans and internal corners which usually produce "dead" space that is not useful for continuous nursing activity (HBN 4 Volume 2, 1998). The 'cruciform' is the most popular kind of cluster ward arrangement which is a variation of the corridor plan, to provide space for larger number of patients as possible around the nursing station while providing privacy improvements such as walls and doors (Catrambone et al, 2009). The cluster wards arrangements were not only intended to decrease walking distances but also to eradicate centrally positioned nursing places, to locate the drugs facility closer to patients and to seize complete benefit of visibility (Morelli, 2007). Figure 3.5 illustrates the typical cruciform cluster ward arrangement.

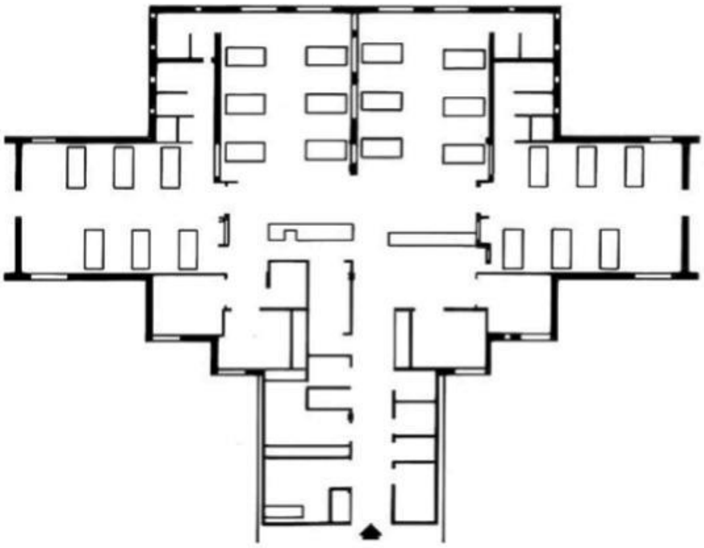


Figure 3.5: Cruciform cluster ward type, Weston general hospital, UK, source: James and Tatton-Brown 1986

3.3.1.6 Radial ward

The radial ward arrangement comprises central nursing station with the patient rooms placed around the nursing sub-stations, whereby increasing direct and obstructive view between the patients and the nurses' areas (Morelli, 2007) as illustrated in figure 3.6. This ward arrangement is largely the most appropriate, because of their ability of reducing nurses' unnecessary ward travel distance and consequently spending more time with patients Catrambone (2009). Moreover, compared to single and double corridor shapes, Nurses are more satisfied with the radial ward arrangement (Trites et al. 1970). Furthermore, the radial ward arrangement is a circle that allows a "fishbowl" view of all patient areas from the nurses station (Catrambone et al, 2009). However, one of the major disadvantages of the radial wards arrangement is its inability to accommodate sufficient quantity of private rooms without enormous waste of central core area (Hamilton, 1993). Thus, radial ward arrangements consume larger space, whereby reducing the bed numbers and consequently escalating the costs of construction and staffing (Morelli, 2007).

However, another variation of the circular ward arrangement is the hub and spoke units. The hub and spoke units include large rooms as radiating spokes, with central nurses' station as a hub (Yau, et al. 2011). The main advantages of the Hub and Spoke ward arrangement include its centralised stocks and equipment and excellent sight lines between nurses and the patients (Hurst, 2008). However, in this type of arrangement, the large and open room accommodations decreases patients' privacy, while increasing the level of noise and patients could see and hear more distressing events (Seelye, 1982; Stichler, 2001).

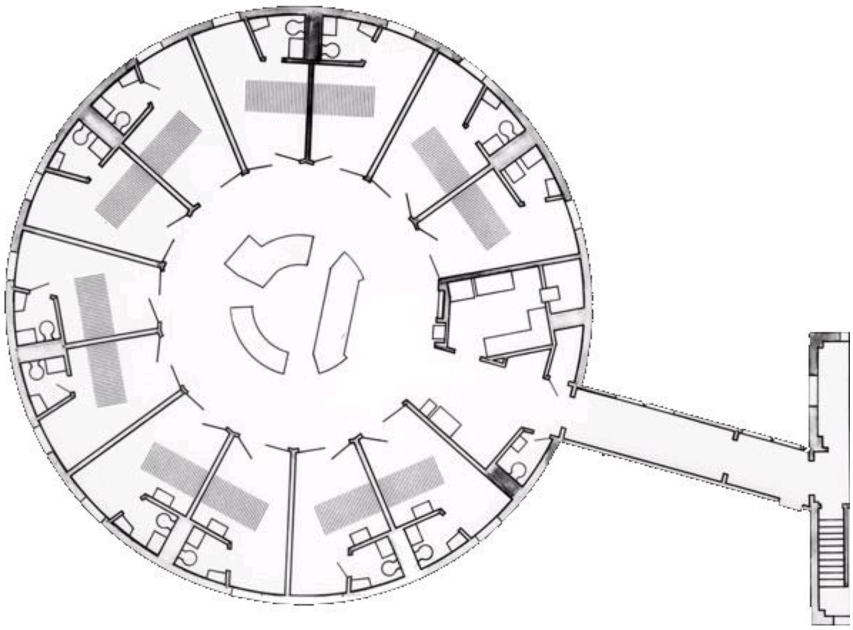


Figure 3.3.6: Circular nursing unit design with one centralized nursing station (Morelli, 2007)

3.4 Ventilation in Buildings

Ventilation can be defined as a controlled movement or changing of air in an enclosed space (Naghman, et al. 2008). It provides outdoor air into an enclosed space (building) and circulates air within the building (Atkinson, 2009). The main function of ventilation in buildings is to provide acceptable indoor air quality and thermal comfort (Heiselberg, 2002). According to Etheridge and Sandberg, (1996) space ventilation can be considered as two different simultaneous processes, which are important in studying ventilation both theoretically and experimentally. The first process is the airflow across openings in the external envelope and the internal partitions, and the second process is the airflow within the indoor space. Both processes above are problems of free and forced convection. Flows that are produced by gravitational force are called free convection, while flows generated by wind pressures are called forced convection.

Moreover, ventilation systems have considerable influence on indoor air quality and thermal comfort, because of its responsibility of delivering fresh air into conditioned indoor space (Srebric, 2011). Ventilation provides healthy air for breathing by diluting indoor contaminants with clean outdoor air and by providing acceptable airflow rate that can change the indoor air at a given rate. It is also employed as a mechanism for odour control, contaminant control and climatic control (temperature and relative humidity). (Atkinson, 2009)

The achievement and subsequent maintenance of ventilation standards requirements will reduce patient's health risk in hospitals (Department of Health / Estates and Facilities Division 2007). The mission of any effective ventilation system design in buildings is to; dilute the indoor air contaminants and concentration of carbon dioxide discharged by breathing, even distribution of air to ensure occupant's equal access to fresh air, and sustainability of air pressure balance between indoors and outdoors (Bas, 2003). Ventilation in buildings is generally divided into two classes including Mechanical and Natural ventilation.

3.4.1 Mechanical Ventilation in Buildings

The application of fans for the supply and/or removal of air in buildings are referred to as mechanical ventilation (Etheridge and Sandberg, 1996). These fans could be directly installed on the windows or walls, or else, it could be installed in air ducts to supply air into, or remove air from, a room (Atkinson, (2009). In the former case the fans are usually controlled individually (Etheridge and Sandberg, 1996). Thus, the mechanical ventilation also known as Heating Ventilating and Air Conditioning (HVAC) system, generally denotes the treatment of air to properly maintain its temperature, humidity, cleanliness quality and motion to satisfy the occupants, a specific process, or certain object in the space (Bradshaw, 2006).

Generally, the major factors that necessitate the provision of mechanical ventilation in buildings include; when natural ventilation strategies cannot penetrate to the essential parts of the room due to plan form or size, where the building is experiencing intolerable levels of external noise, or where air treatment and filtration is required (CIBSE, 1997). In contrast to natural ventilation, the mechanical ventilation system provides the opportunity to control the airflows in indoor environment in accordance with the requirements and the system is basically independent of the weather conditions outside (Awbi, 1998). However, the type of mechanical ventilation used is determined by the climatic condition of an area. In warm and humid climates, it is required to reduce or avoid infiltration to minimize interstitial condensation, which is realised through the provision of positive pressure mechanical ventilation system. On the other hand, in cold climates, it is required to avoid exfiltration to decrease interstitial condensation by employing negative pressure ventilation. Furthermore, negative pressure is also often used in spaces with locally generated pollutants such as a bathroom, toilet or kitchen (Atkinson, 2009).

The mechanical ventilation systems are generally divided into two types including unbalanced systems and balanced systems. The unbalanced systems is the one in which the air is either supplied to the building or removed from the building using a fan, with the air finding its own way out or in respectively. However, the balanced system is the one in which air is supplied and extracted from the building simultaneously using fans (Awbi, 1998). The key advantage of mechanical ventilation is that the ventilation rate is controllable and its ability to introduce the ventilation air evenly across the space (CIBSE, 1997). However, the main disadvantages of mechanical ventilation systems is sometimes it perform below expectation and the possibility of interrupting the normal operation for reasons such as equipment failure, utility service interruption, poor design, poor maintenance or incorrect management (Atkinson, (2009).

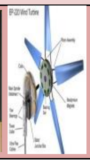
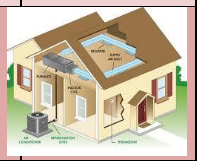
3.4.2 Natural Ventilation in Buildings

Natural ventilation are usually driven by natural forces such as wind and thermal buoyancy force owing to variation in indoor and outdoor air density, which force in fresh air from outside through custom-made building envelope openings (Atkinson, 2009). It relies on pressure differences caused by either wind or buoyancy effect created by temperature or humidity difference to move fresh air through buildings. Moreover, close control of the indoor environment is impractical in naturally ventilated buildings, because it reliance on driving forces that are not fully controllable (CIBSE, 1997).

Natural ventilations remain the most cost effective way of reducing indoor air pollution when the outdoor air quality is less contaminated than indoor air quality (Santamouris, 2005). Some of the custom-made building envelope openings include; windows, doors, solar chimneys, wind towers and trickle ventilators. The use of natural ventilation in buildings becomes increasingly attractive means of cutting energy cost and achieving acceptable quality of indoor environment, due to the improvement in the level of awareness on the cost and environmental consequences of energy utilization (Walker, 2010). The contribution of natural ventilation to the sustainable environment is mainly through the reduction of electrical energy used in buildings. Moreover, this reduction in electrical energy utilization is not only in the areas of chiller operations, but even more considerably in the areas of reducing electricity requirement to drive fans and pumps. However, most naturally ventilated buildings have narrow plans, which could permit enhanced utilization of day light, thus decreasing electric demand for electric lighting (CIBSE, 1997).

The development of suitable strategies and techniques to improve natural ventilation in urban buildings could save millions of lives in developing countries (Santamouris, 2005). The performance of different types of ventilation in relation to hot dry climatic conditions has been illustrated in table 3.1.

Table 3-1 Potential applicability of natural ventilation solutions in ideal conditions (consensus of a WHO systematic review)

Climate	**Natural ventilation**					**Hybrid (mixed method) ventilation**	**Mechanical ventilation**
	Single-side corridor	Stack (Atrium and chimney)	Courtyard		Wind tower		
			Outer corridor	Inner corridor			
Energy Req.	Low Energy Requirement					Medium Energy Requirement	High Energy Requirement
Hot and dry	☆☆☆	☆	☆☆☆	☆☆☆	☆☆☆	☆☆☆☆☆	☆☆☆☆☆
images						 	

Source: (Atkinson, 2009)

Moreover, natural ventilation should not be perceived simply as an alternative to air conditioning, but is a more effective tool to improve indoor air quality in urban areas, to safeguard health, to improve thermal comfort and to decrease unnecessary energy consumption (Santamouris, 2005). The ventilation system in buildings is made up of a number of key components (CIBSE (1997) :

- The ventilation inlet(s) where fresh air is drawn into the building.
- The room outlet(s) where the fresh air is exhausted out of the occupied space. Usually, the inlet to the building is the same components as the room outlet (e.g. an open window); sometimes the ventilation inlet and room outlet may be separated by a distribution system such as a floor plenum.
- A flow path through the space to the exhaust point.
- The exhaust path, such as a stack.
- The outlet, where the air is exhausted outside the building.

Moreover, the natural ventilation design consideration includes; climatic considerations, requirements of high air change rates, thermal comfort, indoor air quality, fire safety, and external noise. The consideration of these factors is essential for the designing of any building with natural ventilation. Natural ventilations are classified based on their basic architectural design features as follows (Atkinson, 2009; CIBSE, 1997);

3.4.2.1 Single-side corridor

The single-side corridor form of natural ventilation system comprises of a corridor on one side of the ward, with a single directional airflow either from the ward to the corridor or from the corridor to the ward, subject to the wind incident direction (Atkinson, 2009). The single-side corridor is generally the simplest kind of natural ventilation in which a simple opening or ventilation device such as window or trickle vent on a wall is employed to let outdoor air into the building and indoor air to exits through the same opening or via another opening located on the same wall (Awbi, 1994). This type of ventilation largely depends on opening(s) being on only single side of the ventilated space (CIBSE 1997). This single directional flow can assist in averting cross-infection and as a result, the design of the openings (windows) is vital for this kind of design. Therefore, the proper placement of window openings consistent with the ward door to establish path for cross-ventilation is important (Allard and Santamouris 1998).

The airflow through a big single ventilation opening in a room is either airtight or bi-directional. The influence of buoyancy happens when cooler air enters through the lower part of the opening and warm air exits through the upper part of the opening. Owing to the effect of turbulence, the wind pressure comprises of a mean and a fluctuating component and in case of a large opening both the two components may not be uniform across the opening (Awbi, 1998). Moreover, the major driving force for natural ventilation when using a single ventilation opening in a room in the summer is wind turbulence. The ventilation rates generated with this system of ventilation are usually lower compared to other strategies, as the ventilation air does not penetrate so far into the room. However, the ventilation rate can be improved using stack effect by providing the ventilation openings at different heights within the façade, (CIBSE 1997). Though, single-side corridor ventilation is widely used and economical, it is difficult to control, and it is only effective over a distance of about 6 m from the opening (Awbi, 1994). The single side corridor ventilation is illustrated in figure 3.7

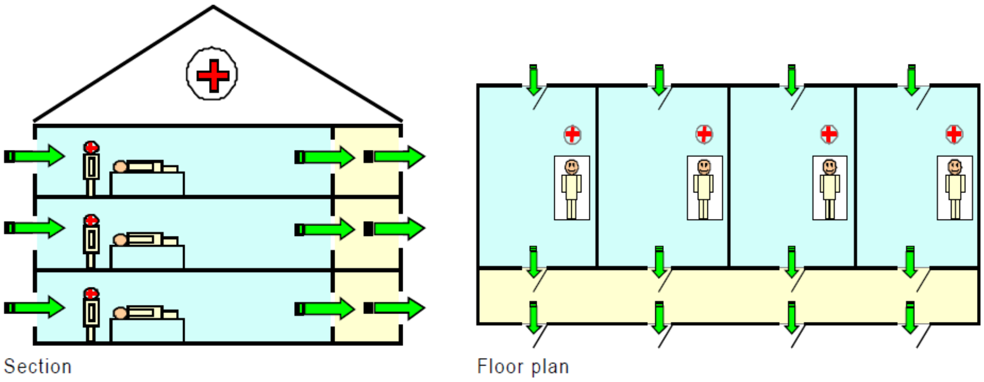


Figure 3.7: Wind-driven natural ventilation in the single-side corridor type hospital with wind entering the ward (Atkinson, 2009)

3.4.2.2 Cross Ventilation

A building is said to be cross ventilated when the ventilation openings are placed on both side of the space, allowing direct passage of air from one side of the building via the inlet window(s) to the other and exiting through another window(s) or door(s) (CIBSE, 1997; Awbi, 1998). In this case, the airflow is driven by wind and buoyancy pressures. Moreover, the openings types employed for cross ventilation ranges from small openings including trickle vents and grilles, or large openings such as windows and doors. Owing to the movement of air from one side of the space to the opposite side, natural ventilation allows deep penetration of air and as such it is the most appropriate for ventilating deep rooms (Awbi, 1998).

Moreover, the moving air across an occupied space usually picks up heat and pollutants along the way and as a result, there is a limit on the depth of space that can be effectively cross ventilated, which subsequently results in a building with a narrow plan depth. The narrow depth plan is normally accomplished using a linear plan arrangement, but a similar outcome can be attained by encircling the accommodation around an open courtyard. Another advantage of the narrow plan depth is its potential for natural lighting (CIBSE, 1997). Cross ventilation is usually needed for rooms with depth of more than 6 m deep. This method is usually employed for rooms with depth of up to 12m and is more efficient compared to the single-sided ventilation as it provides higher airflow rates and thus more appropriate for buildings with larger heat gains. But, it has a disadvantage of airflow control as in single sided ventilation (Awbi, 1994). Moreover, some opening positions should be positioned on the windward facade of the building and others positioned on the leeward facade to retain an appropriate wind pressure difference across the inlet and outlet openings. However, the presence of internal partitions and other obstacles can influence the pattern of airflow within the space and the penetration depth of the air (Awbi, 1998). Figure 3.8 illustrates typical cross ventilation approach.

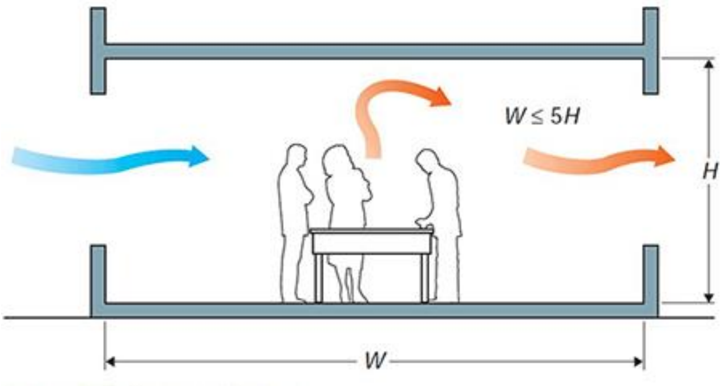


Figure 3.8: Cross ventilation (CIBSE, 1997)

3.4.2.3 Central corridor

Central corridor is a type of natural ventilation that is originally developed from the single-side corridor system by attaching additional series of wards on the other side of the corridor. The likely airflow route into the ward would be from one ward to the corridor, and then to the ward on the other side. Moreover, with incident wind parallel to the openings, the addition of a wing wall assists in pushing the outdoor air into the wards in the beginning, and subsequently exit through the central corridor. The likely transmission of polluted or infectious air from the upstream ward to the downstream ward is higher with this kind of ward floor arrangement (Atkinson, 2009). The typical central corridor ventilation is shown in figure 3.9.

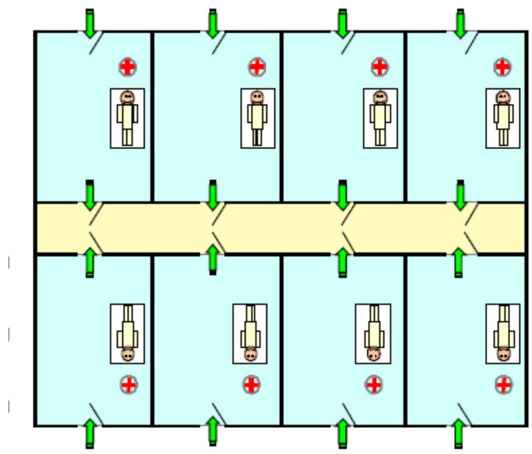


Figure 3.9: Central Corridor Ventilation

3.4.2.4 Courtyard ventilations

Generally, Courtyards are enclosed areas which facilitate in channelling and directing the overall airflow and as a consequence transform the microclimate of the buildings' surrounding environment (Atkinson, 2009). In order to successfully channel and direct the airflow in an enclosed environment as courtyard, large openings such as gates, doors, arches, etc. are required, which consequently produce convective natural ventilation in and around a building (Khan et al. 2008). According to Santamouris and Wouters (2006) "Courtyards are transitional zones that improve comfort conditions by modifying the microclimate around the building and by enhancing the airflow in the building". This kind of natural ventilation system can be categorized into two based on the relative arrangement of wards and corridor to the courtyard, including the inner corridor and outer corridor subtypes as illustrated in figures 3.10 and 3.11 respectively. Compared to other systems courtyard ward arrangements can provide higher ventilation rates, provided that the courtyard is adequately sized. Moreover, the performance of the outer corridor type is better than the inner type, due to their ability to avoid cross-infection through connected corridors by supplying fresh outdoor air into the corridor first (Atkinson, 2009). Figures 3.10 and 3.11 illustrate courtyard ventilation strategies with outer and inner corridors respectively.

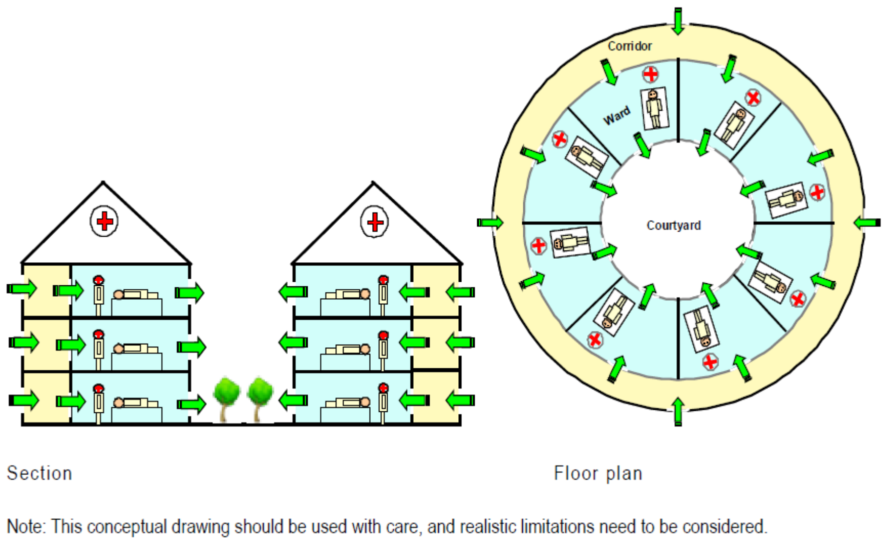


Figure 3.10: Combined wind and buoyancy-driven natural ventilation in the courtyard type (outer corridor) hospital (Atkinson, 2009)

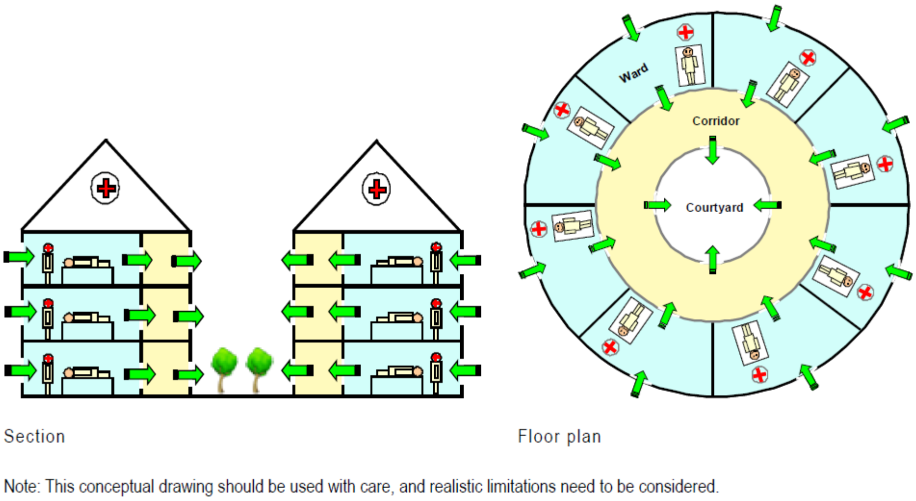


Figure 3.11: Combined wind and buoyancy-driven natural ventilation in the courtyard type (inner corridor) hospital (Atkinson, 2009)

3.4.2.5 Wind tower

A wind tower is a kind of natural ventilation systems which catches wind at the roof height and directs it down to the other part of the building (Atkinson, 2009). The passive attribute and zero energy requirements for their operation are the main benefits of wind towers. They operate with natural ventilation principles, using both wind and stack effect ventilation (Khan et al. 2008). In order to protect the interior part of the building, weatherproof louvres are installed and likewise, the flow is regulated by employing volume control dampers (Atkinson, 2009).

The process of wind tower commences with the infiltration of wind through the windward surface which has a positive pressure coefficient. The air is subsequently directed through the tower into the interior part of the building and eventually disperses through the building and departs wherever negative pressure coefficients exist in relation to air inlet position. This negative pressure at the leeward side of the building and tower is produced by the flow separation as a result of wind flow around the building. The air leaves through openings in the tower or more normally through purpose-made openings to promote cross flow and mixing (Khan et al. 2008). Moreover, the wind tower is usually split into four quadrants, which can run the full span of the building and become air intakes or extractors depending on wind direction (Atkinson, 2009). Typical operating principle of a wind tower is illustrated in figure 3.12

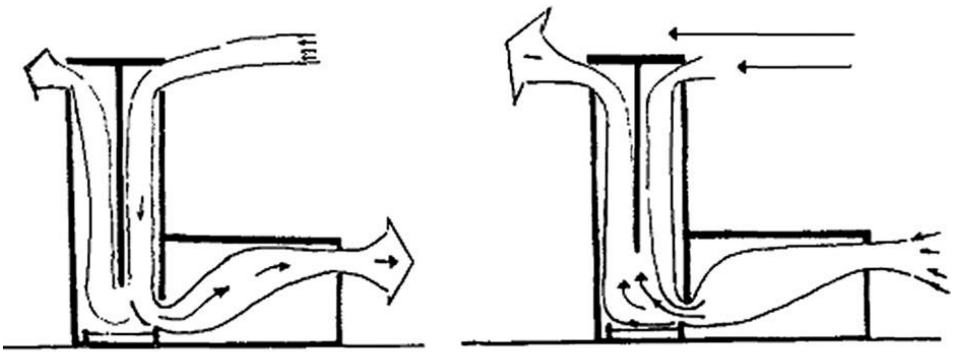


Figure 3.12: Operating principle of a wind tower (Khan et al. 2008)

3.4.2.6 Stack (Atrium and chimney)

An atrium is employed in buildings to provide comfort through an increasingly acceptable transmission of the outdoor environment to the indoor and its operation is similar to courtyard (Khan et al. 2008). The potential of applying natural ventilation in buildings is higher with atrium or chimney. Depending on the relative position of the wards, and the atrium/chimney, the classification of atrium/chimney form of natural ventilation system includes a side-atrium or chimney form, or a central atrium or chimney form (Atkinson, 2009). According to Awbi (1998), in atria integrated buildings, two reasons are responsible for the most suitable incorporation of stack. Firstly, the increase in air temperature due to solar gain in the atrium results in more efficient stack flow. Secondly, the atrium will operate as a buffer zone between the building and the external environment and consequently decrease the heat losses from the building in winter. Thus, solar chimneys are employed to improve stack effects for exhausts at purposefully intended exits and they dominate at low wind speeds (Khan et al. 2008). This is because the influence of stack (or buoyancy) is used to draw the external air into the wards through the windows. Once the polluted air is diluted in the ward, the hot and the contaminated air that converges in the atrium/chimney are discharge via the top openings. The relevance of stack ventilation strategy depends largely on the chimney height, the indoor and outdoor temperature difference and its relationship with the background wind (Atkinson, 2009). The typical buoyancy driven ventilation strategy is illustrated in figure 3.13.

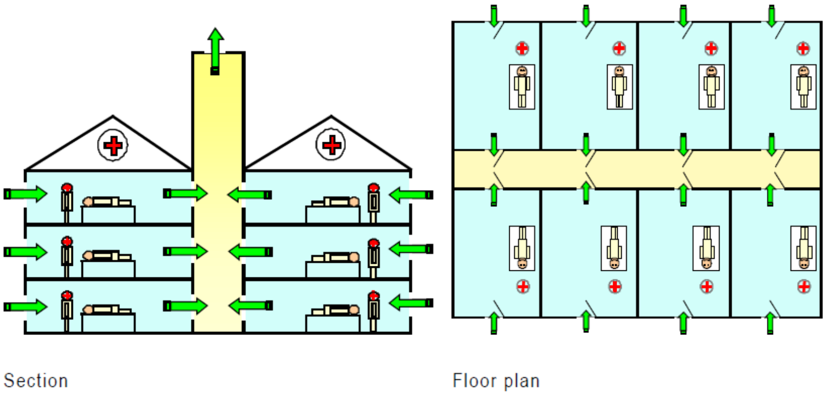


Figure 3.13: Buoyancy-driven (including solar chimney) natural ventilation in the solar chimney type of hospital (Atkinson, 2009)

3.4.3 Driven Forces for Natural Ventilations

The natural ventilation driving forces including wind, temperature/stack and combined (wind and stack) effects will be discussed in the following sub-sections.

3.4.3.1 Wind Driven Ventilation

Wind produces surface pressures that differ around buildings, modifying intake and exhaust system flow rates, natural ventilation, infiltration and exfiltration, and external pressures (Allard and Santamouris, 1998). Wind driven ventilation is a result of pressure differences acting across the external surface of a building. The distribution of this pressure is determined by the following factors (CIBSE 1997):

- The type of terrain surrounding the building (open country/city centre) and existence of any local obstacle (buildings, tree belts etc.) that permit site layout and landscaping to improve wind driven ventilation.
- The wind speed and its direction relative to the building, and
- The building shape; this permits the architectural form and detailing to enhance the potential for wind driven ventilation.

Moreover, the process of airflow through a building originates from areas of high surface pressure to areas of low pressure. Generally, windward building surfaces facing into the wind will experience positive pressures and the leeward surfaces and those parallel to the wind direction will experience negative pressures (suction) (CIBSE, 1997). This phenomenon causes a negative pressure within the interior part of the building, which is adequate to establish substantial flows through the building openings. Thus, as a general rule, an incursion of air is induced on the windward side and discharged on the leeward side (Allard and Santamouris, 1998). The typical wind pressure field around building is shown in figure 3.14.

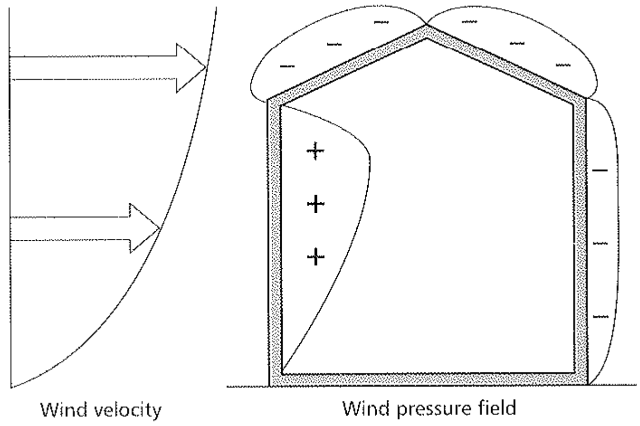


Figure 3.14: Wind pressure field around building (CIBSE, 1997)

Furthermore, compared to ventilation rates from other causes, the measurement of wind-induced ventilation has additional complications. Firstly, when using tracer gas technique for the measurement, the measured rates are expected to be more sensitive to the level of mixing applied, since the effective rate as a result of pulsations is partly dependent on the degree of mixing. Secondly, the variation of wind-induced ventilation with time is usually more noticeable compared to other sources of ventilation. However, these additional complications are not significant, except in a situation where in-depth measurements are being carried out (Etheridge and Sandberg, 1996). Since, natural ventilation is usually dependent on the types of climates, building design and occupant’s behaviour, various wind driven ventilation strategies will be examined in the context of semi-arid climates, in relation to enhanced building design parameters like orientation, wind speed, and insect screens.

3.4.3.2 Stack Effect (Buoyancy) Ventilation

Stack effect ventilation is a system in which the movement of air between inside and outside a building is a result of pressure difference due to air density difference related to indoor and outdoor temperature differences (Building Regulations, 2009). Owing to the lower density of warm air compared to cold air, and when two columns of air with different temperatures are divided by a boundary, there will be a variance in pressure gradients on both side. Usually, in a building where the inside air temperature is higher than outside, the pressure difference acts inwards at the lower levels of the building and outwards at the upper levels of the building. Moreover, when openings are located in the boundary separating the two columns, an upward airflow will be generated through the building height, exhausting warm air through higher level and replacing it by cooler air at lower level as illustrated in figure 3.15. This phenomenon is referred to as 'stack effect' (CIBSE, 1997).

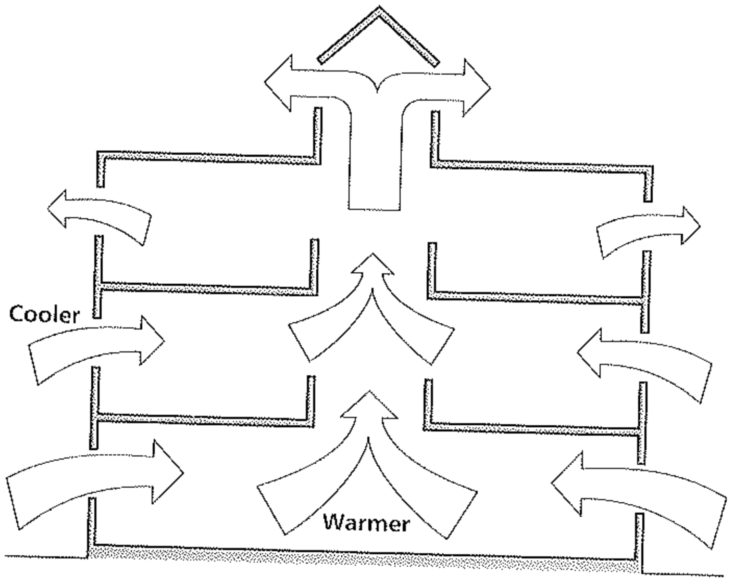


Figure 3.15: Stack-driven flows in atrium

3.4.3.3 High-tech or hybrid Ventilation

Hybrid (mixed mode) ventilation is a system that provides the required air flow rate in buildings based on natural driving forces, but, mechanical ventilations is employed once the natural driving force is not sufficient (Atkinson, 2009). This kind of ventilation systems can provide a comfortable indoor environment employing both natural ventilation and mechanical systems, but applying different characteristics of these systems at different times of the day or season of the year (Heiselberg, 2002). In a situation where the natural ventilation level is not sufficient to remove pollutants, exhaust fans can be installed to improve the ventilation level especially in spaces accommodating patients with airborne infections. Some design methods of hybrids ventilation systems includes (Atkinson, 2009);

a. Fan assisted stack
b. Top-down ventilation (Fan assisted stack plus a wind tower)
c. Buried pipes

The hybrid ventilation combines the influences of both mechanical and natural ventilation in a two-mode system where the operating mode differs depending on the season, and within individual days. Consequently, the active mode reflects the outdoor conditions while taking maximum benefit of ambient situations at any point in time. Moreover, the main advantage of Hybrid ventilation system is its ability to utilize both ventilation modes in one system, while exploiting the advantages of each mode and producing new chances for additional enhancement and improvement of the whole ventilation quality (Heiselberg, 2002).

3.5 Natural ventilation and indoor air quality studies in hospital Wards

The study "Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals of Semi-Arid Climates" was initiated to provide acceptable indoor air quality in the hospital wards of the study area (semi-arid climates). The importance of indoor air quality in hospital multi-bed wards is higher compared to any other facility because of the nature of people it accommodates, who are immunosuppressed and immune-compromised due to certain illnesses. Consequently, the provision of acceptable indoor air quality in such facility is vital to prevent cross-infection among patients and other healthcare workers.

Several studies were conducted establishing the effects of pollutants on indoor air quality in hospital buildings (Cole and Cook, 1998; Anthony, 2002; Sudharsanam, *et al* 2008; Beggs et al. 2008; Pepper and Carrington, 2009; Escombe et al. 2007). Moreover, the facts linking transmission of contagious diseases such as measles, tuberculosis, chickenpox, smallpox, influenza and SARS to ventilation and air movement in buildings are sound and convincing (Li et al. 2007). Sudharsanam, et al (2008) studied indoor air quality in hospitals using petri plate gravitational settling (passive) sampling method and found that the concentration of bio-aerosol varies in different hospital environments and apart from notionally sterile areas and specialised wards with low bacterial count, other wards have been found to have higher concentrations of pathogens capable of causing nosocomial infections. Thus, effective ventilation strategy is required to remove these pathogens in the hospital wards.

Moreover, ventilation strategies are generally divided into two including mechanical and natural ventilation strategies. Mechanical ventilation requires significant energy resources to operate. In the study area, energy intensive ventilation strategies are not applicable due to the protracted energy shortage. As extra energy is required in maintaining acceptable indoor air quality (Wong *et al.* 2008), designers need to reconcile energy demand, indoor air quality, pollutant source control and efficient ventilation (Guenther, 2010). However, natural ventilation is inexpensive and low maintenance and it is specifically suitable for tropical climates, environments with limited-resources and settings with high TB transmission risks (Escombe, et al. 2007). This is the key motivating factor for the choice of natural ventilation in this study.

Furthermore, natural ventilation decreases airborne infection risk by exploiting the opening of windows and doors, compared to expensive mechanical ventilation system (Gilkeson et al. 2013). Escombe, et al. (2007) in their study established that, opening windows and doors in naturally ventilated buildings produced ventilation rates more than double that of mechanically ventilated system. Qian et al. (2010) in their measurements in hospital ward revealed that higher ventilation rate is achieved using natural ventilation particularly when both windows and doors are open. Moreover, natural ventilation is revealed to be efficient in open wards where the potential airborne contamination risk is uniformly spread all over patients' positions (Gilkeson et al. 2013). The interesting feature of natural ventilation in contrast to mechanical ventilation is that it is widely used in healthcare facilities in limited-resource regions of the world (Qian et al. 2010).

Higher ventilation rates are determined by the wind speed, the direction and the openings area (Qian et al. 2010). Gilkeson et al. (2013) in their studies in the UK confirm the effectiveness of cross ventilated wards with satisfactory ventilation rates in accordance with standard requirements. The results also indicate that closing ventilation openings and conditions such as low external wind speed during design affects ventilation effectiveness. Furthermore, Anthony (2002) studied the indoor climate of multi-storey hospital buildings in hot humid regions. The study concluded that North-South orientation of building openings reduces the effects of solar gains and indoor operative temperatures.

When using natural ventilation for infection control, three major concerns need to be addressed (Qian et al. 2010). First, the ventilation rate supplied through natural ventilation may be high sometimes, and low when the natural forces are not available. Second, it is generally accepted that, negative pressure is required for airborne precaution and natural ventilation cannot control the airflow direction through the doorway. Third, it is difficult to control thermal comfort when using the natural ventilation, especially when the outdoor air exceeds comfort temperatures.

Moreover, the contribution of various ventilation strategies in removing airborne pathogens in healthcare facilities is well documented (Qian *et al.* 2010; Yau, *et al.* 2011). The knowledge of the origins, aerodynamics, survival, and infectivity of various airborne infectious pathogens obtainable in hospital indoor environment is essential for the control and prevention of their spread and transmission. Some of the possible preventive measures include source management, activity management, design intervention, dilution intervention, and cleaning (Cole and Cook 1998). Study by Li et al. (2008) established that the air change rate, airflow direction and airflow pattern are the key factors influencing ventilation performance in Severe Acute Respiratory Syndrome (SARS) wards. Beggs *et al.* (2008) in their studies established that the supply and extraction of ventilation air through the ceiling significantly reduces the concentration of bio-aerosol in hospital wards.

However, limited studies have been conducted in the semi-arid climates, which resulted in the creation of an obvious knowledge gap in ventilation studies in the tropics compared to the temperate climates (Yau, et al. 2011). This gap in knowledge is more prevalent in open ward facilities, which accommodate most patients in the tropical hospitals. Table 3.2 shows various ventilation and indoor air quality studies conducted with their areas, climates, year and limitations.

Table 3-2 Natural Ventilation and Indoor Air Quality Related Studies

No	*Study*	*Authors/ Year*	*Area*	*Climate*	*Limitations*
1.	Natural ventilation for reducing airborne infection in hospitals	Qian, et al. 2010	Wards and Isolation rooms	Hot-Humid Climate of Hong Kong	Not for Semi-arid Climate
2.	The Ventilation of Multiple-Bed Hospitals in the Tropics: A Review	Yau, et al. 2011	Multi – Beds Wards	Tropics	Review and recommend studies for Multi Bed
3.	Study of the Indoor Air Quality in Hospitals in South Chennai, India – Microbial Profile	Sudharsanam, et al. 2008	Wards, Intensive care units and Operating theatre	Chennai India	Concern with Microbial Profile
4.	Indoor Climate of Multi-storey Hospital Buildings in Hot Humid Regions	Anthony C. K. S. M. 2002	Building material and orientation	Hot-Humid Climate-Sri Lanka	Thermal comfort
5.	The ventilation of multiple-bed hospital wards: Review and analysis	Beggs et al. 2008	Multi Bed Wards	Isothermal-Constant Temperature	UK and USA Standards
6.	Rethinking hospital general ward ventilation design using computational fluid dynamics	Yam, et al. 2011	General Wards	No Climatic Reference	No Climatic Reference
7.	Control and management of hospital indoor air quality	Leung and Chan. 2006	Entire Hospital	No Climatic Reference	Management and control Strategies only
8.	Perceived Indoor Air Quality, Air-Rated Symptoms and Ventilation in Finnish Hospitals	Hellagren et al. 2011	Entire Hospital	Temperate-Finland	Not for Semi-arid Climate
9.	The application of heat pipe heat exchangers to improve the air quality and reduce the energy consumption of the air conditioning system in a hospital ward: A full year model simulation	Ahmadzadehtehtalatapeh and Yau, 2011	Orthopaedic Ward	Tropical Climate-Malaysia	Not Multi Bed Wards
10.	Improvement of the Indoor Environment and Airborne Contamination Control in an Operating Room	Wang et al. 2011	Operating room	District hospital in Taiwan	Not Multi Bed Wards
11.	Determining Relationship Between Physical Health Care Settings and Mycobacterium Tuberculosis	Shakri et al. 2011	Respiratory clinic and TB isolation ward	Tropical Climate-Malaysia	Not Multi Bed Wards
12.	Air quality in hospital operating rooms	Dascalaki et al. 2008	Operating room	Temperate/ Hellenic Climate	Not Multi Bed Wards
13.	The predictions of infection risk of indoor airborne transmission of diseases in high-rise hospitals: Tracer gas simulation	Lim et al. 2010	General Wards	Temperate –South Korea	High-Rise and Not Semi-Arid
14.	Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: a case-study of hospital wards	Lomas, and Giridharan, 2012	Hospital Wards	Temperate-UK	Not Semi-Arid Climate
15.	Predictions and measurements of the stack effect on indoor airborne virus transmission in a high-rise hospital building	Lim et al. 2011	General hospital wards	Temperate – South Korea	Not Semi-Arid Climate
16.	Distributions of respiratory contaminants from a patient with different postures and exhaling modes in a single-bed inpatient room	Yin et al. 2011	Single-bed inpatient room	Environmental chamber	Not Multi Bed Wards
17.	An Evaluation of the Ventilation Performance of New SARS Isolation Wards in Nine Hospitals in Hong Kong	Yuguo et al. 2007	Isolation Wards	Hot-Humid Climate of Honk Kong	Not Multi Bed Wards

3.5.1 Openings in Hospital Buildings

Openings in buildings are generally classified into purpose-provided (ventilation) and adventitious (infiltration) openings. Any type of openings that is purposefully installed to provide ventilation, such as air vents and openable windows are called Purpose-provided openings. The adventitious openings in the other hand are not purpose-provided, but due to components openings such as gaps in openable components and background openings such as envelope cracks (Etheridge and Sandberg, 1996). Bangalee et al. (2012) studied a common shape single storey building with multiple windows under the influence of usual wind speed to investigate the capacity of wind-driven ventilation system using computational fluid dynamics (CFD). They found out that, based on the distribution of pressure coefficient in cross ventilation, the front wall is the most appropriate for inlet openings while all other wall can function as exit opening.

3.5.2 Wire Mesh Screens

The rate of air exchange between the indoors and the outdoors remain one of the major parameters to control the microclimate of an indoor environment (Harmanto, et al. 2006). However, this exchange is affected by many factors including the effect of insects and other outdoor air pollutants that require filters in form of insect screen to prevent the entrance of these unwanted pollutants. Mosquito screens are insect screens that are usually made of wire gauze to prevent mosquitoes and other insects from entering the interior space. They are installed directly to the openings such as doors, windows and trickle ventilators. Insect screens are used for various reasons in airflow system including; the creation of uniformity in velocity distribution, air stream turbulence reduction, production of artificially high turbulence, introduction of known turbulence drops in experimental systems, and the regulation of dusts and insects entrance into buildings (Sharples and Chilengwe, 2006). The investigation into the relationship between insect screens and natural ventilation was informed by the formers' perceived effects on the microclimatic condition of the indoor spaces. While admitting the effectiveness of these insect screens in preventing Mosquitoes and other insects into the building, installing the screens on the ventilation openings may result in restriction to the airflow, which requires a larger screen area to permit the same airflow as without the screens (Harmanto, et al. 2006). Hence, the use of larger ventilation opening sizes will significantly reduce the effect of the insect screens. Therefore, the ratio of ventilation opening to floor area is an important consideration in designing ventilators with insect screens.

3.5.2.1 Pressure drop due to Insect Screens

The reduction in fluid pressure due to insect screens is usually affected by the porosity of the screens and the outdoor air velocity. Sharples and Chilengwe (2002) in their studies found that at low pressure differences and using a louver with a lower insect screen porosity, the airflow decreases by 50% and with a higher screen porosity (bird and animal screens) the airflow decrease is about 20%. Harmanto, et al. (2006) have investigated the effect of three different mesh sizes on airflow resistance and reported 50% and 35% reduction in ventilation rate for meshes with 0.30 and 0.38 porosity level respectively compared to a mesh with 0.41 porosity level. Thus, the finer the insect screen, the higher the airflow reduction.

3.5.2.2 Effect of Insect Screens on Indoor air Temperature and Relative Humidity

One of the major determinants of climatic condition in an indoor environment is ventilation efficiency. The quality and quantity of outdoor fresh air received in the indoor environment dictates the level of thermal comfort, which is largely the product of indoor temperature and relative humidity. According to the research conducted in the humid tropics by Harmanto, et al. (2006), when the porosity of the insect mesh is increased, internal air temperature increases by 1 to 3°C and the humidity level increases as well.

The screening of openings such as doors and windows in buildings is to prevent mosquito borne diseases such as Malaria. The insect screen mesh size should be 1.5 mm or less, to prevent mosquito insects from entering. Table 3-3 shows the mesh characteristics of different types of insect screens. The table illustrates the difference between the normal mosquito screen, the No-see-um screen that can block a tiny fly called *No-see-um*, and the shade that can block 80% of sunlight and it is use for privacy, sun and insect protection.

Table 3-3: Characteristics of different mesh types

Mesh	Mosquito	No-see-um	Shade
Max height (m)	3.66	3.05	3.05
Max width (m)	45.72	45.72	45.72
Holes/ sqm	0.15	0.52	n/a
Hole size (mm)	1.7 x 0.8	0.6 x 0.6	n/a
Air flow	85%	65%	40%

3.5.3 Indoor Ventilation Conditions Assessment Criteria

The knowledge of the distribution of air velocities within ventilated space is as equally important as the overall amount of airflow within that space when assessing ventilation for human comfort. The evaluation of ventilation in indoor space requires quantitative assessment criteria. These criteria as employed in various studies as collected by Givoni (1994) include the following:

- Air speed at the inlet opening.
- Maximum speed of air at any point in the space.
- Average air speed in the space.
- Average speed at occupancy level (that is, at about 1 m above the floor).

According to ASHRAE standard, the maximum indoor air speed allowed in air-conditioned space is 0.8 m/s. However, indoor environment in free-running non air-conditioned spaces reacts to the variations in outdoor climate and the occupants of these buildings generally adjust to a wider diurnal and annual climatic variation than they will in air-conditioned buildings. Hence in naturally cross ventilated buildings, indoor air speed regularly extents from 1 to 2 m/s, and the occupants of these buildings usually accept such a wider span of air speeds as normal. Moreover, the most conventional remedy to minimize discomfort related to high temperatures and humidity is the provision of a higher air speed in the interior space. Hence the ASHREA standard of 0.8 m/s is not realistic for naturally ventilated buildings especially in hot countries (Givoni, 1994).

3.5.4 Ventilation Guidelines, Codes and Standards in Hospital Wards

Various organizations are responsible for guiding the design of healthcare facilities in the United States and the United Kingdom. Some of these organizations include, the American Institute of Architects (AIA) and the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), which guide and regulate the design of healthcare facilities in the United States. However, HTM 2025, which is a publication of the Department of Health, is the guideline for designers of healthcare facilities in the United Kingdom (Beggs et al. 2008). The comparison of the various guidelines for these organizations has been shown in table 3.4 as adopted from (Beggs et al. 2008).

Table 3-4 Comparison of the various guidelines governing the ventilation of general and intensive care ward spaces in the United Kingdom and the United States

Code	Country	Pressure Relationship	Minimum Outdoor Air Change Rate (AC/h)	Minimum Total Air Change Rate (AC/h)	Design Air Temperature (°C)	Design Relative Humidity (%)
Patient rooms/general wards						
AIA	United States	Neutral	2	6	21 to 24	Not specified
ASHRAE	United States	Neutral	2	6	21 to 24	30 to 60
HTM 2025	United Kingdom	Neutral	Not specified*	Not specified†	20 to 22	40 to 60
Intensive care wards						
AIA	United States	Neutral	2	6	21 to 24	30 to 60
ASHRAE	United States	Neutral	2	6	21 to 24	30 to 60
HTM 2025	United Kingdom	Neutral	Not specified*	Not specified†	20 to 22	40 to 60

*Minimum outdoor air (ie, fresh air) rate of 8 l/s per person specified.
†100% outdoor air encouraged.

Source: Beggs et al. (2008)

The minimum outdoor air change rates denote the quantity of fresh outside air required in the hospital wards, while the minimum total air change rates refer to the minimum ventilation requirements from all sources including natural and mechanical sources. Based on table 3.4, both the minimum outdoor air change rates and the minimum total air change rates standard requirements of 2 ach^{-1} and 6 ach^{-1} for patients rooms/general wards are the same for both AIA and ASHRAE standards.

3.5.5 Ventilation performance prediction and modelling approaches

Ventilation performance can be evaluated through experimental techniques such as analytical or semi-empirical formulae, zonal and multi-zone network models simulations and computational fluid dynamic (CFD) models (Ramponi and Blocken, 2012). These methods are presented in the following sub-sections.

3.5.5.1 Semi-empirical equations modelling approach

Semi-empirical equations, also known as single zones models are the simplest ventilation performance prediction models (Srebric, 2011). The application of empirical models in predicting ventilation system performance is very similar to analytical models (Chen, et al. 2010). The semi-empirical equations represent a class of analytical models calibrated with empirical coefficients to calculate bulk ventilation airflow rates through various types of openings. The airflow for openings at the building envelope such as doors and window is driven by pressure difference between the indoor and outdoor environments. This pressure difference is instigated by wind airflow around buildings referred to as wind effect and also by temperature variations between the indoors and the outdoors referred to as stack effect. However, the combination of wind and stack effect is only correct when there is no mechanical system such as heating ventilating and air-conditioning (HVAC) system install in the building, that result in indoor pressure changes subject to the system balancing and maintenance. Hence, this assumption is reliable for ventilation performance predictions due to building openings in a natural ventilation regime (Srebric, 2011).

Supposing the airflow through openings is proportional to the square root of the pressure difference across the opening, the total airflow rate as a result of the combined wind and stack effect can be estimated as follows (Srebric, 2011):

$$Q_{tot} = \sqrt{Q_w^2 + Q_S^2} \quad (1)$$

Where
Q_{tot} is the total volumetric flow rate (m^3/s),
Q_w and Q_s are volumetric flow rates due to wind and stack effects respectively (m^3/s).
Moreover, in case of single-sided natural ventilation airflow via a single opening for a single room in a building the correlation for the volumetric flow rates due to wind and stack effects is as follows (Allard and Santamouris, 1998; Butcher, 2005):

$$Q_w = 0.05 A U_H \quad (2)$$

$$Q_S = 0.2A\sqrt{\frac{gh\Delta T}{T_{avg}}} \quad (3)$$

Where:
A is the opening area (m^2),
U_H is the wind velocity at the building height H (m/s),
g is the gravitational acceleration (m/s^2),
h is the opening height (m),
ΔT is the inside-outside temperature difference (K), and
T_{avg} is the average of inside and outside temperature (K).

Moreover, numerous factors are responsible for the complex pressure distribution generated on the exterior surface of a building. These factors include wind direction, wind velocity, air density, building geometry, surface orientation, and nature of the surrounding environment (Ethridge and Sandberg 1996). However, many of these factors are very difficult to predict due to the stochastic nature of the wind. Moreover, wind pressures on building surfaces are normally positive on the windward and negative on the leeward (Srebric, 2011).

3.5.5.2 Multi-zone airflow network modelling approach

The multi-zone airflow network modelling approaches are the easiest mathematical models for determining the distribution of indoor airflows, temperature, and contaminant concentrations. The models solve the conservation equation for mass, energy, and species concentration based on the number of approximations. The models separate a given building space into a number of volumes called zones. Subsequently, the mass, energy, and concentration equations for each zone will be solved using the multi-zone airflow network models to acquire a solution for particular boundary conditions and the perfect mixing assumption. Hence, due to their simplicity and ease in understanding, the multi-zone airflow network models are the preferred models for solving design problems (Srebric, 2011).

3.5.5.3 CFD Modelling Approach

CFD is widely used in building design and the choice of a CFD solution is often determined by several factors. These factors include the complexity of the building system being considered, unavailability of other suitable methods, cost and time implications, promoting the design feasibility, and the confidence in the use of CFD (Nielsen et al. 2007).

CFD simulation models can furnish researchers with detailed information on indoor environment design parameters such as air velocities, temperatures, and contaminant concentrations in a fast and reliable way. These models are suggested as an economical approach compared to the measurements and they are more detailed approach compared to the multi-zone airflow network models. CFD models usually splits the interior space into a number of cells, in which the conservation of mass is satisfied for each cell, in order to balance the sum of mass flows into or out of a cell from all its neighbours to zero. Likewise the momentum exchange from the flow into or out of a cell have to be balanced in each direction with pressure, gravity, viscous shear, and energy transport by turbulent eddies (Srebric, 2011).

The major challenge for transitional and fully turbulent flows that usually exist in room flows is to appropriately describe the transport of energy and momentum. Turbulent flows are three-dimensional and random with many turbulent eddies (vortices) that improve mixing in the flow field. Additionally, mixing usually leads to reduction in velocity gradients and dissipation of kinetic energy of the fluid stream. Therefore, to examine the effect of turbulent mixing on thermal comfort and indoor air quality it is essential to solve the partial differential equation governing turbulent flows. The governing equations of the instantaneous flow are (Srebric, 2011; Nielsen et al. 2007):

Continuity for an incompressible fluid:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4)$$

x-momentum conservation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{dx} + v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (5)$$

Where $v = \frac{\mu}{\rho}$

y-momentum conservation (Vertical):

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{dx} + v\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + g\beta_T(T - T_0) \ldots\ldots\ldots\ldots\ldots\ldots\ldots. (6)$$

The last term in the above equation is called the Archimedes or buoyancy term, which represents the difference between the hydrostatic pressure gradient $-\rho_0 g$ and the weight of the elementary fluid $-\rho g$.

Energy conservation:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (7)$$

Where

u = the instantaneous x velocity components
v = the instantaneous y velocity components
p = the instantaneous static pressure
T = the temperature
ρ = *the* density
μ = *the* kinematic viscosity
β_T = the expansion coefficient due to temperature change
a= the thermal diffusivity of the fluid$\left(a = \lambda/_{\rho C_p}\right)$.
T_0 = the fluid temperature at a reference location and
g = the gravitational acceleration.

According to Ramponi and Blocken, (2012), CFD simulation has edge over other ventilation performance evaluation methods in the following ways;

1. CFD provides whole flow field data on relevant parameters at all points of the computational domain.
2. Due to its ability to performed full scale simulation, CFD avoids incompatible similarity requirements that usually happen in reduced-scale testing.
3. CFD permits full control over the boundary conditions and allows parametric studies to be performed easily and efficiently.
4. CFD models are presently the most popular and specifically appropriate for studying indoor air quality and natural ventilations.

3.6 Indoor Air Quality (IAQ) in Buildings

The quality of indoor air dictates the health status of an environment and its occupants. As clean indoor air quality is critical for healthy indoor environment. Poor indoor environmental qualities are responsible for many health problems including allergies, eye irritations, and respiratory problems (Yau, et al. 2011). However, improved indoor air quality provides the required level of comfort, enhances occupant health and workplace productivity (U.S. Environmental Protection Agency-EPA, 1991). The quality of air indoors is important because, people spend most of their time indoors. Robinson and Nelson (1995) in their examination of time budget amongst US resident established that, on average, people spent 88% of their day inside buildings, and 7% inside vehicles, while spending only 5% outside.

According to ASHRAE, *“an acceptable indoor air is one in which there are no known contaminants in harmful concentrations, as determined by the competent authorities and a substantial majority (80% or more) of occupants are not exposed to dissatisfaction”* (Orosa and Oliveira, 2012).

The level of air quality in hospital environment has an influential effect on the concentration of pathogens in the air, and subsequently dictates the rate of airborne infectious diseases obtainable indoors (Ulrich *et al.* 2008). The United Nations Centre for Human Settlements revealed that indoor air quality is insufficient in 30 per cent of the buildings around the world (LRC, 1993). The provision of acceptable indoor air quality in hospital wards is necessary to reduce risk of infection and cross infection among patients, nurses and other healthcare workers. Thus it is essential to control indoor air pollutants of both indoor and outdoor sources.

3.6.1 Indoor Air Pollution and control

Usually, the level of pollution in the interior part of buildings is slightly lower compared to those simultaneously obtained outdoors (Bradshaw, 2006). The external conditions are normally beyond the scope of the designer to regulate, but should be considered in selecting fresh air inlets, whether for natural or mechanical ventilation. Conversely, the indoor air quality is affected by design and specification (Baker and Steemers, 2000). Generally, building occupants are subjected to a combination of airborne contaminants comprising chemicals and micro-organism originating from both outdoor and indoor sources (Appleby, 2011). But the interest of this study is tailored towards pollutants with outdoor sources.

When fresh air flows through a building, it will pick up both heat and pollutants and becomes less ‘fresh’. Hence, the employment of natural ventilation in buildings suggests that it is very challenging to clean the air entering the building (CIBSE, 1997). As such, filtration measures should be employed to filter the incoming air from all contaminants before admitting it to the buildings’ indoor environment. Moreover, the employment of pressurization techniques to prevent building from outdoor Chemical, Biological and Radiological (CBR) emissions has been recommended. This is achieved through pressurizing the building indoor environment in relation to the outdoors and filtering and cleaning the incoming air to eliminate CBR agents. With sufficient filtration and effective pressurization, this method has the ability to provide the required protection against such outdoor emissions, provided that the problem of pollutant infiltration into the building through envelope leaks is not neglected (Persily, 2004).

The three basic strategies that could be employed individually or together to reduce occupants exposure to indoor contaminants includes building air tightening and pressure management, ventilation and air infiltration, and contaminant removal (Santamouris, 2005). CIBSE specifies valuable regulations on reducing the effect of outdoor contamination indoors by understanding outdoor pollutants behaviour and assessing their effect on indoor air quality for both mechanically and naturally ventilated buildings (CIBSE, 1999). In order to eradicate or reduce the exposure to airborne contaminants in buildings, it is beneficial to implement the following decision-making hierarchy (CIBSE, 2006) Paragraph 8.4 Air Quality and Ventilation (Appleby, 2011).

i. Eliminate contaminants at sources;
ii. Substitute with substances that produce non-toxic or less malodorous emissions;
iii. Reduce emission rate of substances;
iv. Segregate occupants from potential sources;
v. Improve ventilation, e.g. by local exhaust, displacement or dilution;
vi. Provide personal protection.

3.6.2 Health Consequences of Indoor Air Pollution

There is a growing concern over the health consequences of indoor air quality globally in hospital buildings, especially after the recent outbreak of diseases like severe acute respiratory syndrome (SARS), Swine Flu (H1N1) and other airborne infections such as tuberculosis. The recent investigations by the World Health Organisation (WHO) revealed that 30 to 40 per cent of 760 million incidents of respiratory diseases reported globally are caused by particulate air pollution only (Santamouris, 2005). Moreover, investigations in Latin America, Asia and Africa have also indicated that indoor air pollution is responsible for pregnancy associated disorders, such as stillbirths and low birth weight. It has also been linked with blindness and immune system depression (Schwela, 1996). In hospitals, complications related to shortcomings in indoor air may be among the most frequent environmental health concerns handled by most doctors (Seltzer, 1995). The highest risk of infections is obtainable in healthcare facilities because it brings together communicable and susceptible individuals, causing frequent airborne nosocomial transmission (Yau et al. 2011). Moreover, indoor air contaminants have the potential to cause transient morbidity, disability, disease, and extreme circumstances result in death (Berglund et al. 1992).

3.6.3 Indoor Air Quality and velocity Models

3.6.3.1 Percentage of dissatisfied with Ventilations

In designing any natural ventilation system, the first step is to establish the quantities of airflow needed to meet the indoor air quality and thermal comfort requirements (CIBSE, 1997). This is because of the association between the quality of indoor air and the required ventilation level in most standards and guidelines. This is contrary to the concept applied to the thermal environment because it is difficult to settle on a method for specifying the level of indoor air quality in a building. As a substitute, ventilation rates requirements are specified for different categories of space and occupation (Olsen, 2004). This is because the primary use of ventilation is to satisfy the requirements of indoor air quality, which is the basis for determining minimum air change rates (CIBSE, 1997). Figure 3.16 illustrate the level of dissatisfaction caused by a standard person at different ventilation rates. The study by Berg-Munch et al. (1986) with Danish subjects is the basis for Figure 3.16. Moreover, related studies by Iwashita et al. (1990) using Japanese subjects and Cain et al. (1983) using North-American subjects obtained similar outcomes (Olsen, 2004). In the present study, the relationship between indoor air quality dissatisfaction level and ventilation rates in figure 3.16 was employed in determining the occupants' level of dissatisfaction with different ventilation rates obtained in the simulation results.

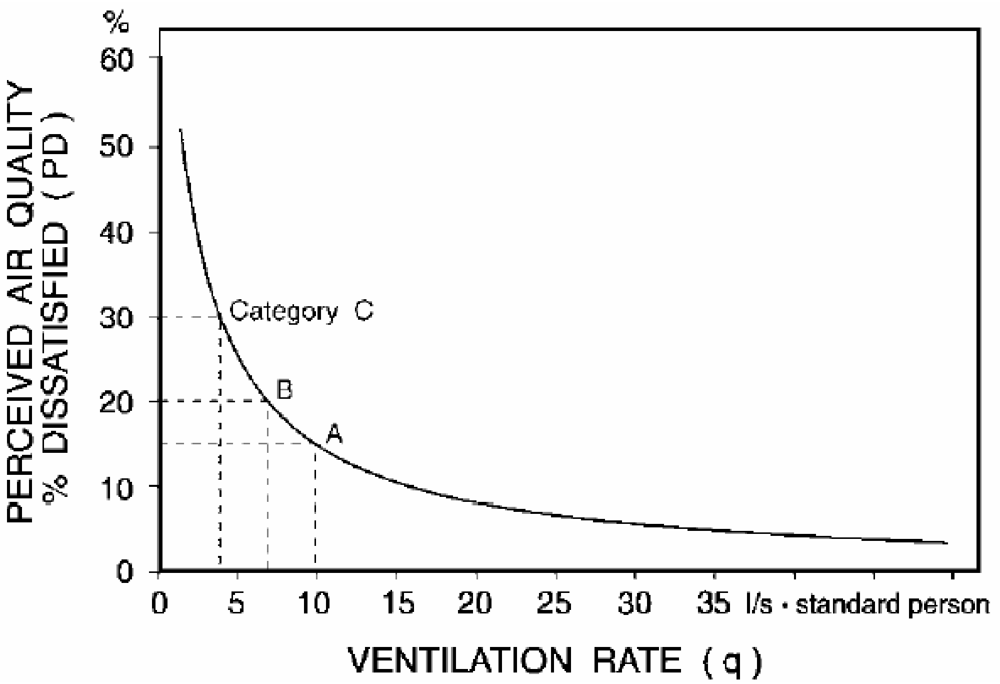


Figure 3.16: Dissatisfaction caused by a standard person at different ventilation rates (Olsen, 2004)

3.6.3.2 Air velocity models

According to the ISO 7730:2005, draughts create an unwanted local cooling in the human body. The airflow risk can be expressed as the percentage of annoyed persons and calculated using equation (8). The draught risk model is developed based on feedbacks from 150 subjects exposed to air temperatures between 20 and 26ºC, with average air speed between 0.05 and 0.4 m/s and turbulence intensities from 0 to 70%. The model is also relevant to low densities of people, with sedentary activity and a neutral thermal sensation over the full body. The draught risk is lower for non-sedentary activities and for individuals with neutral thermal sensation conditions (Orosa, 2010). In the present study, equation (8) was used to evaluate draught risks of the simulated cases.

$$DR = (34 - t)(v - 0.05)^{0.62}(0.37vT_u + 3.14) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$$

Where:
'v is the air velocity (m/s)
t is the air temperature (ºC)
T_u is turbulence intensity (%)

3.6.4 Building-related illness (BRI)

Building-related illness (BRI) can be defined as a term referring to any illness caused by human exposure to building indoor air in which symptoms of diagnosable illness are identified. Such illnesses can be attributed to environmental agents in the air. Some serious and even life threatening examples includes Legionnaire's disease and hypersensitivity pneumonitis (U.S. Environmental Protection Agency-EPA, 1991). Some of the main building related illnesses are discussed in the following sub-sections.

3.6.4.1 Sick Building Syndrome

Bas, (2003) defines Sick Building Syndrome (SBS) as a situation in which at least 20 per cent of building occupants experience symptoms of illness for a period of two weeks or more, without determining the actual source of the symptom. Moreover, SBS is a condition where the inhabitants of the concerned buildings repeatedly express a complex range of unclear and often subjective health complaints, which are often linked with poor indoor air quality. Many occurrences of SBS have been reported since the early 1970s, usually involving offices, and sometimes schools, hospitals, elderly homes, or apartments (Jones, 1999).

However, many studies have been conducted on the influence of ventilation strategies on SBS in buildings, showing reduced SBS symptoms with high ventilation rates (Nagda et al., 1991; Sundell et al., 1993). This assertion is also supported by Jones (1999), confirmed that, workers in air conditioned offices reported an increased incidence of work related sicknesses including headache, lethargy and upper respiratory/mucus membrane symptoms. Moreover, Harrison et al. (1987) also revealed that, compared to the occupants of 8 naturally ventilated buildings, the occupants of 19 mechanically ventilated buildings reported considerably higher occurrences of eye and nose irritation, headaches, attacks of lethargy, and dry skin. Hence, some ventilations system instead of removing contaminants indoor, they end up contributing to the indoor pollutant concentration (Jones, 1999). The following conditions should be present to classify a building as sick;

a. Irritation of eyes, nose and throat
b. Dry mucous membranes and skin
c. Erythema (redness due to inflammation)
d. Hoarseness of voice, wheezing
e. Unspecified hypersensitivity reactions
f. Nausea and dizziness

3.6.5 Nosocomial infection (hospital-associated infection)

The emergence of any infectious disease not presents and without evidence of incubation at the time of patient admission to a healthcare environment or receiving treatment for other conditions is referred to as Healthcare Associated Infections (HAI). The term Healthcare Associated Infection is used as a replacement for previous terminologies like nosocomial, hospital acquired and hospital onset infections (Mirza, 2011). The presence of most clinically evident infections 48 hours after admission of patients to healthcare setting are considered hospital acquired. Moreover, the presence of most infection after discharge of patient from healthcare setting can also be considered healthcare associated, if the organisms were acquired during the hospital stay.

Healthcare associated infections in hospitals are caused by broad diversity of organism, which display many symptoms ranging from minor discomfort to serious disability, and some time death. In United States, a particular multi drug resistant organism (MDRO) called methicillin-resistant Staphylococcus aureus (MRSA), which is one of the most common healthcare associated infection (HAI) pathogens lead to 64% of intensive care unit infections in 2003, an increase from 38% in 1992 (GAO-08-808, 2008). The consequence of nosocomial infections is that, it extends hospitalisation period and subsequently increase patients' hospital expenditure (Yau et al. 2011).

Moreover, healthcare associated infections are of various types, depending on the thickness, weight, and speed of an individual organism in air. Some infectious organisms may dispersed over long distances through air currents and infect other vulnerable individuals. These organisms include Mycobacterium tuberculosis, Rubeola virus (measles), and Varicella-zoster virus (chickenpox) (Atkinson, 2009). Several investigations have acknowledged that, nosocomial infections are caused by contaminated air and deficiencies in ventilation system, (Ulrich et al. 2004; Australian Government Department of Health and Ageing, 2004; Tai and Ng 2005; Qian et al. 2006).

Hence, the prevention of airborne infection spreading in hospital environments require a holistic approach that involve implementation of airborne prevention strategies including; administrative controls, environmental and engineering controls, and employment of particulate respirators by healthcare workers whenever necessary (Atkinson, 2009) . But, this research is interested in implementation of environmental and engineering controls as airborne prevention strategy in healthcare facility. These will be achieved by implementing sustainable, energy efficient ventilation systems and air handling strategies that will consider, various building systems design, building orientation, building size and building materials selection. Table 3.5 described some disease syndromes associated with exposure to bacteria and fungi.

Table 3-5 Diseases and disease syndromes associated with exposure to bacteria and fungi

Disease/Syndrome	Examples of causal organisms cited
Rhinitis (and other upper respiratory symptoms)	*Alternaria, Cladosporium, Epicoccum*
Asthma	Various aspergilli and penicillia, *Alternaria, Cladosporium, Mucor, Stachybotrys, Serpula* (dry rot)
Humidifier fever	Gram-negative bacteria and their lipopolysaccharide endotoxins, Actinomycetes and fungi
Extrinsic allergic alveolitis	*Cladosporium, Sporobolomyces, Aureobasidium, Acremonium, Rhodotorula, Trichosporon, Serpula, Penicillium, Bacillus*
Atopic dermatitis	*Alternaria, Aspergillus, Cladosporium*

Source: lEH, 1996.

3.7 Indoor Air Chemical Contaminants in Hospitals

The important indoor air pollutants in commercial and public facilities have been already identified and they includes; carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), formaldehyde (CH_2O), total volatile organic compounds (TVOC), Respirable Suspended Particulates (RSP), radon and total bacteria count. In addition, hospitals have other serious chemical contaminants that are of considerable concern including glutaraldehyde ($C_5H_8O_2$), nitrous oxide (N_2O), and latex allergens (Leung and Chan 2006).

Indoor air contaminants are very difficult to predict as they generate from both indoor and outdoor sources, and contain different types of substances. This is usually depends on the nature and type of facility, building materials, furnishing, carpets, climatic condition, surrounding environments, occupant’s activities and purpose of the facility.

The indoor air in contemporary facilities comprises of the combination of particulates like, dust and pollens; gases like, nitrogen dioxide, ozone, carbon monoxide and VOCs; and biological agents like, bacteria, fungi (mould and viruses) (Hobday, 2011).

3.7.1 Particulates

3.7.1.1 Dust

Dust can be defined as a particulate matter like any airborne of finely divided solid or liquid material with a diameter less than 100 micrometers. Dust as a component of particulate matter when inhaled, can cause breathing problems, damage tissues, and worsen existing health problems (Sharma, 2009).

Dust mites on the other hand are small and tiny difficult to see bugs in the air that usually present in human environments such as homes, hospitals and offices. They depend on human skin flakes for their feeding and found in mattresses, pillows, carpets, upholstered furniture, bedcovers, clothes, stuffed toys and fabric and fabric-covered items. Their body parts and droppings can trigger asthma in people with allergies to dust mites and even children who have not previously shown signs of asthma.

3.7.1.2 Respirable Suspended Particulates (RSP)

Respirable Suspended Particulate (RSP) is a generic terminology referring to a small solid or liquid particle or piece of substance in the air (Vermont Department of Health, 2005). Sources of particulates include soil, plants, and road dust. They are also obtainable from fumes of combustion process like tobacco smoke, car exhaust, power plants, wood stoves, oil burners, and other heating systems; dust from mechanical process like grinding or sweeping and common household dust including mold, pollen, small insect parts etc.; and mist like that of spray painting.

3.7.1.3 Pollen

Pollens are small seedy part of a plant anatomy that are scattered by insects and wind in a short-term and long-term styles respectively (Environmental Assay Inc. 2011). In healthy people, Pollen may lead to sneezing, running nose, coughing and swollen, itchy eyes, while in people with severe allergies, it cause asthma attacks (Lennox, 2011).

3.7.2 Gases

3.7.2.1 Carbon Dioxide (CO_2)

Carbon dioxide is a substance that is naturally present in the atmosphere at levels of approximately 0.035% (Canadian Centre for Occupational Health and Safety, 2011). In buildings, carbon dioxide is a by-product of human respiration that usually not regarded dangerous except in higher concentrations (Bas, 2003). A CO_2 concentration level of 40,000 ppm is regarded as instantly dangerous to life and health due to the fact that a 30-minute exposure to 50,000 ppm causes intoxication and concentrations more than that (7-10%) result in unconsciousness (NIOSH 1996; Toxicology Review, 2005). The American Society of Heating, Refrigerating, and Air Conditioning Engineer, Inc. (ASHRAE), recommends that indoor air CO_2 concentration levels be less than 700 ppm above the outdoor air CO_2 concentration (Aerias 2005).

Short-term human exposure to CO_2 at less than 2% (20,000 parts per million or ppm) is not regarded as harmful, while, higher concentrations can lead to respiratory disease and affect the central nervous system. Higher concentrations of carbon dioxides in buildings are responsible for the oxygen displacement in air, causing lesser oxygen presence for breathing. Hence, the effects of insufficient oxygen in spaces are related to CO_2 toxicity (Canadian Centre for Occupational Health and Safety, 2011). Hospitals are environment characterised with dense population including patients, staffs and visitors. As such the concentration of CO_2 especially in wards and reception will be high which require enough ventilation to facilitate appropriate removal of the contaminant. The various degrees of severity upon exposure to CO_2 are as follows;

Exposure to 10% for 1.5 minutes has caused eye flickering, excitation and increased muscle activity and twitching. Concentrations greater than 10% have caused difficulty in breathing, impaired hearing, nausea, vomiting, a strangling sensation, sweating, and stupor within several minutes and loss of consciousness within 15 minutes. Exposure to 30% has quickly resulted in unconsciousness and convulsions. Several deaths have been attributed to exposure to concentrations greater than 20%. Effects of CO_2 can become more pronounced upon physical exertion, such as heavy work. (Canadian Centre for Occupational Health and Safety, 2011)

3.7.2.2 Carbon Monoxide (CO)

Carbon monoxide can be defined according to U.S. Environmental Protection Agency-EPA, (2010a) as an asphyxiant. *An accumulation of this odourless, colourless gas may result in a varied constellation of symptoms deriving from the compound's affinity for and combination with haemoglobin, forming carboxyhemoglobin (COHb) and disrupting oxygen transport.*

Carbon monoxide is formed due to incomplete burning of fuel. The concentration of CO indoors is commonly cause by combustion appliances such as gas stoves, portable kerosene and gas space heaters, and wood stoves. Likewise the major sources of CO outdoors include diesel generators, and vehicles emissions (Baechler, et al. 1991). The most sensitive to elevated CO levels includes the elderly, the fetus, persons with cardiovascular and pulmonary diseases. Methylene chloride, obtainable from common domestic products such as paint strippers, can be metabolized to form carbon monoxide which combines with haemoglobin to form COHb (U.S. Environmental Protection Agency-EPA, 2010a). In the United States, carbon monoxide poisoning is frequent resulting in more than 50,000 emergency visits per year in the hospitals. The slight exposures to carbon monoxide causes headache, myalgia, dizziness, or neuropsychological impairment, while the considerable exposures result in confusion, loss of consciousness, and sometimes death (Weaver, 2009)

3.7.2.3 Nitrogen Dioxide (NO_2)

Nitrogen dioxides (NO_2) mostly act as irritants, affecting the mucosa of the eyes, nose, throat, and respiratory tract. Inhaling high concentration of NO_2 may cause pulmonary edema and diffuse lung injury, and prolong exposure to high level will result in development of acute or chronic bronchitis. According to some recent findings, human exposure to low-level NO_2 may result in increased bronchial reactivity in some asthmatics, decreased lung function in patients with chronic obstructive pulmonary disease, and an increased risk of respiratory infections, especially in young children (U.S. Environmental Protection Agency-EPA, 2010a). The indoor concentrations of NO_2 are mainly influenced by gas stoves, unvented kerosene and gas space heaters, and, to a minor extent, tobacco smoking. The infiltration of NO_2 from outdoor sources is considerable in highly populated, industrialized urban environments where combustion of fossil fuel and vehicle emissions are main outdoor sources of NO_2 (Baechler et al. 1991).

3.7.2.4 Sulphur dioxide (SO_2)

Sulphur dioxide (SO_2) is similar in effects to NO_2 as it also acts as irritants affecting the mucosa of the eyes, nose, throat, and respiratory tract. People with asthma and hypersensitivity to SO_2 are likely to suffer from acute SO_2 related constrictions. Epidemiologic studies shows that chronic exposure to SO_2 is related to increased respiratory symptoms and decrements in pulmonary function. Studies have shown that some asthmatics react to bronchoconstriction to even short exposure to SO_2 level as low as 0.4 ppm. The concentrations of SO_2 above six parts per million (ppm) will result in the production of mucous membrane irritation (U.S. Environmental Protection Agency-EPA, 2010a).

3.7.2.5 Ozone (O_3)

Ozone is a colourless gas with a noticeable odour, when inhaled can lead to lung damage and throat irritation (Vermont Department of Health, 2005). Besides its natural production in the atmosphere, ozone is also a main part of air smog pollution. Even though, it is naturally found and produced in the atmosphere. It serve as a protective measure from the sun, but it existence closed to the earth can be harmful for human, especially when inhaled.

In healthy people, the effect of inhaling small quantity of ozone causes signs and symptoms like, coughing, wheezing, breath shortness, and chest pain, while in the people with existing ailments, like asthma, bronchitis, heart disease, and emphysema, the situation will be worse. Breathing ozone can increase the danger of getting certain lung infections (Vermont Department of Health, 2005; World Health Organization, 2003). Owing to the photochemical origin of O_3 they display strong seasonal and diurnal patterns, with higher concentration in summer and in the afternoon which is a variation from the seasonal pattern of other pollutants (World Health Organization, 2003).

3.7.2.6 Formaldehyde (CH_2O)

Formaldehyde is a flammable colourless gas with a typical odour found in some form in eight percent of the entire product used by humans. Its availability in adequate quantities can cause skin, respiratory, throat, and eye irritation; headache, fatigues, nausea, dizziness, breathlessness, and problems with concentration and memory (Bas, 2003).

Formaldehyde (HCHO) substance is mostly common in insulation, hardwood plywood, particleboard and the fibreboard found in countertops, furniture and cabinets. Table 3.6 below as adopted from (Bas, 2003) shows some potential indoor source of formaldehyde, while table 3.7 shows the acute health effects of the substance formaldehyde exposure.

Table 3-6 Potential Indoor Source of Formaldehyde

S/N	Products	Types with formaldehydes
1.	Pressed wood product	Hardwood plywood, particleboard medium density fibreboard, decorative panelling
2.	Insulation	Urea-formaldehyde, foam insulation, fibreglass made with HCHO Binders
3.	Combustion sources	Natural gas, kerosene, tobacco, auto exhaust
4.	Paper products	Grocery bags, waxed paper, facial tissues, paper towel, disposable sanitary products.
5.	Stiffeners, fabric treatments	Floor coverings, carpet backings, adhesive binders, fire retardants, permanent press fabrics.
6.	others	Plastics, cosmetics, deodorants, shampoos, disinfectants, laminates, paints, ink, fertilizer, fungicides

From (Bas, 2003)

Table 3-7 Acute health effects from formaldehyde exposure

Formaldehyde concentration (ppm)	Observed health effects
< 0.05	None reported
0.05–1.5	Neurophysiologic effects
0.05–1.0	Odour threshold limit
0.01–2.0	Irritation of eyes
0.10–25	Irritation of upper airway
5–30	Irritation of lower airway and pulmonary effects
50–100	Pulmonary edema, inflammation, pneumonia
> 100	Coma, death

Sources: Hines et al. (1993)

3.7.2.7 Total Volatile Organic Compounds (TVOC)

Volatile organic compound (VOC) is a term referring to a substance that contains carbon, which evaporates and becomes a vapour or off-gases at room temperature (Vermont Department of Health, 2005). The building indoor environment is a home to over 900 different volatile organic compounds (Baechler et al. 1991). Some of the most common TVOCs includes, toluene; benzene; ethylbenzene; tetrachloroethylene; 1, 1, 1, trichloroethane; styrene; limonene; isopropanol; ethanol; and xylenes (Bas, 2003). The major environmental factors contributing VOCs indoors includes the application of products that emits organic compounds indoors, cleaning agents and building materials. The factors influencing the discharge and interaction of these vapours are complicated and include temperature, humidity, time, ventilation, source quantity, the volume of the affected space, the age of the material, and the tendency of walls and other surfaces to absorb and re-admit the pollutant (Baechler et al. 1991).

In the last two decades, the increase in buildings indoor air pollutants like VOC was linked to widespread employment of new materials and products, which lead to indoor air pollution and consequently affects human health. Some of the adverse health effects of VOCs include irritation of mucous membranes, mainly of the eyes, nose and throat, and long-term toxic reactions of various kinds (ECA-IAQ, 1997). Table 3.8 demonstrates the sources of some frequent volatile organic compounds found in indoor air.

Table 3-8 Sources of common volatile organic compounds in indoor air

Sources	Examples of typical contaminants
Consumer and commercial products	Aliphatic hydrocarbons (*n*-decane, branched alkanes), aromatic hydrocarbons (toluene, xylenes), halogenated hydrocarbons (methylene chloride), alcohols, ketones (acetone, methyl ethyl ketone), aldehydes (formaldehyde), esters (alkyl ethoxylate), ethers (glycol ethers), terpenes (limonene, alpha-pinene).
Paints and associated supplies	Aliphatic hydrocarbons (*n*-hexane, *n*-heptane), aromatic hydrocarbons (toluene), halogenated hydrocarbons (methylene chloride, propylene dichloride), alcohols, ketones (methyl ethyl ketone), esters (ethyl acetate), ethers (methyl ether, ethyle ether, butyl ether).
Adhesives	Aliphatic hydrocarbons (hexane, heptane), aromatic hydrocarbons, halogenated hydrocarbons, alcohols, amines, ketones (acetone, methyl ethyl ketone), esters (vinyl acetate), ethers.
Furnishings and clothing	Aromatic hydrocarbons (styrene, brominated aromatics), halogenated hydrocarbons (vinyl chloride), aldehydes (formaldehyde), ethers, esters.
Building materials	Aliphatic hydrocarbons (*n*-decane, *n*-dodecane), aromatic hydrocarbons (toluene, styrene, ethylbenzene), halogenated hydrocarbons (vinyl-chloride), aldehydes (formaldehyde), ketones (acetone, butanone), ethers, esters (urethane, ethylacetate).
Combustion appliances	Aliphatic hydrocarbons (propane, butane, isobutane), aldehydes (acetaldehyde, acrolein).
Potable water	Halogenated hydrocarbons (1,1,1-trichloroethane, chloroform, trichloroethane).

Source: Maroni et al., (1995).

The materials utilised in the building fabric and finishes could result in unwanted emissions (CIBSE, 1997). Godish, (2001) has summarized the low emission characterization of different building materials, furnishing, and office equipment based on Total Volatile Organic Compounds (TVOC) theory of exposure, an engineering assessment and mucous membrane irritation as illustrated in table 3.9.

Table 3-9 Low TVOCs Recommended Emission Limits for Building Materials and Furnishings

S/N	Material/product	Maximum acceptable emission rate $mg/h/m^2$
1.	Flooring Materials	0.6
2.	Floor Coatings	0.6.
3.	Wall Coverings	0.4
4.	Wall Coatings	0.4
5.	Movable Partitions	0.4
6.	Office Furniture	1.5 mg/h/workstation

Source: (Godish, 2001)

3.7.2.8 Radon

Radon is a naturally occurring cancer causing radioactive gas that cannot be seen and smelled, which result from decay of uranium (Bas, 2003; Vermont Department of Health, 2005). Based on the statistical report from the U. S. National Academic of Sciences, radon is estimated to cause from 15,000 to 22,000 lung cancer deaths per annum, which is next foremost cause of lung cancer after smoking (Vermont Department of Health, 2005).

3.7.2.9 Glutaraldehyde ($C_5H_8O_2$)

Hospitals and other health facilities employ large quantity of disinfectants like glutaraldehyde to eliminate pathogenic organisms due to the prevalent cases of nosocomial infection diseases, which infect health care staffs, visitors and patients during hospitalization.

Glutaraldehyde ($C_5H_8O_2$) is a dialdehyde that is slightly acidic and in a buffered alkaline solution is a highly effective microbacterocidal agent (*Nayebzadeh, 2007).*

Glutaraldehyde disinfectants and cleaners are generally used as cold sterilants in hospitals and clinics in heat-sensitive medical devices like surgical instruments, endoscope, bronchoscope, and instruments for nose, ear and throat to eliminate pathogenic organisms causing nosocomial infectious diseases (Nayebzadeh, 2007; Emmanuel, et al. 2004). Recent studies suggest that, employing proper work practices in hospitals can extensively lower the risk of exposure to glutaraldehyde among health care workers (Nayebzadeh, 2007).

3.7.2.10 Nitrous Oxide (N_2O)

Nitrous oxide (N_2O) is produced as a result of both natural and human related sources. The main human related sources of N_2O include; agricultural soil management, animal manure management, sewage treatment, adific acid production, nitric acid production and stationary combustion of fossil fuel such as cars and diesel generators. Owing to the frequent power shortage in the study area, diesel generators are employed in supplementing electric power generation. It is also formed at high temperatures due to incomplete burned of fuel, possibly as a result of faulty appliances. In terms of natural sources, Nitrous oxide is produces as a result of many biological sources in soil and water, especially microbial action of wet tropical forest (U.S. Environmental Production

Agency-EPA, 2010b). The amount of Nitrous oxide emitted differs from region to region or country to country which is largely dependent on aspects such as nature of climate, animal and agricultural production, combustion technologies, and practice of waste management.

3.7.3 Biological agents and Pathogens

Biological agents are species like bacteria and fungi (mould and virus), which emanates from building indoor dust in carpets, sofas, and air ducts are major sources of biological allergens, which cause disease through atopic mechanisms, infectious processes, or direct toxicity (Jones, 1999). The presence of large quantity of species such as bacteria and fungi indoors is associated with the presence of organic matter like wall coatings, wood, and foodstuffs. One of the major sources of fungi and bacteria in the indoor environment is outdoor air. The growth of fungi is largely associated with high level of humidity (Jones, 1999).

Mold is generic terminology also known as mildew describing a type fungus, and they are of different types common throughout nature. They vary in colours and appearance, usually found in foods, damp surfaces, cloth, and other porous materials. Moulds are spread through very small in size spores (Vermont Department of Health, 2005). Table 3.10 below described various sources of airborne microbial contaminants and tables 3.11 shows common indoor allergic agents.

Table 3-10 Sources of Airborne Microbial pollutants

Pollutants	Sources
TB bacteria	• When an active TB patient coughs, sneezes, or speaks, airborne TB droplets will be generated.
Legionella bacteria	• A common source of this bacterium in hospitals is the water mist discharged from the cooling towers and then drawn into the indoor environment through the outdoor air intake. • Other probable sources include evaporative condensers, potable water systems, and hot water systems.
Staphylococcus aureus	• The bacteria are present on the skin and in the nose, blood, and urine of an infected patient. During some surgical procedures that require the use of power tools, such as oscillating bone saws and bone drills, microbial aerosols will be generated.
Aspergillus spores	• Hospital renovation or nearby construction work are major sources of aerosolized *Aspergillus spores*. • The fungal spores from soil, plants, animals, and dust particles can attach themselves to the clothing of healthcare workers or visitors.

Source: (Leung and Chan, 2006)

Table 3-11 Common indoor allergic agents

Source	Genus	Species	Allergen
Dust-mite	*Dermatophagoides*	*pteronyssinus*	*Der p*
	Dermatophagoides	*farinae*	*Der f*
	Euroglyphus	*maynei*	*Eur m*
	Hirstia	*domicola*	*Hir d*
	Lepidoglyphus	*destructor*	*Lep d*
	Malayoglyphus	*intermedius*	*Mal I*
	Malayoglyphus	*carmelitus*	*Mal C*
	Sturnophagoides	*brasiliensis*	*Stu b*
Cat	*Felis*	*domesticus*	*Fel d*
Dog	*Canis*	*familiaris*	*Can f*
Rodent	*Mus*	*musculus*	*Mus m*
	Rattus	*norvegicus*	*Rat n*
Cockroach	*Blattela*	*germanica*	*Bla g*
	Periplanetta	*americana*	*Per a*
Fungi	*Alternaria*	*alternato*	*Alt a*
	Aspergillus	*fumigatus*	*Asp f*
	Cladosporium	*herbarium*	*Cla h*

Source: Jones (2002)

3.7.4 Sources of Indoor Air Contaminants

Indoor air pollutants emanate from many sources, and they are emitted by the building fabric and also by the consequence of the activities that are undertaken in the building (Jones, 1999). The major sources of indoor air pollution and discomfort could be as a result of contaminants originating from indoors, outdoors and within the mechanical system used in the building (U.S. Environmental Protection Agency-EPA, 1991). Human activity, outdoor pollution, and the presence of compounds emitting products and materials indoors are the three known sources of indoor contaminants in buildings (Santamouris, 2005). The concentration of a contaminant indoors is determined by the relationship between the volume of air enclosed in the indoor environment, the pollutant rate of production or release, the pollutant rate of removal from the air through reaction or settling, the air change rate with the outside environment, and the concentration of pollutant outdoors (Maroni et al., 1995).

However, the focus of this research is the outdoor air contaminants, which are direct product of climatic condition. It is imperative to mention that outdoor source of air pollutants may contributes greatly to indoor concentrations, especially a number of non-biological pollutants normally obtainable in indoor air (Jones, 1999). Moreover, the major factors responsible for the contribution of outdoor air contaminants to indoor air quality includes the ventilation type employed (natural or mechanical), the air change rate (ach^{-1}), and the nature of the contaminant under consideration (Wanner, 1993).

Indoor air Contaminants appears in many forms and types including gases, solids, and liquids or combinations. Some of the most frequent indoor air contaminants and their emission sources are shown in table 3.12 and 3.13.

Table 3-12 Indoor Air Contaminants and Sources

Contamination	Sources	
VOCs (Volatile Organic Compounds)	Perfumes, hairsprays, furniture polish Cleaning solvents Hobby and craft supplies Pesticides Carpet dyes and fibers Glues, adhesives, sealants.	Paints, stains, varnishes, strippers Wood preservatives Dry cleaned clothes, moth repellents Air fresheners Stored fuels, and automotive products Contaminated water Plastics
Formaldehyde	Paricleboard, interior-grade plywood Cabinetry, furniture	Urea Formaldehyde foam insulation Carpet, fabrics
Pesticides	Insecticides, (including termiticides) Rodenticides	Fungicides, disinfectants Herbicides (from outdoor use)
Lead	Lead-based paint	Exterior dust and soil
Carbon Monoxide carbon dioxide, nitrogen dioxide	Improperly operating gas or oil furnace/hot water heater, fireplace, wood stove	Unvented gas heater/kerosene heater
Sulfur Dioxide	Combustion of sulfur-containing fuels (primarily kerosene heaters)	
RSP (respirable particulates)	Fireplace, woodstove Unvented gas heater	Tobacco products Unvented kerosene heater
PAHs (polycyclic aromatic hydrocarbons)	Fireplace, woodstove Unvented kerosene heater	Tobacco products
ETS (Environmental Tobacco Smoke)	Tobacco products	
Biological contaminants	Plants, animals, birds, humans Pillows, bedding, house dust Wet or damp materials	Standing water Humidifiers, evaporative coolers Hot water tank
Asbestos	Pipe and furnace insulation Ceiling and floor tiles Full list of Asbestos Sources	Decorative sprays Shingles and siding
Radon	Soil and rock Some building materials	Water

Source: (Bluepoint Environmental, 2011)

Table 3-13 Major indoor pollutants and emission sources

Pollutant	Major emission sources
Allergens	House dust, domestic animals, insects
Asbestos	Fire retardant materials, insulation
Carbon dioxide	Metabolic activity, combustion activities, motor vehicles in garages
Carbon monoxide	Fuel burning, boilers, stoves, gas or kerosene heaters, tobacco smoke
Formaldehyde	Particleboard, insulation, furnishings
Micro-organisms	People, animals, plants, air conditioning systems
Nitrogen dioxide	Outdoor air, fuel burning, motor vehicles in garages
Organic substances	Adhesives, solvents, building materials, volatilisation, combustion, paints, tobacco smoke
Ozone	Photochemical reactions
Particles	Re-suspension, tobacco smoke, combustion products
Polycyclic aromatic hydrocarbons	Fuel combustion, tobacco smoke
Pollens	Outdoor air, trees, grass, weeds, plants
Radon	Soil, building construction materials (concrete, stone)
Fungal spores	Soil, plants, foodstuffs, internal surfaces
Sulphur dioxide	Outdoor air, fuel combustion

Source: Spengler and Sexton (1983)

3.8 Building Indoor Environmental Parameters

3.8.1 Ventilation rates in buildings

The ventilation rate in buildings is the number of times within an hour in which a volume of air equal to the volume of a room/building is exchanged with fresh outdoor air. It can be expressed in terms of Air Change per Hour (ach^{-1}), which is also specified in litres per second (litre s^{-1}) or cubic metres per hour (m^3h^{-1}). The minimum ventilation rate is essential to dilute odours and the indoor CO_2 concentration to an acceptable level, and to provide occupants with the required amount of oxygen. To satisfy these requirements, various level of fresh air is necessary which is significantly dependent on the occupants' occupation and activity level, which eventually influences the production rate of occupant-related pollutants (Allard and Santamouris 1998).

However, ACR can also be connected technically to the incoming wind velocity and temperature difference between indoor and outdoor environments, since they are the two motivating forces that established airflow rates through open windows by producing the pressure difference (Srebric, 2011). Air change can be defined as the ratio of air supply Q(t) into a room/space relative to the volume of the room/space VR. It is generally expressed as air change per hour (ach^{-1}) (Detlef and Dieter, 2011). The following equation (9) expresses this definition:

$\lambda(t) = Q(t)/VR$………………………………………………………………………. (9)

$\lambda(t)$ is the ventilation rate or air change rate [h^{-1}],
Q(t) is the air supply into a room [m^3/s],
VR is the room's volume [m^3], and t = time [s].

3.8.2 Air temperature

Temperature in general term referred to the measure of the degree of heat intensity. The amount of convective and evaporative body heat loss is influence by the Air (dry-bulb) temperature. Since a narrow range of comfortable temperatures can be created nearly independently of other variables, air temperature is possible the most significant determinant of comfort. In an enclosed environment, air temperature normally rises from floor to the ceiling (Bradshaw, 2006). However, the study area (semi-arid climates) is characterised with high air temperatures and due to the importance of air temperature in determining convective heat dissipation, it remains one of the major environmental factors (Szokolay, 2008).

According to CIBSE (1997), increased air movement can provides a sense of freshness and enhanced occupant satisfaction with the internal environment, even with similar indoor and the outdoor temperatures. However, the thermal comfort requirement for a hospital patient is different from that of a healthy people in terms of temperature (Yau et al. 2011). In the study carried out by Hwang et al. (2007) in summer season, the preference temperature for hospital patients is higher than thermal neutrality in the range of 0.4-0.6 ^{o}C, but lower for the healthy people at the range of 0.8-1.0^{o}C. The comfort perceptions are determined by local conditions including adaptation to high temperatures and humidity (Mallick, 1996).

3.8.3 The radiant temperature

The exchange of radiation in building indoor environment is determined by the temperature of the surrounding surfaces, measured by the Mean Radiant Temperature (MRT). The MRT is the mean temperature of the surrounding surface components, each weighted by solid angle it subtends at the measurement position (Szokolay, 2008). In a case of a person in an enclosed environment with insignificant temperature difference between a body and the surrounding indoor surfaces, the radiation exchange is determined by the Mean Radiant Temperature (M.R.T.) of the environment (Givoni, 1976). The measured temperature of surrounding walls and surfaces and the positions of these surfaces in relation to a person location in the enclosed space, can be used to estimate the MRT. Moreover, all surfaces in the room can be assumed to be black due to the high emittance ε of most building materials.

3.8.4 Relative humidity

The amount of water vapour in a given space is referred to as Humidity is (Bradshaw, 2006). The atmosphere surrounding the human environment is made up of humid air, as air is a combination of oxygen and nitrogen. The air can only hold a limited quantity of water vapour at any given temperature, which is referred to as saturated (Nicol et al. 2012). In semi-arid climate the relative humidity is hardly reach saturation level, as the highest average monthly humidity is 72% in the month of August (rainy season). The detail climatic condition of the semi-arid climate is presented in Chapter 4. According to Szokolay (2008), the effects of medium humidity levels between 30 to 65% on comfort is negligible, however, with high humidity levels, the degree of evaporation from the skin and in respiration is restricted, thereby limiting the dissipation mechanism, whereas very low humidity levels cause drying out of the mucous membrane (mouth and throat) in addition to skin, and consequently creating discomfort. Moreover, the heat load operating in the body is not directly influenced by the level of humidity in the air; however, it affects the evaporative ability of the air and consequently the cooling efficiency of sweating (Givoni, 1976).

CIBSE guide recommends that the indoor relative humidity for most functions should be maintained between 40 and 70%. Even though it is difficult for natural ventilation to control humidity, the levels of relative humidity in non-air-conditioned buildings will hardly exceeds 70% except a substantial amount of moisture is produced internally (CIBSE, 1997). Moreover, desirable humidity according to ASHRAE Handbook of fundamentals is 30% in winter and 50% in summer. ASHREA manual give a range of 30 to 60% as the desirable relative humidity in indoor environment. CIBSE guide B prescribed 40 to 70 % relative humidity for hospital wards. HTM 2025 guideline prescribed 40 to 60 % as desirable relative humidity in patient rooms. However, the human tolerance to variations in humidity is much higher than tolerance to variations in temperature, but it is also crucial to control humidity in building (Bradshaw, 2006).

3.8.5 Indoor Air Velocity

There are two different ways in which air velocity can affects the human body. The first effect is the determination of the convective heat exchange of the body and the second effect is it influences the evaporative ability of the air and consequently the cooling efficiency of sweating. There is an interrelation between the influences of air velocity and air temperature on the convective heat exchange, since convection is a function of the velocity and the temperature variation between the skin and the air (Givoni, 1976). As air movement speed up convection, but it also changes the heat transfer coefficient of the skin and clothing surface by decreasing surface resistance (Szokolay, 2008). However, the influence of air velocity on the evaporative capability is connected to the effect of humidity, since an increase in air velocity increases the evaporative capacity and consequently may offset the influence of high humidity (Givoni, 1976). Hence, air movement creates physiological cooling effect by increasing the evaporation from the skin (Szokolay, 2008).

Furthermore, air velocity is associated with sensible heat released through convection and latent heat released through evaporation and, therefore the quality of thermal comfort indoor spaces is influenced by draught (Orosa and Oliveira, 2012). Owing to the capability of sensible air velocity in providing physiological cooling, it is important for passive thermal comfort. The crucial objective is to ensure a comfortable air velocity at the body surface of the occupants and this could be provided through cross ventilation, which depends on the wind effect (Szokolay, 2008).

Moreover, indoor air velocity should not exceed 0.9 m/s in the summer season and should not go below 0.15 m/s during the winter (Orosa and Oliveira, 2012). This study is supported by another research by Gong et al. (2006), also identified the acceptable air velocity range from 0.3 to 0.9 m/s, which is higher than the maximum permissible velocity indoors under ASHREA standard 55 in circumstances where occupants have no control over air movement. However, according to Liping and Hien, (2007), high air velocity between 0.8-1.2 m/s is often required to attain thermal comfort at midday (11:00-14:00). This is because of the high temperature associated with the noon periods. However, owing to the variation in metabolic rates and clothing among patients and hospital staffs, which leads to different perception and requirements, a local air speed of 0.25 m/s or lower is considered comfortable and acceptable for occupants (Yau et al 2011). The subjective reactions to air movement are presented in tables 3.14 and 3.15. However, in heated environments air velocities of up to 2 m/s may be comfortable (Szokolay, 2008).

Table 3-14: Subjective reaction to air movement (Szokolay, 2008)

Air speeds (m/s)	Perceptions
<0.1m/s	Stuffy
To 0.2	Unnoticed
To 0.5	Pleasant
To 1	Awareness
To 1.5	Draughty
>1.5	Annoying

Table 3-15: Subjective response to air motion

Air Velocity		
fpm	**m/s**	**Occupant Reaction**
0 to 10	0 to 0.05	Complaints about stagnation
10 to 50	0.05 to 0.25	Generally favorable (air outlet devices normally designed for 50 fpm in the occupied zone)
50 to 100	0.25 to 0.51	Awareness of air motion, but may be comfortable, depending on moving air temperature and room conditions
100 to 200	0.51 to 1.02	Constant awareness of air motion, but can be acceptable (e.g., in some factories) if air supply is intermittent and if moving air temperature and room conditions are acceptable
200 (about 2 mph) and above	1.02 and above	Complaints about blowing of papers and hair, and other annoyances

Source: (Bradshaw, 2006)

3.8.6 Adaptive Comfort based on Thermal Neutrality

The consideration of high outdoor air temperatures in designing natural ventilation strategies for acceptable thermal comfort in semi-arid climates is essential. When the outdoor air temperature is high, simply allowing it indoors will not create the required thermal comfort. In dry season the temperature in Maiduguri (Study area) peaks with wide diurnal and annual ranges of dry bulb temperatures, with the hottest months of April, May and June. Dry bulb temperatures can exceed 43^{o}C but falls to values between 24^{o}C and 29^{o}C with the start of the rainfall. The coldest night of the year are experienced in the months of December, January and February (Harmattan). Owing to these climatic conditions, the achievement of indoor thermal comfort is more difficult compared to the temperate climates. The situation is further complicated by the lack of enough energy resources to employ mechanic methods, as the outdoor temperatures in summer usually goes above the indoor values which make it difficult to achieve acceptable thermal comfort through natural ventilations.

Since, the thermal preference of people has been realized to have geographical components. The neutrality temperature of the study area (Maiduguri) has been estimated using the outdoor average ambience temperature (T_{oav}) using the formula $T_n = 17.8 + 0.31T_{oav}$ (Szokolay, 2008). The thermal neutrality temperature of Maiduguri is found to be 26.7^{o}C, and considering a temperature band of ±2.5K as recommended in Szokolay, S. V. (2008), the thermal comfort zone will fall between 24.2^{o}C and 29.2^{o}C. Figure 3.17 illustrates the total ambient temperature in the study area in relation to comfort temperature range. The only ambience average temperatures that are within the comfort zone includes February, August and November, while the remaining nine months are out of the comfort temperature zone. However, the months of March, April, May, June and October are above the acceptable adaptive comfort limits. This means the possibility of experiencing discomfort in hospital wards' indoor environment is higher in these five months. The discomfort level is higher in the months of April and May and less in the months of March, June and October because, they just exceed the adaptive comfort limits.

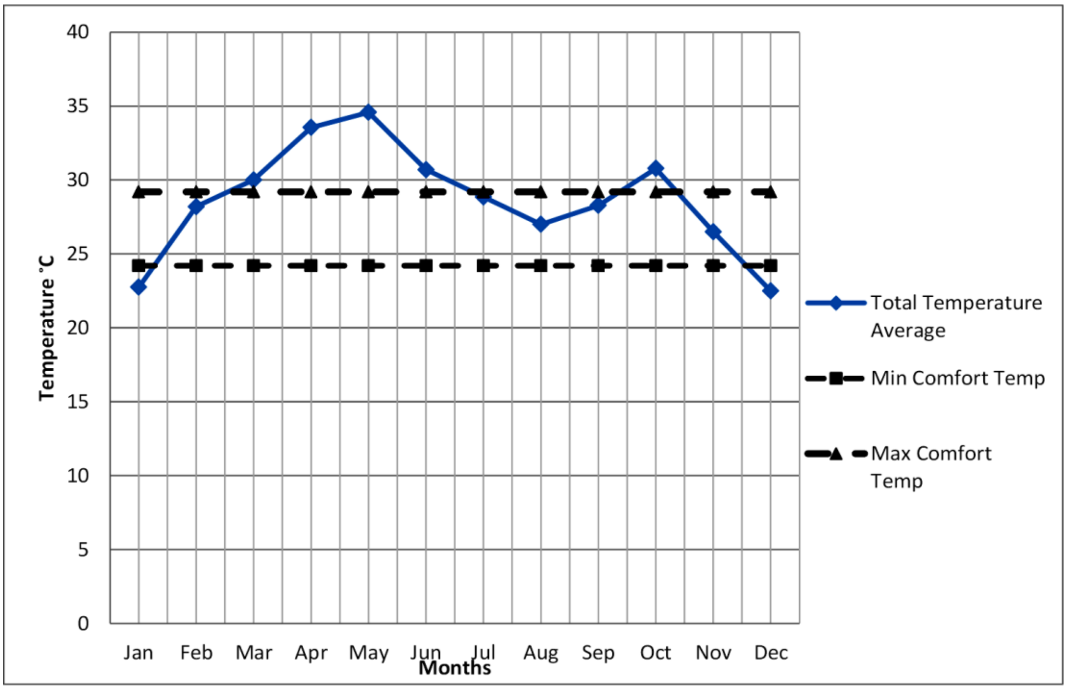


Figure 3.17: Total Average Ambience Temperature of the Study Area in Relation to Comfort Temperature Zone

3.9 The Effects of Energy Efficiency on Ventilation in Hospital multi-bed wards

3.9.1 Energy Efficiency and Ventilation

Energy conservation is important for the growth of developing countries especially with protracted power and energy shortages and increase in its cost. Wong et al. (2008) in their study indicated that, extra energy is required to maintain a higher IAQ acceptability. Consequently, to pursue energy conservation in hospitals without taking the quality of indoor air into consideration puts occupants at unnecessary health risk. On the contrary, to pursue good IAQ without considering the efficient use of energy may unnecessarily increase energy demands and emissions of greenhouse gases, thereby contributing to outdoor air pollution and possibly even global warming (Air Quality Sciences, Inc. 2006). According to ASHRAE Position Document (2011) IAQ and building energy performance are significantly connected and these connections must be considered from the very beginning stages and throughout the processes of design retrofit and renovation. Therefore, the major concern is to provide sustainable and clean indoor air in hospitals wards with less energy and without compromising occupants comfort.

In the new global economic trend, energy conservation and management in buildings have become a central issue for concern. Hence, it is important to adopt energy efficient operating scheme in hospitals especially in the areas of ventilation system designs for acceptable indoor air quality. Kohonen, (2005) identified various design steps that can lead to designing energy efficient hospital ventilation system as follows.

i. Zones and spaces classification
ii. Ventilation strategy identification
iii. Energy analysis conduction
iv. System selection for desired indoor air quality (IAQ) with minimum life-cycle cost (LCC)
v. Systems' Components Optimisation
vi. Systems simulation and analysis

3.10 Chapter Conclusion

Literature review is generally performed to provide the necessary information and issues of consideration in conducting any research work. This chapter introduces and discusses the general background of indoor air quality and ventilation and various factors influencing ventilation and indoor air quality in hospital wards. In developing countries and regions with limited resources, the application of open multi-bed wards dominates the hospital environments.

In this chapter, the previous studies on natural ventilation and indoor air quality have been presented, which helpfully identified the existence of knowledge gaps in ventilation and indoor air quality studies in hospital wards of the tropics compared to the temperate climates. The effect of indoor air quality in buildings has been discussed and it has been established that, poor indoor air quality in buildings, especially in hospital wards causes many diseases/illnesses such as respiratory disease, asthma and in severe cases even death. Moreover, the various indoor air chemical contaminants obtainable in hospital indoor environments and their consequences on health have been presented. Thus enhancing the ventilation rates in the hospital wards suggests the improvement in contaminants removal capacity.

The study identified various ventilation guidelines/standards applicable to patients' rooms in hospital environment including American Institute of Architects (AIA), American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and Health Technical Memorandum (HTM) 2025. Both AIA and ASHRAE required that, the minimum total air change rate of 6 ach^{-1} should be provided in patients' rooms or hospital wards. In this study, this criteria will applied in ascertaining the performance of different natural, ventilation strategies. It has been established that, parameters such as air change rates, airflow direction, and airflow pattern are the key factors influencing ventilation performance in buildings. Moreover, the indoor ventilation condition assessment criteria including air speed at inlet openings, maximum speed of air at any point in the space, average air speed in the space and average air speed at occupancy level have been identified and used in the results analysis.

The main function of ventilation is to provide acceptable indoor air quality and thermal comfort. Ventilation provides healthy air for breathing by diluting indoor air contaminants with clean outdoor air and through the provision of acceptable airflow rate that can change the indoor air at a given rate. The review established that natural ventilation having low/zero energy requirements is the most suitable option for the study area (Semi-arid climate of Nigeria). This is because, both mechanical and hybrid ventilation strategies require energy to operate. However, due to the protracted energy shortage in the study area, energy intensive strategies are not applicable.

The implementation of natural ventilation in the study area requires the installation of insect screen on the openings to prevent the penetration of mosquitoes and other insects to the hospital wards. However, the installation of these insect screens results in pressure drop across the openings, which subsequently decrease the airflow rate across the openings.

The strategies for assessing indoor environmental conditions in buildings has been presented and discussed, including ventilation rates/air change rates, indoor air temperature, indoor air velocity, and adaptive comfort based on thermal neutrality. The study determined that, the adaptive thermal neutrality temperature of between 24.2^{o}C in wet season and 29.2^{o}C in dry season is required to achieve thermal comfort indoors in the study area Maiduguri. Indoor air quality and velocity models are presented to assess the level of dissatisfaction with indoor air quality and draught of different ventilation strategies. The effect of draught in the study area is insignificant. Because, in naturally ventilated buildings in hot climates, indoor air speed regularly extents from 1 to 2 m/s and occupants of these buildings accept such a wider span as normal.

Furthermore, the literature review also assisted in identifying and analysing different ventilation prediction models including semi-empirical equation modelling approach, multi-zone airflow network modelling, and CFD modelling approach. As a result, the CFD modelling approach was selected for the purpose of this study due to its numerous advantages over the remaining two approaches. Thus, the information such as ventilation guidelines and standards, adaptive thermal neutrality temperature obtained from the literature review were used in analysing the results of the full-scale measurement and the CFD simulation.

Chapter Four

Research Methodology

Chapter Structure

4.1 Introduction

4.2 Data Collection Methods

4.3 Psycho-Social Perception

4.4 Physical (Full-scale) Measurements

4.5 Quantitative Research Method

4.6 Data analysis methods

4.7 Methodology for Achieving Acceptable Indoor Air Quality in Hospital Wards

4.8 Chapter Conclusion

4 Chapter Four: Research Methodology

4.1 Introduction

This chapter introduces the methodology employed in carrying out the present study including quantitative research based on psychosocial perception, full-scale measurement and computational fluid dynamic (CFD) simulation. These methods are selected by considering the nature of study, reliability, accuracy, practicality, easiness and cost effectiveness. This chapter only provides summary of top level methodology and the detailed methodology description of each method will be presented in the relevant chapters. The previous chapter (chapter 3) presented the general literature review of the study.

Moreover, the major consideration in adopting any research methodology or approach is its capability to answer the research questions effectively. In this research, case study research design and quantitative research strategies has been employed in answering the research questions. Since the study is looking into the possibilities of using natural ventilation for improving indoor air quality in hospital wards of semi-arid climates of Nigeria. Five case studies were selected in the city of Maiduguri being the largest city in the semi-arid climatic of Nigeria. All the five case studies have been assessed using questionnaire survey (chapter 5) and four of the five case studies were used for the full-scale measurement (chapter 6), to ascertain their indoor air quality and ventilation levels. The data obtained has been used as an input to state-of-the-art Computational Fluid Dynamic (CFD) software (Fluent 13.0) to simulate the potentials of various natural ventilation design strategies (chapter 8 and 9). Moreover, the result obtained from the questionnaire survey, walkthrough evaluation has been used to formulate the research problem.

In this chapter, section 4.2 introduces data collection methods used in the research; section 4.3 discusses the psychosocial perception; section 4.4 deliberates on physical (full-scale) measurement; section 4.5 introduces the quantitative research methods; section 4.6 presents methods employed in analysing the collected data and section 4.7 present the general methodology for achieving acceptable indoor air quality and ventilation in hospital wards of the study area. The complete research methodology is illustrated in the figure 4.1.

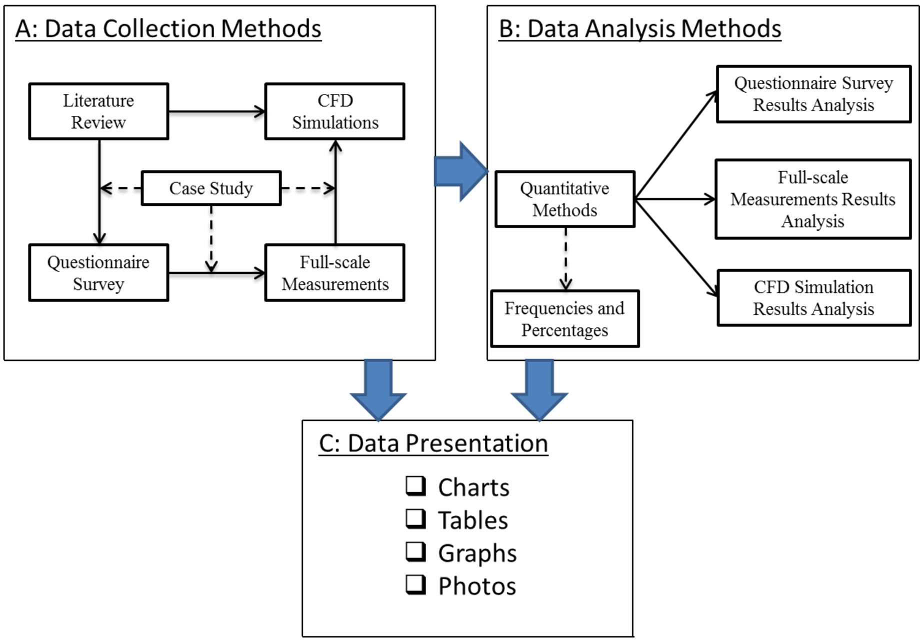


Figure 4.1: The General Research Methodology

The research methodology comprises of data collection and analysis methods on selected case study hospital wards (Figure 4.1). The data collection methods include secondary and primary data. The primary data was collected on the selected case study hospitals including psychosocial perception (Questionnaire Survey), full-scale measurement and CFD simulation of design strategies, while the secondary data was collected through literature review. These data were analysed using simple quantitative methods such as frequency and percentages. The results were presented in form of charts, tables, graphs and photos. The detailed discussion about the data collection and analysis methods is presented in the following sections.

4.2 Data Collection Methods

The measurement of Indoor Air Quality (IAQ) and ventilation performance in hospital wards is very complicated, as a result of the complexity of hospital institution and concern for patient's vulnerability, privacy and research ethics. The complete data collection methods are shown in figure 4.2. This method includes the collection of primary data using the selected hospital case studies and the secondary data were obtained through literature review.

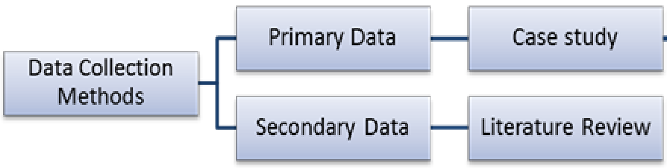


Figure 4.2: Data Collection Methods

The research was started by identifying the research needs and problems through the secondary data collection method of literature review. The primary data collection methods were then employed to ascertain the authenticity of the problems identified through literature review. First, questionnaire survey was conducted to ascertain the psychosocial perception of the selected hospital case study wards occupants on the condition of indoor air quality and ventilation in these wards. The outcome of the psychosocial perception is then supported and triangulated using a different scientific method (Full-scale measurement). Thus, full-scale measurements of the selected hospital case study wards were conducted and the results were used as an input to the CFD simulation software Fluent 13.0. The CFD simulation was used initially to validate the full-scale measurements and later used to evaluate the performance of different natural ventilation strategies. Figure 4.3 illustrated the relationship between the Full-scale measurement, Questionnaire survey and CFD simulation, all of which have been applied to the selected case study hospital wards.

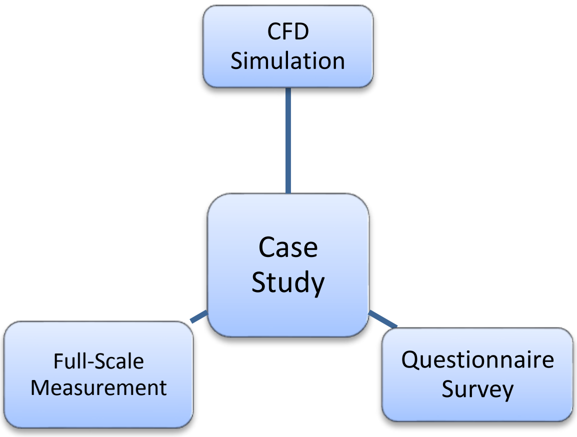


Figure 4.3: The application of data collection methods on the case study hospitals

The parameters and instruments used in the two approaches employed in ascertaining the level of IAQ and ventilation performance including Psycho-Social Perception and physical (Full-scale) measurements is illustrated in Figure 4.4. The psychosocial perception was conducted through questionnaire survey and walkthrough evaluation. The detailed discussion about the psychosocial perception approach including self-administered questionnaire, walkthrough evaluation and building drawing and image analysis is presented in section 4.3. However, the full-scale measurement was carried out using tracer gas measurement and other indoor parameters such as temperature and humidity, while the data on wind speed and direction were obtained from the nearby meteorological station. The detailed discussion of the full-scale measurement approach is presented in section 3.4.

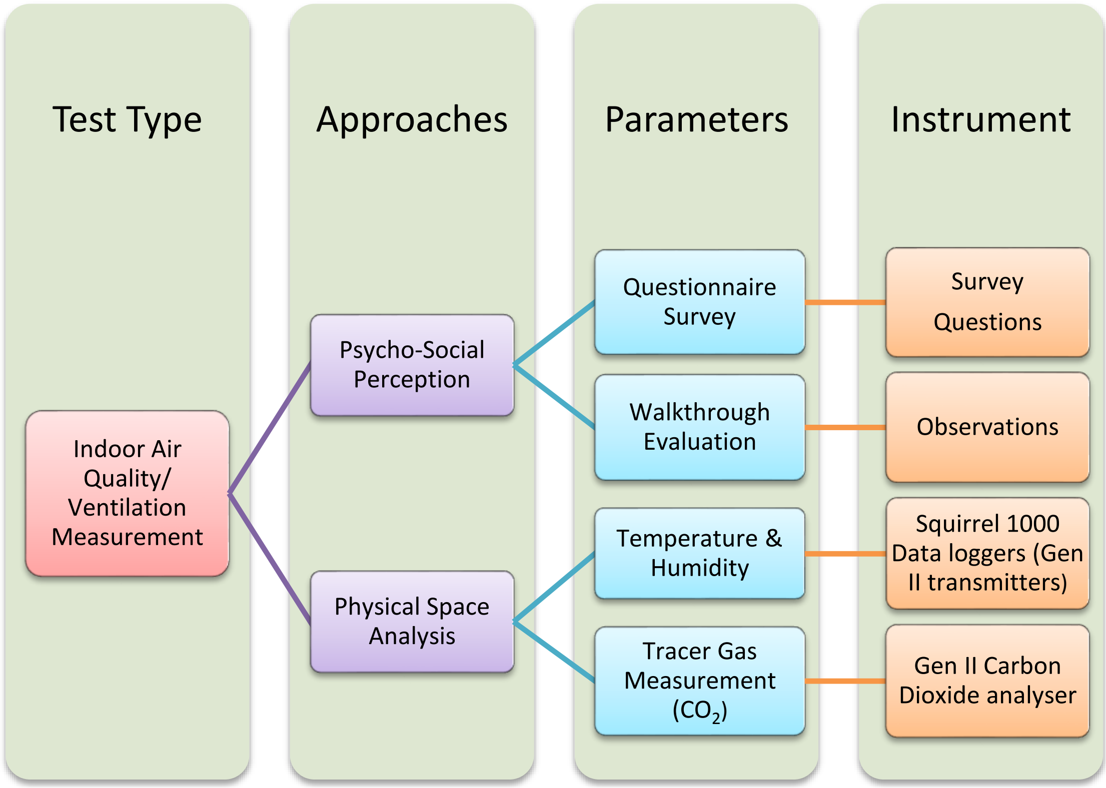


Figure 4.4 Framework for Ventilation and Indoor Air Quality measurement

4.2.1 Case study research design

Since the choice of any research methods is dependent upon three conditions including; the type of research question, the investigator's control over actual behavioural events, and the focus on contemporary against historical phenomena (Yin, 2009). Hence, the research design that can suite the requirement of this study is case study research. Therefore, some existing practical cases are required to ascertain the actual nature and level of indoor air quality and ventilation in the hospital wards of semi-arid climates. Five existing hospital ward cases in the study area (semi-arid climatic zone of Nigeria) have been selected the actual state of their ventilation has been studied and analysed.

4.2.1.1 Case study selection

The case studies for this research were selected based on guidelines including building size, design pattern, surrounding landscape, and construction materials and methods. The five selected case studies are located in Maiduguri within the semi-arid climatic zone of Nigeria including; University of Maiduguri Teaching Hospital (UMTH), Federal Neuro-

Psychiatric Hospital Maiduguri (FNPH), Umaru Shehu Ultra-Modern Hospital Maiduguri (USUHM), State Specialist Hospital Maiduguri (SSHM) and Nursing Home Hospital Maiduguri (NHHM). One of the major criteria employed in the selection of these hospitals was purpose built design. The selected case study hospitals were originally designed as a hospital. The common practice in the study area is that, buildings that are not originally designed and build as hospitals (but either residential or institutional buildings) are being transformed to hospitals. Since the aim of the study is to find out the potentials of enhancing architectural design and ventilation strategies for acceptable indoor air quality, it is counter-productive to use buildings that were not originally designed as hospitals.

4.3 Psycho-Social Perception

4.3.1 Self-Administered Questionnaire

Self-administered questionnaire simply involves respondents answering questions by completing the questionnaire themselves (Bryman, 2008). A questionnaire is important in this study to ascertain the perception of the immediate users of hospitals wards about the quality of indoor air, ventilation, thermal comfort, Harmattan dust and mosquitoes. This will enable the researcher to obtain first-hand information about the exact situation in the multi-beds wards under investigation and formulate the research problem. The questionnaires were handed in person to the potential respondents and were collected at a later time or on the same date in some cases. A self-administered questionnaire has many advantages compared to other types of data collection. Some of these advantages include; respondents are free to responds at their convenience, setting up an interview appointment is not required, absence of any interviewer eliminates interviewers error and biased, and it is cost effective and economical. Therefore, a self-administered questionnaire not only reduces costs of research, however, it also increases on the reliability of the outcome (Sudman, et al. 1965). The results and analysis of the questionnaire survey is presented in chapter five.

4.3.2 Walkthrough Evaluation

The purpose of conducting walkthrough evaluation in buildings is to obtain a general idea of occupant activities, building function and to detect indoor air quality problems indicators (Cheremisinoff, 2002). The process will help an investigator in pinpointing the highly potential indoor air quality problem areas in a building. Measurement tools are often used to get readings all through the walkthrough inspection process as a means of identifying problems locations by ascertaining the normal operating conditions. In this study, the walkthrough evaluation has been conducted to ascertain the various building design and ventilation types and problems that affect indoor air quality in the selected case studies. This evaluation together with the result obtained from the field measurements and the questionnaire survey will assist in adopting better ventilation strategies for achieving acceptable indoor air quality in the healthcare facilities.

4.3.3 Building Drawings and Images Analysis

Building and engineering drawings of the case study hospitals have been collected, studied and analysed to ascertain the original ward characteristics and ventilation systems design with the aim of comparing it with the facilities' existing features as observed from the walkthrough evaluation. Furthermore, these drawings assisted in providing the exact dimensions and other building characteristics to be used as an input for CFD simulation. Measuring building physical characteristics require a lot of time and energy, which will be saved by extracting such features directly from the building drawings.

However, the collection of photos during the entire fieldwork served as a reminder when analysing the data collected from the field measurements. These photos were documented for easy identification, especially by marking them with alphanumerical identities.

4.4 Physical (Full-scale) Measurements

Field measurements of existing facilities are required to ascertain the performance of ventilation systems and other indoor environmental parameters. The results obtained from these measurements will offer a vital resource in understanding the mechanics of ventilation and airflow in buildings (*Liddament, 1996).* Many measurement techniques have been established for different aspects of airflow measurements including the following (*Liddament, 1996)*:

i. Tracer gas testing for ventilation rate and ventilation efficiency evaluation (used in this study)
ii. Pressurisation measurements to determine building and component air-tightness

iii. Anemometry techniques to measure air flow velocity and turbulence throughout a space
iv. Sheet light and laser methods to visualise air flow patterns
v. Flume models to design and predict ventilation performance
vi. Wind tunnel techniques for pressure distribution evaluation

In this study the tracer gas testing for ventilation rate and ventilation efficiency evaluation was selected due to its advantages including; simplicity, cost effectiveness, practicality, reliability and accuracy. The detailed analysis of the tracer gas techniques is presented in chapter 6.

4.4.1 Air Change Rates (ACR) Measurement using Tracer Gas Techniques

Tracer gas dilution techniques are of high efficiency and accuracy in evaluating the airflow patterns within buildings and air handling units. The technique operates by injecting a readily detectable tracer into the room, and recording the concentration history (Etheridge and Sandberg, 1996). They consist of marking the air with a tracer gas that dilutes well with the air and easy to analyse in trace amounts (Roulet, 2008). To simulate the behaviour of contaminants having similar densities, non-toxic tracer gas could be helpful. Tracer gas concentration is analysed at a time or place where the tracer is well mixed with the air. The evolution of the evaluated concentration depends on both injection flow rate and mixing airflow rate (Roulet, 2008). Tracer gas techniques can be generally classified into three depending on the type of control and injection methods including; decay method, constant injection methods, and constant concentration methods. The release and sampling techniques used and the cost for the three methods is shown in table 4.1 below (Etheridge and Sandberg, 1996).

Table 4-1 Different Tracer Gas Methods

Methods	Release	Sampling	Cost
Rate of concentration Decay	*Release of a shot burst of tracer gas*	*Continuous monitoring. Long-Term integrated samples Several shot-term integrated samples*	*Moderate*
Constant Injection	*Continuous release at known flow rate*	*Long-term integrated*	*Moderate*
Constant Concentration	*Controlled release at varying flow rate*	*Continuous monitoring*	*Relatively high*

In the present study, rate of concentration decay methods was used due to its moderate cost and practicality. The concentration decay method is usually done by releasing a small amount of gas initially, after which there is no injection of gas throughout the measurement period (Etheridge and Sandberg, 1996). Once the injected tracer gas is mixed with the space air, the concentration is measured at a regular time interval (Laussmann and Helm, 2011). Concentration decay is the most commonly used method in practice, which provides a direct measurement of the nominal time constant or the air change rate and gives unbiased estimate of the mean airflow rate. It is a transient method which measures the air change rate by recording the change in tracer gas concentration (Roulet, 2008). When using concentration decay methods to calculate the total flow rate, it is essential to be conversant with the total volume of the ventilated space and make sure that thorough mixing is established within the space (Etheridge and Sandberg, 1996).

4.4.2 Indoor Temperature and Humidity Measurement

Based on the adaptive neutrality temperature calculated, the quality of indoor air in the study area is considered to be poor when the temperature is less than 24.2^{o}C and greater than 29.2^{o}C, regardless of the actual air quality. Likewise, the recommended level of humidity for acceptable indoor comfort is between 30% and 60%, below this level may cause discomfort (Cheremisinoff, 2002).The level of humidity in indoor spaces is affected by the level of outdoor humidity, indoor–outdoor air exchange, indoor moisture generation, and indoor moisture removal (Francisco and Rose, 2010). The indoor temperature and relative humidity for this study were measured onsite using state-of-the-art measuring instrument comprising Squirrel 1000 Series Data Logger, dry bulb thermometers and hygrometers from Eltek.

4.4.3 Outdoor Temperature, Wind Speed and Direction Measurement

Outdoor temperature, wind speed and wind directions data could be ether measured onsite or collected from a local meteorological weather station (ASTM Standards, 2011). Wind speed and direction are the most basic airflow measurement, when the air flowing past a given point in space at a given time (McWilliams, 2002). The indoor airflow data is very essential in estimating the air change rate in buildings. The indoor air flow has been measured from the simulation output. In the present study, an hourly outdoor wind speed and directions data were obtained from the nearby meteorological station. These data are collected for the days and time of the tracer gas measurements. However, the outdoor temperature was measured onsite using Squirrel 1000 Series Data Logger and Gen II transmitter.

4.5 Quantitative Research Method

A quantitative research method involves the collection of numerical data through a natural science prediction approach (positivism), and objectivist conception of social reality with deductive view of relationship between theory and research (Bryman, 2008). The major quantitative data collection and analysis used for the purpose of this research is field experiment and questionnaire survey. The aim of conducting field experiments is to assess the existing indoor air quality status of the case studies and obtain the necessary quantitative ventilation data to be used as input in the CFD computer simulation software.

4.6 Data analysis methods

The source of data for this study is mainly a quantitative output from simulation. State-of-the-art Computational Fluid Dynamic (CFD) software Fluent 13.0 was used to simulate the airflow characteristics in hospital wards of the study area (Maiduguri). The Fluent outputs are in the form of charts and numbers showing airflow patterns, air speed and direction and air temperature of the interior space. The Fluent solver together with design modeller (geometry creation software) and ANSYS meshing (meshing program) are integrated into an application called ANSYS Workbench. In this study the geometric models were created using design modeller, while harpoon meshing was used for meshing. The meshed geometries were simulated using FLUENT solver. The simulation and data analysis process is illustrated in figure 4.5.

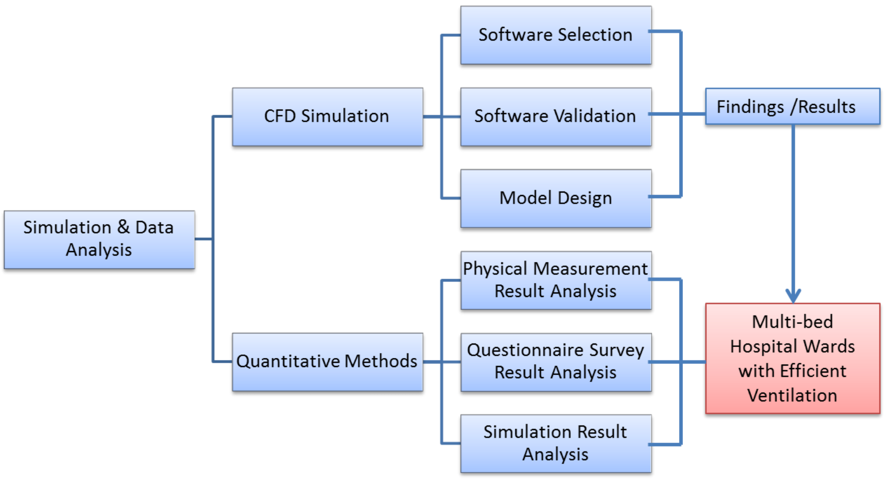


Figure 4.5: Data Analysis and Simulation Method

The first part of the data analysis in figure 4.5, which is the CFD simulation and the simulation results analysis methods will be discussed in chapter 7 of this study. The data obtained from the CFD simulation are quantitative data that will be analysed based on frequencies and percentages. However, the first two points in the second part of the data analysis including data obtained from the full-scale measurement, data analysis and questionnaire survey analysis has been presented in the following subdivisions.

4.6.1 Full-scale measurement (Tracer gas) result analysis

The analysis of tracer gas concentration could be either done on site simultaneously with the sampling process or off site when the gas samples are collected in sealed containers (ASTM Standard, 2011). However, for the purpose of this study, the tracer gas concentration analysis was conducted on site concurrently with the sampling process. The measurement was carried out using tracer decay techniques with CO_2 as the tracer gas. The tracer gas concentration was analysed and recorded with the aid of CO_2 analyser and data loggers respectively. The results obtained from these measurements were used to estimate the air change rates of the hospitals wards using the mathematical expression in equation 10.

$$N = \frac{\ln C(0) - \ln C(\tau 1)}{\tau 1} \tag{10}$$

Where
N = Air Change Rate
C = Tracer Gas Concentration in Rooms
τ = Time (h)

The results from the full-scale measurement were compared with simulation and the error was found to be ≤15%. These errors are due to many factors including climatic considerations such as wind direction, temperature and building orientation. Moreover, the existing of cracks and gaps in the building also affects airflow rates.

4.6.2 Questionnaire survey result analysis

The data obtained from the questionnaire survey covers important factors affecting ventilation in the study area. These factors include Harmattan dust, mosquitoes, high temperatures, thermal comfort and indoor air quality. Owing to the purpose of the survey which is to ascertain the existence or otherwise of the above mentioned factors and subsequently used the outcome in the formulation of the research problem. The data collected were analysed using simple frequency distribution in terms of percentage of response.

4.7 Methodology for Achieving Acceptable Indoor Air Quality in Hospital Wards

The current design approaches employed to achieve acceptable indoor air quality in hospitals of semi-arid climates indicate the difficulty of achieving efficient natural ventilation. When factors like mosquitoes and Harmattan dust are prevented through insect filters and dust separation techniques, the consequences will lead to the reduction in ventilation and air change rates. Then, the question remains, what opening sizes and positions are required to make up for the pressure drops due to insect nets and dust filters? The methodological framework to achieve acceptable indoor air quality through natural ventilation in hospital wards of semi-arid climates is illustrated in figure 4.6. Thus, due to the energy shortage in the study area, any ventilation solutions should be achieved with less or zero energy techniques.

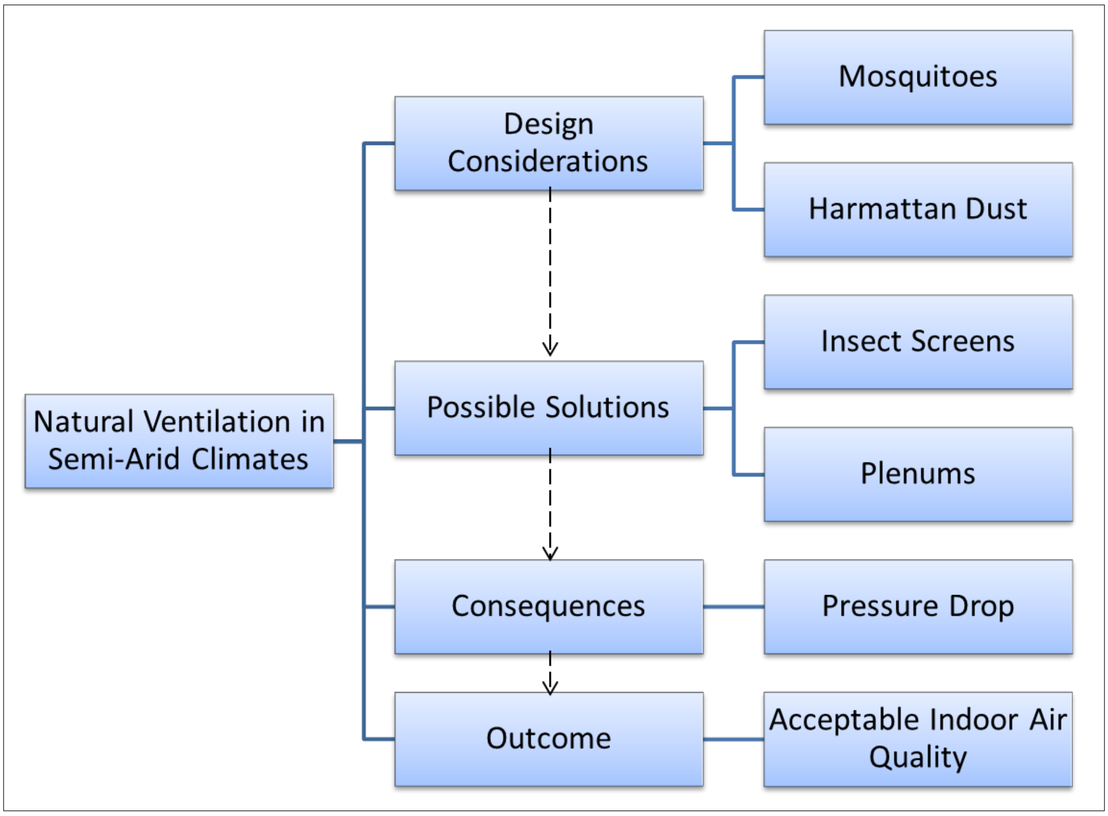


Figure 4.6: Methodological Framework for Natural Ventilation simulation in Multi-Bed Wards of Semi-Arid Climates

4.8 Chapter Conclusion

This chapter presented the general research methodology employed in carrying out this research. These methodologies include questionnaire survey, full-scale tracer gas measurements and CFD simulation. The chapter discusses the various methods of quantitative data collection used in the study, including the primary data collected from the selected case study hospital wards and the secondary data collected through literature review.

The data collection was generally conducted in two stages. In the first stage, the conditions of the existing case study hospital wards were assessed using questionnaire survey and the second stage include the full-scale measurements of ventilation rates in four existing hospital wards. The questionnaire survey was conducted to ascertain the psychosocial perception of the healthcare workers with the hospital wards on the status of indoor air quality and ventilation in these wards. The full-scale measurement was employed to verify and triangulate the results of the psychosocial perception. The measurements included CO_2 concentration decay measurement, dry bulb temperature and relative humidity. The CFD simulation (Fluent 13.0) was applied to validate the hospital wards models using the results from full-scale measurements and subsequently used the CFD software to evaluate and enhance the performance of different natural ventilation strategies.

The data obtained through the psychosocial perception, full-scale measurement and the CFD simulation were analysed using simple quantitative analysis methods such as frequencies and percentages. The analysed data were presented using charts, tables, graphs, contours, diagrams and photographs. The detailed methodology in relation to full-scale measurement and CFD simulation are presented in chapters 6 and 7 respectively.

Chapter Five

Physical, Environmental and Social Assessment of the Existing Hospitals Wards

Chapter Structure

5.1 Introduction

5.2 The Physical Properties of the Existing Hospital Wards

5.3 Environmental Properties of the Existing Hospital Wards

5.4 Questionnaire Survey Result Analysis

5.5 Chapter Conclusion

5 Chapter Five: Physical, Environmental and Social Assessment of the Existing Hospitals Wards

5.1 Introduction

In the previous chapter (chapter 4), the general research methodology used in the present study have been presented. In this chapter (chapter 5), the physical, environmental and psychosocial perception of five existing hospital wards has been examined and analysed. The results from this chapter were used to relate the hospital occupants' perceptions and actual hospital wards measurements to air quality problems identified in the literature. This is executed by ascertaining the actual situation of the selected hospital wards through physical observation, environmental assessment and psychosocial perception.

The chapter (chapter 5) was designed as a response to objective number 1 and 2. The first part of the chapter which is the description of the existing hospital wards design parameters was intended as a response to research objective number 1, which is *"To investigate the nature of existing ventilation systems used in healthcare facilities of semi-arid climates".* The second part of the chapter which is the questionnaire survey results analysis was initiated to satisfy objective number 2, which is *"To determine the effects of the identified ventilation strategies on indoor-air pollution in healthcare facilities of semi-arid climates"*.

In this chapter, section 5.1 introduces the physical properties of the existing hospital wards and section 5.2 discusses the environmental properties of the existing hospital wards. Section 5.3 presents the results of the questionnaire survey including indoor air quality, mosquito, Harmattan dust, thermal comfort, ventilation, and relationship between indoor air quality and health.

5.2 The Physical Properties of the Existing Hospital Wards

The information about the physical properties of hospital wards is significant in studying their indoor air quality and ventilation. This is due to the fact that, understanding building parameters such as general outdoor and indoor physical parameters, multi-bed ward parameters, opening characteristics, furniture characteristics, building components, and ventilation systems, helps in relating the actual problems of indoor air quality and ventilation to their causes and effects.

5.2.1 Selected Hospital Building Parameters

The general outdoor and indoor physical parameters of the five selected hospitals in the study area have been documented. These parameters include number of storeys, surrounding vegetation, building density and existing type of ventilation. The selected case-study hospitals are low rise buildings typical of Maiduguri, the study area. Three of the five hospitals including Federal Neuro-Psychiatric Hospital (FNPHM), Umaru Shehu Ultra-Modern Hospital (USUHM) and Nursing Home Hospital (NHHM) are bungalow while the remaining two including University of Maiduguri Teaching hospital (UMTH) and State Specialist Hospital (SSHM) have two and one storey height respectively. However, the studied multi-bed wards in the UMTH and SSHM hospitals are located in the first floor levels of their respective buildings. Some of the multi-bed wards in the two hospitals (UMTH and SSHM) have balconies. Out of the five multi-bed wards studied only SSHM has balcony like corridor in the entrance. Balconies are important as a sun shading device in buildings. Most of these hospital wards have vegetation cover in their surroundings. This vegetation cover is important in changing the microclimate of the surrounding and shields the wards from Harmattan dust. However, vegetation cover around hospital wards also have disadvantage of serving as breeding ground for mosquitoes.

The density of the hospital multi-wards in relation to other surrounding buildings differs from one hospital to the other. The wards are closely compacted about 4-5m apart in SSHM, NHHM and USUMH; about 40m apart in UMTH; and 100m apart in FNPHM. Furthermore, the ventilation system in all the five hospital multi-bed wards studied is natural ventilation assisted by fans, to enhance air circulation when needed. Some of these hospitals also have air-conditioning system installed but not in operation all the time due to energy shortage and maintenance. Apart from the existing ventilation systems, patients usually bring their standing or table fans to improve the level of air circulation in their immediate surrounding environments. Table 5-1 shows various building parameters characterising the five selected hospitals in the study area.

Table 5-1: The Building Parameters of the Selected Hospitals in the Study Area

S/N	Building Parameters	Hospital Names and Evaluations				
		UMTH	SSHM	FNPHM	USUHM	NHHM
1.	Number of storeys	2	1	Bungalow	Bungalow	bungalow
2.	Availability of Balcony	In some wards	Yes (Corridor)	N/A	N/A	N/A
3.	Surrounding vegetation	Trees	Few Trees	Few trees, grasses & shrubs	Trees	Few trees
4.	Building Density Nearby	About 40m apart	Compacted about 4-5m apart	About 100m apart	Compacted about 4-5m apart	Compacted about 4-5m apart
5.	Existing type of ventilation	Natural and Fan	Natural and Fan	Natural and Fan	Natural and Fan	Natural and Fan

5.2.2 Hospital Multi-Bed Wards Parameters

The planning and design of hospital multi-bed wards differs from one hospital to the other, depending on the type and requirement of these hospitals. Moreover, one of the major factors of consideration while designing hospital wards is the type of patients to be accommodated. The ward design for paediatrics patients will not be the same as medical or surgery ward for adult, because, in paediatrics apart from the patients, their mothers are also provided with beds. The multi-bed wards studied include medical ward in UMTH, Paediatrics ward in SSHM, Psychiatric ward in FNPHM, orthopaedic ward in USUHM and Medical Ward in NHHM as illustrated in Figures 5.1 to 5.5 and Table 5-3.

The shapes and form of these wards are rectangular with flat surfaces and their floor areas ranges from the smallest 57.6 m^2 to the largest 359.15 m^2 as illustrated in table 5-2. The ward shapes are usually determined by the general shape of the building where the ward is situated and most hospital buildings in the study area are rectangular in shape. Furthermore, all hospital wards investigated are either linked to a larger building or isolated with attached supporting facilities as shown in table 5-2. In terms of storey heights, two of the investigated hospital wards including UMTH and SSHM are located in the first floor of their respective buildings, while the others are bungalow.

Moreover, all the investigated hospital multi-bed wards are generally oriented toward the North/South direction with some variations (Figures 5.1 to 5.5) and their floor to ceiling height ranges from 3.0 m to 3.2 m. The hospital wards where the measurements were conducted have been marked with dotted lines in figures 5.1 to 5.5 and the two frequent wind flow directions of North-East trade wind and South-West monsoon wind has been illustrated in all the five hospital wards. The nearly North-South orientation in most of the wards is probably adopted to benefit from the south-westerly monsoon wind that is normally moderate and comfortable and the North-easterly trade wind that is hot and dusty but can provide enough ventilation to remove indoor air pollutants. This type of orientation will also assist in controlling solar radiation by the openings on the North and South façade. The interior space in the three of the five wards investigated including UMTH, FNPHM and USUHM are divided into cubicles with about 1.0 to 1.2m height dwarf walls, while the remaining two have no partitions. These partitions are important in providing some sort of privacy and restrict unnecessary movement of patient relatives and healthcare workers.

Furthermore, all the investigated hospital multi-bed wards have no staircase located indoors to suggest vertical air movement between spaces, except the wards located in the SSHM which has one staircase linking to the ground floor. However, all the hospitals wards have spaces allocated for Nurses and utility rooms except the ward at NHHM which has a small capacity of 3 beds, without any supporting facilities inside. The wards in the NHHM were designed to accommodate fewer beds with supporting facilities zoned in one place outsides the wards. Furthermore, out of the five hospital wards studied, only UMTH and SSHM have doctors' rooms located within the multi bed wards. Moreover, the multi-bed wards in UMTH, SSHM, and USUHM have treatment rooms located within the ward spaces, while the other two including FNPHM and NHHM do not have treatment rooms located within the wards.

Conveniences (toilets) are an essential consideration in designing and planning of hospital multi-bed wards. Toilets can be located inside or outside the wards space, provided that it has direct link to the hospital wards. The advantage of locating toilets within the ward spaces is ease in accessibility, while the disadvantage is odour and smell if not maintained properly. All the toilets in the investigated multi-bed wards are situated within the wards space except that of NHHM which is located outside as illustrated in figures 5-1 to 5-5.

The number and design of the access in and out from the multi-bed ward is important and is usually planned according to the occupancy and type of patients to be accommodated in these wards. In the five investigated multi-bed wards, three including UMTH, SSHM and FNPHM have 2 entrances, one from outside and the other to the toilets, and the remaining two wards including USUHM and NHHM have three and one entrances respectively as illustrated in table 5-2 and Figures 5-1 to 5-5. Furthermore, the level of occupancy in these wards varies from one hospital to the other. The occupancy levels are

40, 16, 24, 20 and 3 for UMTH, SSHM, FNPHM, USUHM, and NHHM respectively as illustrated in table 5-2. This occupancy levels only considered the number of beds or patients with little allowance for patients' relatives and staff in these wards. Moreover, the occupant densities in these wards are 8.98m^2/person, 7.2m^2/person, 12.8m^2/person, 7.13m^2/person and 10.13m^2/person for UMTH, SSHM, FNPHM, USUHM, and NHHM respectively.

Table 5-2: The Building Parameters of the Selected Multi-Bed Wards

S/N	Multi-Bed Ward Parameters	Multi-Bed Wards and Evaluations				
		UMTH	SSHM	FNPHM	USUHM	NHHM
1.	Investigated Ward Floor Area	359.15 m^2	57.6 m^2	307.2 m^2	142.5 m^2	30.38 m^2
2.	Investigated Ward Shape and Form	Rectangular Flat	Rectangular Flat	Rectangular Flat	Rectangular flat with gable roof	Rectangular Flat
3.	Isolated or space within building	Linked to buildings	Linked to buildings	Isolated with supporting facilities	Joint with some single bed wards	Linked with other wards in a building
4.	Investigated Ward Level	1st floor	1st Floor	Bungalow	Bungalow	Bungalow
5.	Investigated Ward Height	3m	3m	3m	3.2m	3m
6.	Ward Orientation	North-south	North-south	North-south	North-south	North-South
7.	Internal partitions	Cubicles partition with Dwarf Wall	No partition	Cubicles partition with Dwarf Wall	Cubicles partition with Dwarf Wall	No partition
8.	Stair case inside the ward	No	Yes (1)	N/A	N/A	N/A
9.	Nurses area	Yes	Yes	Yes	Yes	No
10.	Doctors room	Yes	No	No	No	No
11.	Utility rooms	Yes	Yes	Yes	Yes	No
12.	Conveniences	Yes (at one side)	Yes (at both side)	Yes (at one side)	Yes (patient and staff toilets)	No
13.	Treatment area	Yes	yes	No	Yes	No
14.	No of access and entrance Lobby	2 (from toilet & corridor)	2 (from corridor & stair)	2 (from toilet & lobby)	One major entrance and 3 other doors to toilets	1
15.	Investigated Ward Occupancy	40 Beds	8 Bed (and 8 beds for Mothers)	24 beds	20 beds	3
16.	Occupant density	8.98 m^2/person	7.2 m^2/person	12.8 m^2/person	7.13 m^2/person	10.13 m^2/person

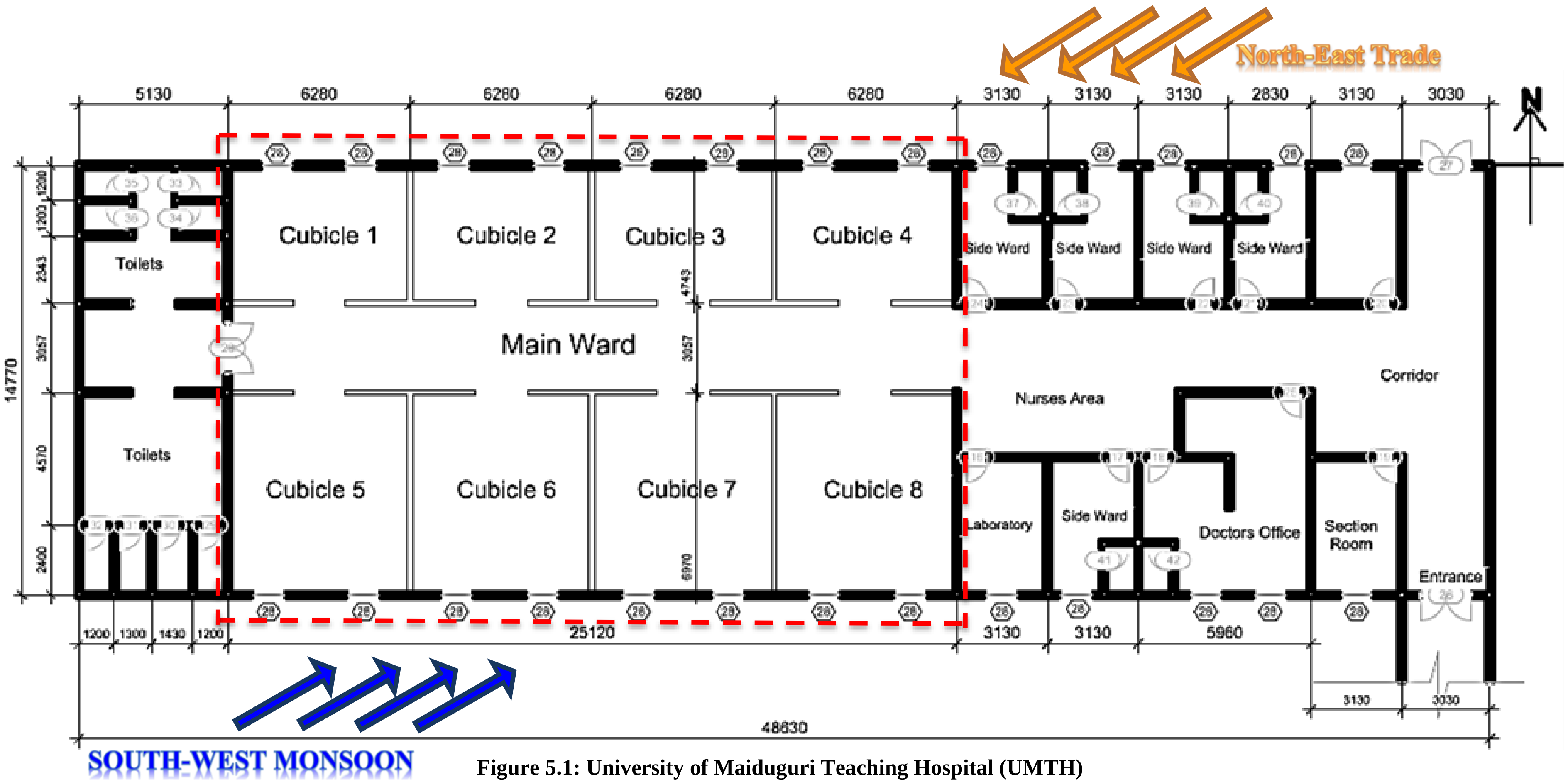


Figure 5.1: University of Maiduguri Teaching Hospital (UMTH)

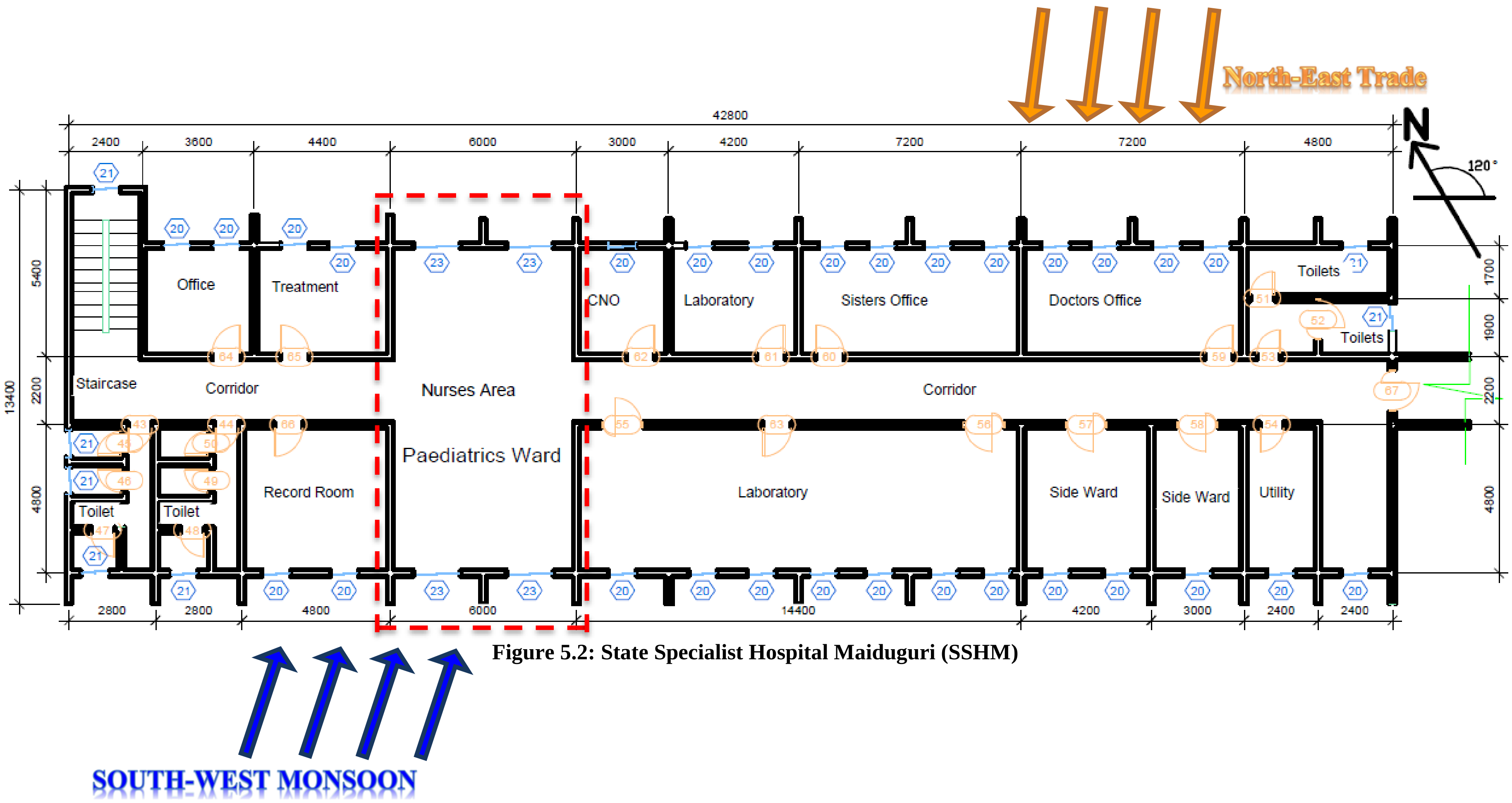


Figure 5.2: State Specialist Hospital Maiduguri (SSHM)

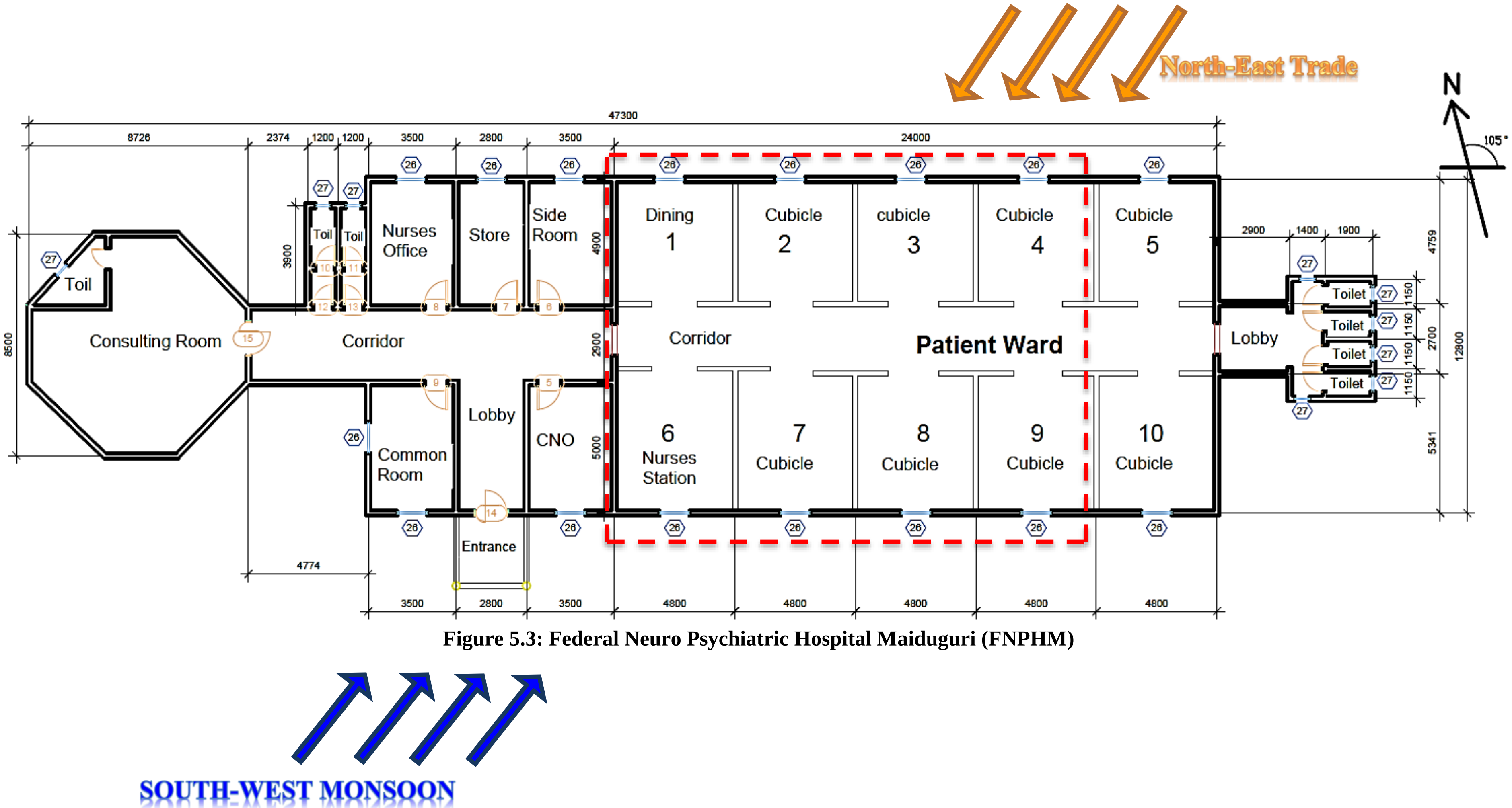


Figure 5.3: Federal Neuro Psychiatric Hospital Maiduguri (FNPHM)

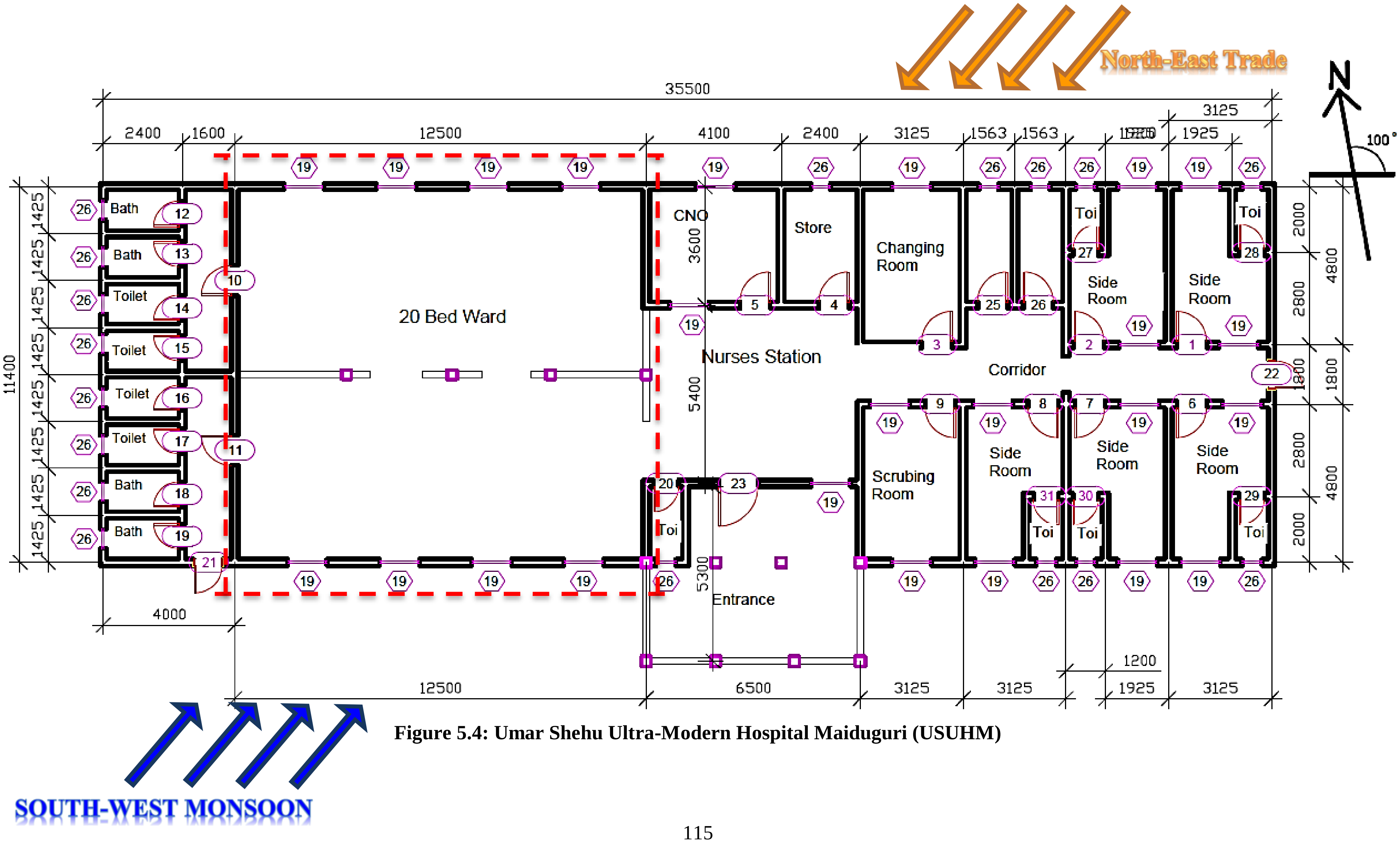


Figure 5.4: Umar Shehu Ultra-Modern Hospital Maiduguri (USUHM)

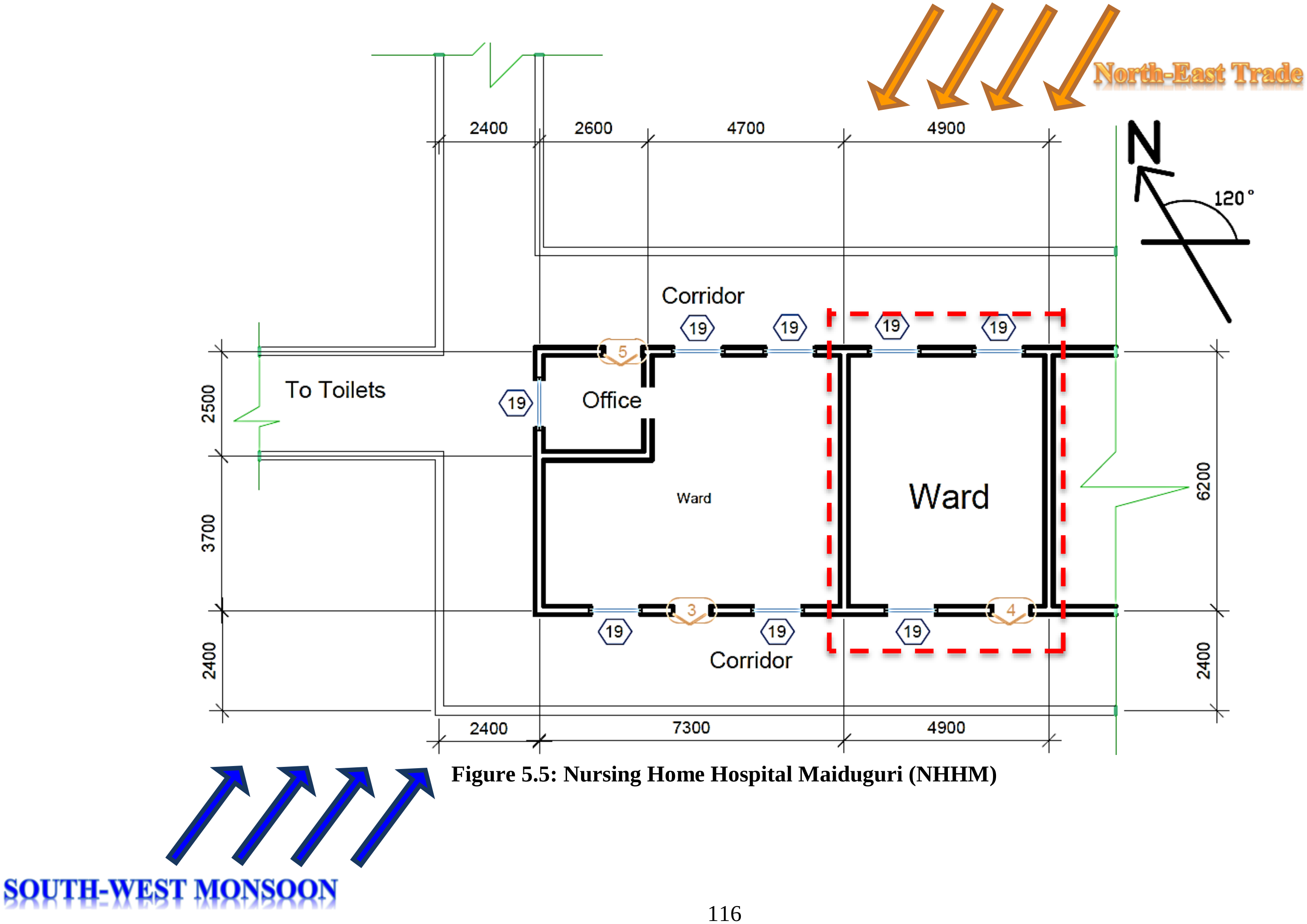


Figure 5.5: Nursing Home Hospital Maiduguri (NHHM)

Table 5-3: The images of the hospital wards investigated

UMTH	SSHM	FNHM	USUHM
			
UMTH	**NHHM**	**FNHM**	**USUHM**
			

5.2.3 The Characteristics of the Multi-bed Wards Window Openings

The study of the various characteristics of window openings is used to analyse their compliance with ventilation rates requirements. The nature, size and type of openings such as windows and doors are an important consideration when designing natural ventilation and considering the improvement of indoor air quality in buildings. The number of windows in the investigated multi-bed wards includes 16 for UMTH and SSHM, 12 in FNPHM, 8 in USUHM and 3 in NHHM. The efficiency of these windows in terms of providing the required natural ventilation and improving the indoor air quality will only be ascertained by measuring the ventilation rate in these buildings. However, these windows are all sliding except that of UMTH which are side-hung windows. The disadvantage of sliding windows is that, it only provides 50% operable area for direct airflow into the buildings. The sizes of these windows range from minimum of 0.9m x 0.9m to the maximum of 1.2m x 1.5m with roughly North-South orientation as shown in table 5-4 and figures 5.1 to 5.5.

The consideration of forms and materials of window is important in selecting window systems for hospital wards. Because, type and form of material usually dictates the heat and mass transfer ability of the window system. All the windows used in the selected hospitals wards are flat rectangular or square windows made of single glazing with Aluminium or Steel frames. Furthermore, out of the five selected hospital wards, only SSHM has high level windows. High level windows are also important especially when stack ventilation is used in a building.

Multi-bed hospital wards are public apartments that houses patients, hospital staff and their visitors, which makes accessibility an important aspect in their design and planning. The number of entrance doors to the selected hospital wards ranges from one to four. Three of the five hospital including UMTH, SSHM, and FNPHM have 2 doors one linking from the outside and the other to the toilets. USUHM has four doors one from the outside and the other three linking to the toilets while, NHHM has only one entrance from the outside. Furthermore, the door materials used in these hospital wards includes wood, glass, steel and rubber with steel and aluminium frames. All these doors are double rectangular swinging with sizes ranging from the smallest 0.9 x 2.1m to the largest 2.0 x 2.1m. The curtain materials used for these openings are polyester, and cotton while the steel wire gauze is used as insect screen to prevent mosquitos' incursion. Table 5-4 illustrate in detail the various multi-bed wards opening characteristics.

Table 5-4: Multi-Bed Ward Openings Characteristics

S/N	Multi-Bed Ward Opening Parameters	Multi-Bed Wards and their Parameters				
		UMTH	**SSHM**	**FNPHM**	**USUHM**	**NHHM**
1.	Number of windows	16	16	12	8	3
2.	Type of Windows	Double side hung	Sliding windows	Sliding windows	Sliding windows	Sliding windows
3.	Size of Windows	0.9m x 1.2m	0.9m x 0.9m	1.2m x 1.2m	1.2m x 1.2m	1.2m x 1.5m
4.	Forms and Materials of Windows	Normal flat steel frame glazed windows	Normal flat Aluminium frame glazed windows	Normal flat steel frame glazed windows	Normal flat Aluminium frame glazed windows	Normal flat steel frame glazed windows
5.	High level windows	No	Yes (8 out of 16 are high level)	No	No	No
6.	Number of Doors	2 (from toilet & corridor)	2 (from lobby & stairs)	2 (from toilet & lobby)	4 (1 major, 3 to toilets)	1
7.	Type of Doors	Double wooden and aluminium framed glazed (1 each)	Steel door	No door only doorway open to lobby	Flush rubber doors	steel framed glazed door
8.	Size of Doors	2m x 2.1m & 1.5m x 2.1m	1.2m x 2.1m	1.5m x 2.1m	1.2x2.1m (Main) & 0.9x2.1m (3 toilet)	1.2m x 2.1m
9.	Forms and Materials of Doors	Flat Timber and Glass	Flat doors made of steel	Rectangular doorway	Rubber flat doors and glazed Aluminium frame doors	Flat glass doors steel frame
10.	Types and Materials of Curtains	No Curtains	Polyester curtains covering bed spaces	Polyester	Cotton material	No Curtains
11.	Types and Materials of Netting	No Netting	Steel Nets incorporated to windows	Steel Nets fixed to window frame	Steel Nets inbuilt with windows	Steel Nets inbuilt with windows

"Natural ventilation shall be through windows, doors, louvers or other approved openings to the outdoor air with ready access to and controllable by the building occupants" International Code Council Inc., (2009). The existing hospital wards in the study area are typical rectangular wards with windows in the longer perimeters as illustrated in Figures 5-1 to 5-5. The window system used in all the five hospitals examined is sliding windows, except in University of Maiduguri Teaching Hospital (UMTH), where side-hung windows were used. According to the International Mechanical Code (IMC), *"The minimum openable area to the outdoors shall be 4% of the floor area being ventilated and when the openable area is provided through adjoining rooms, the openable area must be >8% of floor area of the interior room, and not less than 25 unobstructed feet (2.3m^2) away".* The openable area air intake openings shall be placed a minimum of 10 feet (3048mm) from contaminant sources, (International Code Council Inc., 2009).

Moreover, according to the results obtained from the investigated existing hospital wards in the study area, all the wards measured have fulfilled the International Mechanical Code requirement of operable areas should be at least 4% of the total ward floor areas except FNPHM, which has window operable area of 2.34% as shown in table 5-5.

Table 5-5: Window Area in Relation to the Hospital Ward's Floor Area

S/N	Hospital Wards	Window Type	Floor Area	Opening Area	Openable Area %
1.	**UMTH**	Side-hung	25.08 x 14.32 = 359.15 m^2	1.2 x 1.2 x 16 = 23.04 m^2	6.4%
2.	**SSHM**	Sliding	6.0 x 9.6 = 57.6 m^2	1.8 x 1.8 x 4 = 12.96 m^2	11.25%
3.	**FNPHM**	Sliding	24.0 x 12.8 = 307.2 m^2	1.2 x 1.2 x 10 = 14.4 m^2	2.35%
4.	**USUHM**	Sliding	12.5 x 11.4 = 142.5 m^2	1.2 x 1.2 x 8 = 11.52m^2	4.05%
5.	**NHHM**	Sliding	4.9 x 6.2 = 30.38 m^2	1.5 x 1.2 x 3 = 5.4 m^2	8.9%

5.2.4 The Furniture Characteristics of the Multi-bed Wards

Furniture in buildings remains among the major contributors of contaminants in indoor environment, because they emit certain chemicals such as Formaldehydes, Volatile Organic Compounds (VOC) and dusts that are harmful in higher concentrations. The major types of furniture obtainable in hospital wards include beds and chairs. Furniture types obtainable in the hospital wards studied includes Rubber framed steel reinforced bed, steel frame steel beds, steel and timber chairs, and timber cupboards. The number of beds obtainable in these hospital wards ranges from 3 to 40 as illustrated in table 5-6.

Table 5-6: Multi-Bed Ward Furniture Characteristics

S/N	Multi-Bed Ward Furniture	Name				
		UMTH	SSHM	FNPHM	USUHM	NHHM
1.	Furniture Types	-	Rubber framed steel reinforced bed, Foam mattress, and steel and timber chairs	Steel beds, Foam mattress, & pillows, with 3 cupboards per cubicle	Steel framed beds and chairs with foam	-
2.	Number of Beds	40 beds	16 (8 infant beds and 8 mothers beds)	24 beds (3 per cubicle)	20 beds	3 beds
3.	Material and type of waiting chairs	-	Steel and timber chairs	Plastic chairs	Steel frame, rubber arm rest with foams cover	-

5.2.5 The Building Components of the Multi-bed Hospital Wards

The walling type used in all the multi-bed wards considered is flat vertical masonry wall typical of Maiduguri buildings and the walling material for all these wards is hollow concrete block walls except in NHHM where plastered red brick walls are used. There is no insulation in the walls.

The flooring system used in all the five hospital investigated is reinforced concrete floors with terrazzo finishing except in NHHM where the floor finishing is unpolished tiles. Tile skirting is also applied in one of the hospital wards (NHHM) to the interior meeting point of the wall and flooring system. The type of ceiling used in the multi-bed hospitals includes suspended ceiling in UMTH, USUHM, and NHHM, asbestos ceiling in SSHM and plastic ceiling in FNPHM. The colours of these ceiling are white except the asbestos ceiling which is pink. All the ceilings are flat-square except the asbestos which is corrugated, while skirting is not used except with the plastic ceiling. Table 5-7 shows the various components of the multi-bed wards and their characteristics.

Table 5-7: various components of the multi-bed wards and their characteristics

S/N	**Multi-Bed Ward Ceiling**	**Name**				
		UMTH	**SSHM**	**FNPHM**	**USUHM**	**NHHM**
01	Type ceiling	Suspended Ceiling	Asbestos ceiling	Rubber ceiling	Suspended Ceiling	Suspended Ceiling
02	Ceiling colour	White	Pink	White	White	White
03	Ceiling shape/form	Flat/Square	Corrugated	Flat (0.3m)	Flat/square	Flat/square
04	Ceiling skirting	No	No	Rubber skirting	No skirting	No skirting
Multi-Bed Ward Floor						
01	Types of floor finishing	Terrazzo floor finishing	Terrazzo floor finishing	Terrazzo floor finishing	Terrazzo floor finishing	Unpolished Tiles finishing
02	Type of floor tiles	Terrazzo	Terrazzo	Terrazzo	Terrazzo	Tiles
03	Tiles shape and form	Flat Square	Flat Square	Flat Square	Flat rectangular tiles	Flat square tiles
04	Tiles colour	Mixture of Black, white & ash	Mixture of Black, white & ash	Mixture of Black, white & ash	Mixture of Black, white & ash	Brown
05	Type and shape of floor Skirting	No Skirting	No Skirting	No Skirting	No skirting	Tiles skirting
Multi-Bed Ward Wall						
01	Wall type	Normal flat Masonry wall	Normal flat Masonry wall	Normal flat Masonry wall	Normal flat Masonry wall	Normal flat Masonry wall
02	Walling Material	Hollow Concrete Block wall	Hollow Concrete Block wall	Hollow Concrete Block wall	Hollow Concrete Block wall	Plastered Red brick walls
03	Wall shape and form	Flat vertical	Flat vertical	Flat vertical	Flat vertical	Flat vertical
04	Type and colour of paint	Milk colour emulsion	Milk colour emulsion	Upper (yellow emulsion) & lower (Ash Rubber)	1/3 (upper) milk colour emulsion & 2/3 (bottom) dark milk colour rubber paint	1/3 (upper) milk colour emulsion & 2/3 (bottom) green colour rubber paint

5.2.6 The Ventilation Parameters of the Studied Multi-bed Wards

The ventilation system in the selected multi-bed hospital wards is hybrid combining natural ventilation through window and mechanical ventilation through fans and air condition systems. The windows are casement and sliding windows with insect screen netting and steel burglary proof bars. Natural ventilation from windows is supported by ceiling and wall fans, apart from FNPHM which is a ward for psychiatric disease and is supported by split system air conditioning units. The characteristics of these ventilation systems have been shown in table 5-8.

Table 5-8: Multi-Bed Ward Ventilation Parameters

S/N	Multi-Bed Ward Ventilation	Name				
		UMTH	**SSHM**	**FNPHM**	**USUHM**	**NHHM**
01	Mechanical Ventilation	Fan	Fan	Window AC and Fans	Fan	Fan
02	Natural Ventilation	Windows	Windows	Window	Window	Window
03	Hybrid Ventilation	Fans and windows	Fans and windows	Window AC, Fans and windows	Fans and windows	Fans and windows
04	Ceiling Fans	24	2	10 ceiling and 10 wall mounted fans	15 ceiling fans	1
	Air-conditioning	-	-	6 window AC units	-	-

5.3 Environmental Properties of the Existing Hospital Wards

According to the ASHRAE Handbook of Fundamentals (ASHRAE, 2011), patients room should have minimum Air Change Rate (ACR) of 6 ach^{-1}. The maximum relative humidity of 60% and design temperature of 21^{o}C to 24^{o}C has been recommended. The indoor and outdoor temperature and relative humidity of the five hospitals wards in the study area has been measured between 27th April 2012 and 19th May 2012. The date and time of these measurements are dependent on the availability of access from the management of these hospitals. The results indicated that the indoor temperature of the five wards measured is above the calculated neutrality temperature of 24.2^{o}C to 29.2^{o}C as shown in table 5-9. The temperatures indoors were slightly cooler than outdoors by a variation range between 1^{o}C to 5^{o}C as illustrated in figure 5.6. However, all the relative humidity measurements are within the ASHRAE (2011) acceptable limit of less than 60% as illustrated in table 5-9.

Table 5-9: Randomly Measured Temperature and Relative Humidity of Hospitals wards in Maiduguri

S/N	*Space Identity*		*Temperature*		*Relative Humidity*		*Measurement Time*	
	Hospital	***Ward***	***Indoor***	***Outdoor***	***Indoor***	***Outdoor***	***Date***	***Time***
1.	UMTH	Occupied	35.0°C	-	30%	-	3/5/2012	12:55pm
2.	UMTH	Occupied	35.6°C	-	28%	-	3/5/2012	12:34pm
3.	UMTH	Occupied	35.4°C	-	30%	-	3/5/2012	12:22pm
4.	UMTH	Empty	35.6°C	36.9°C	32%	27%	5/5/2012	10:20am
5.	UMTH	Empty	36.4°C	39.4°C	30%	28%	6/5/2012	10.40am
6.	UMTH	Empty	36.0°C	36.6°C	30%	28%	6/5/2012	11:15am
7.	SSHM	Empty	36.3°C	37.6°C	12%	11%	27/4/2012	10:10am
8.	SSHM	Empty	36.0°C	38.8°C	10%	8%	27/4/2012	10:30am
9.	SSHM	Occupied	37.4°C	-	11%	-	27/4/2012	11:12am
10.	FNPHM	Empty	34.0°C	39.0°C	26%	17%	28/4/2012	10:50am
11.	FNPHM	Empty	32.5°C	-	27%	-	28/4/2012	11:03am
12.	USUHM	Empty	36.6°C	41.8°C	22%	13%	19/4/2012	11:26am
13.	USUHM	Empty	36.7°C	-	19%	-	19/4/2012	11:46am
14.	NHHM	Empty	34.1°C	34.7°C	30%	28%	19/5/2012	11:50am
15.	NHHM	Empty	36.3°C	37.6°C	30%	30%	9/5/2012	10:08am
16.	NHHM	Empty	35.4°C	39.6°C	32%	25%	9/5/2012	10:50am
17.	NHHM	Empty	33.8°C	35.0°C	35%	33%	14/5/2012	12:15pm
18.	NHHM	Empty	36.0°C	36.6°C	33%	30%	17/5/2012	10:30am
19.	NHHM	Empty	35.0°C	39.4°C	34%	26%	17/5/2012	11:00am

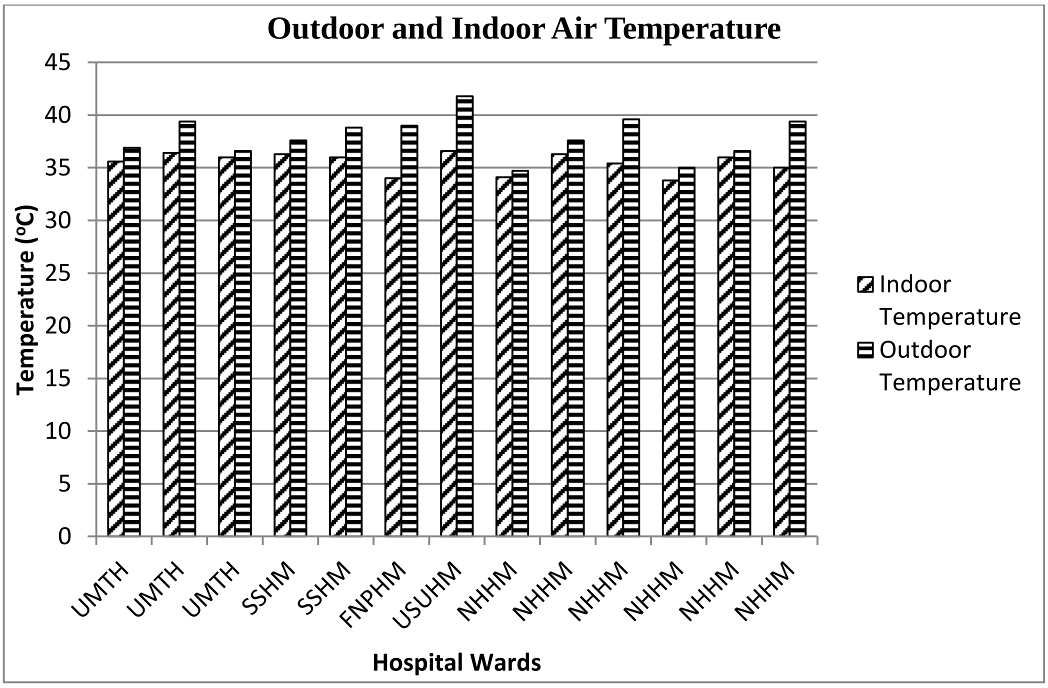


Figure 5.6: The Difference between Measured Indoor and Outdoor Temperatures

5.4 Questionnaire Survey Result Analysis

5.4.1 Introduction

The survey method used in this research is cross-sectional survey in which the data or responses were collected at one point in time (Creswell, 2003). This type of survey usually involves more than one case and data obtained are quantifiable (Bryman, 2012). The form of data collection employed is self-administered questionnaire, in which the questionnaire was handed physically to the potential respondents. The self-administered questionnaire survey has been discussed in detailed in section 4.3.1. This form of data collection was chosen for convenience, because in this study area, there is no constant access to internet and mail, as such physical delivery is the only practical way of administering questionnaires. Moreover, since the questionnaire is targeted toward particular set of healthcare workers that frequently work in multi-bed wards, a convenience or non-probabilistic sampling was used in this research. In this type of sampling, respondents are usually selected based on their availability and convenience (Creswell, 2003).

The survey was conducted within five different hospitals in the study area. The respondents who are medical doctors, nurses and other healthcare workers, who were selected based on whether they worked in multi bed ward or not. Thus the questionnaire was given to only those respondents that frequently work in the multi bed wards within the studied hospitals. The major objective of the questionnaire is to understand indoor air quality and ventilation within multi bed hospitals from perceptions of the immediate users of the facility. The responses from patients were not collected due to the fact that their health condition might influence their perception on air quality and thermal comfort.

The total number of healthcare workers (HCW) in the five selected hospitals is 131 and the number of HCW in the individual hospitals is presented in table 5-10. The total number of questionnaire administered was 120 and total of 95 people responded and the responses from individual hospitals are illustrated in table 5-10. Thus, the average total response rate for the five hospitals is 79% while the response rates for the individual hospitals are presented in table 5-10.

Table 5-10: The Questionnaire response rates

Parameters	UMTH	SSHM	NHHM	USUHM	FNPHM	Total
Number of HCW the hospitals	47	29	24	17	14	131
Number of administered questionnaire	45	26	22	15	12	120
Number of responses	38	21	16	11	9	95
Response rates	84%	81%	73%	73%	75%	79%

The first step in the questionnaire design is the identification of the topics that will be covered by the survey. These topics were deduced from the 'study area' and 'literature review' chapters including indoor air quality, ventilation, thermal comfort, Harmattan dust and Mosquitoes, which are the major factors of consideration when designing hospital wards in the study area.

The second step in designing questionnaire is the choice of open-ended or closed ended questions. In this study both open and closed ended questions have been used. The closed ended questions such as 'Yes or No' were used where there are precise options to be selected by the respondents. However, opened-ended questions were employed where the required information does not require restriction. This is because dictating certain number of options will restrict the opinion of the respondents to the provided options only, while allowing the questions opened-ended will give greater opportunity to the respondents to express their view without any restriction. Finally, the questions were written using a simple and precise language for ease of understanding and comprehension by the respondents. The questionnaire survey results were analysed based on simple statistical techniques including frequency of occurrence and percentages and the results were presented using tables and graphs.

5.4.2 Indoor Air Quality (IAQ) Consideration

Indoor air quality is one of the major issues of consideration in design and subsequent utilization of any facility. The level of air quality in hospital environment has an influential effect on the concentration of pathogens in the air, and subsequently dictates the rate of airborne infectious diseases obtainable indoors (Ulrich et al. 2008). However, the importance of IAQ is higher in hospital buildings due to the presence of immunosuppressed and immunocompromised patient that will be easily infected by any communicable disease. These transferable diseases are transmitted in form of airborne droplets between patients, from patients to hospital staff or visitors and vice versa.

Medical doctors, nurses and other healthcare workers do consider indoor air quality in the cause of their day to day work in the hospital environment especially multi bed wards. When the medical doctors, nurses and other healthcare workers in the five hospitals surveyed were asked “Have you ever considered indoor air quality as a problem in the wards?” about 84% responded that they do consider indoor air quality and the remaining 16% said they don't consider IAQ as illustrated in table 5-11 and figure 5.7.

Table 5-11: Indoor Air Quality Problem Consideration in Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	27	9	75%	25%	36
2.	*State Specialist Hospital (SSH)*	18	3	86%	14%	21
3.	*Nursing Home Hospital (NHH)*	14	1	93%	7%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	11	0	100%	0%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	7	2	78%	22%	9
	Total Response	**77**	**15**	**84%**	**16%**	**92**

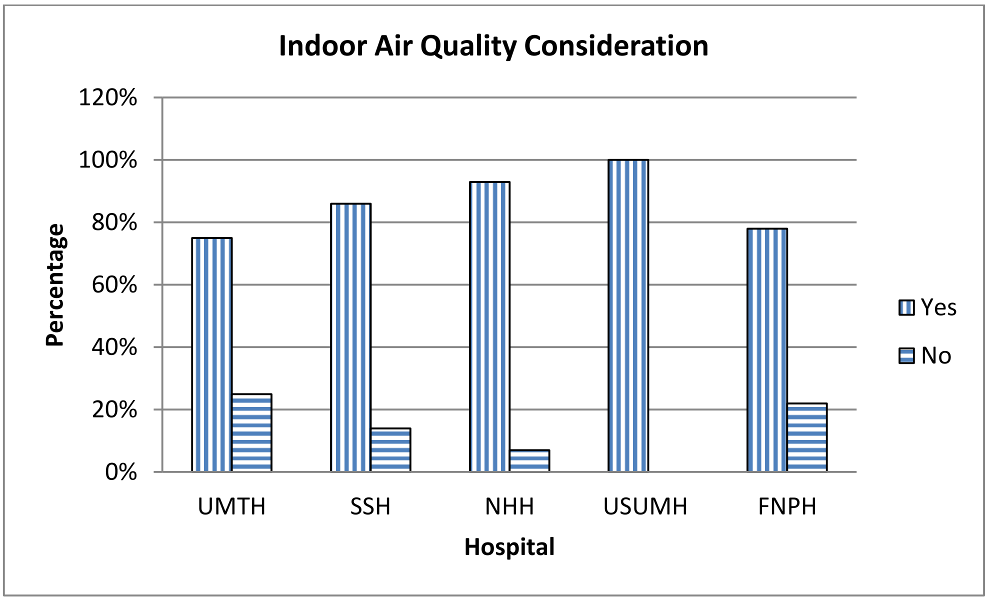


Figure 5.7: Indoor Air Quality Problem Consideration in Wards

The consideration of indoor air quality in hospital wards in semi-arid climates is as a result of so many factors as deduced from the outcome of the survey. Inadequate ventilation is the major factor leading to the consideration of IAQ in hospital wards, as it has the highest frequency of response as shown in table 5-12. The major consequences of these inadequacy in ventilation according to the survey includes; high temperature, stuffiness, discomfort, CO_2 concentration, which are mainly as a result of inadequate fans, lack of enough doors and windows in the wards. The second prominent factor for IAQ consideration is congestion and overcrowd of patients and their relatives in the multi-bed wards due to shortage in space and compacted bed spacing. Congestion problems will be solved by adopting existing codes and standards in terms of the relationship between ward floor area and allowed number of beds. The third reason for indoor air quality consideration is odour, smell and stinking due to infected wounds, patients’ properties and toilets in the multi-bed wards. This constraint is likely caused by inadequate ventilation and will be solved by optimizing the ventilation system by increasing the amount of air change per hour. The fourth likely motivator for indoor air quality consideration among medical doctors, nurses and other healthcare workers is the fear for the spread of pathogens in form of airborne disease or respiratory droplets and Healthcare Associated Infections (HCAI) within the multi-bed wards. This problem will be solved by providing enough ventilation in the multi-bed wards. The fifth reason for IAQ consideration in hospital wards is its effect on patients' health especially respiratory conditions such as Asthma, hypodermic consequences, heat stroke and delay healing. The last motive for IAQ consideration according to the survey outcome is lack of stable electricity in the study area, which leads to reliance on natural means for ventilation and IAQ control. Therefore, owing to the energy shortage to adopt mechanical systems for ventilation and IAQ treatment, there is a need to look into the potentials of using natural means to solve ventilation and indoor air quality problems in the hospitals wards of the study area. Table 5-12 shows the frequency of response about the reasons for indoor air quality consideration in the study area Maiduguri.

Table 5-12: Frequency of responses for Reason IAQ Considerations in different Hospitals in Maiduguri

S/N		Frequency of responses in different Hospitals					
	Reasons for IAQ Consideration	UMTH	SSHM	NHHM	USUMH	FNPH	Total
1.	Inadequate Ventilation (High temperature, stuffiness, discomfort, CO2 Concentration, Inadequate Fans, Lack of enough Doors & Windows)	14	15	4	8	2	42
2.	Congestion and overcrowding e.g. Inadequate bed spacing	2	9	5	-	-	16
3.	Odour/smell/ Stinking due to infected wounds, patient properties, toilets	10	1	-	1	1	13
4.	Spread of pathogens in form of airborne disease or respiratory droplets and HCAI	6	1	5	-	-	12
5.	Affects patients health especially respiratory conditions e.g. Asthma, Hypothermic consequences, Heat stroke, Delay healing	5	-	1	3	-	9
6.	Lack of stable electricity	2	-	3	1	1	7

5.4.2.1 Experience of Smell and Odour in the Wards

Smell or odour in a shared environment like that of multi beds hospital wards is usually as a result of many factors. Moreover, one of the major factors that will aggravate the smelly situation is insufficient ventilation in these wards. When there is insufficient airflow to remove contaminants in an indoor space, then these contaminants will remain indoors and create unpleasant air quality. When the respondents were asked "Do you usually experience some smell or odour in the wards?" about 97% said they do usually experience some smells or odour in the hospital wards and the remaining 3% said they don't as shown in table 5-13 and figure 5-8.

Table 5-13: Experience of Smell and Odour in the Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	36	2	95%	5%	38
2.	*State Specialist Hospital (SSH)*	21	0	100%	0%	21
3.	*Nursing Home Hospital (NHH)*	15	0	100%	0%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	11	0	100%	0%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	8	1	89%	11%	9
	Total Response	**91**	**3**	**97%**	**3%**	**94**

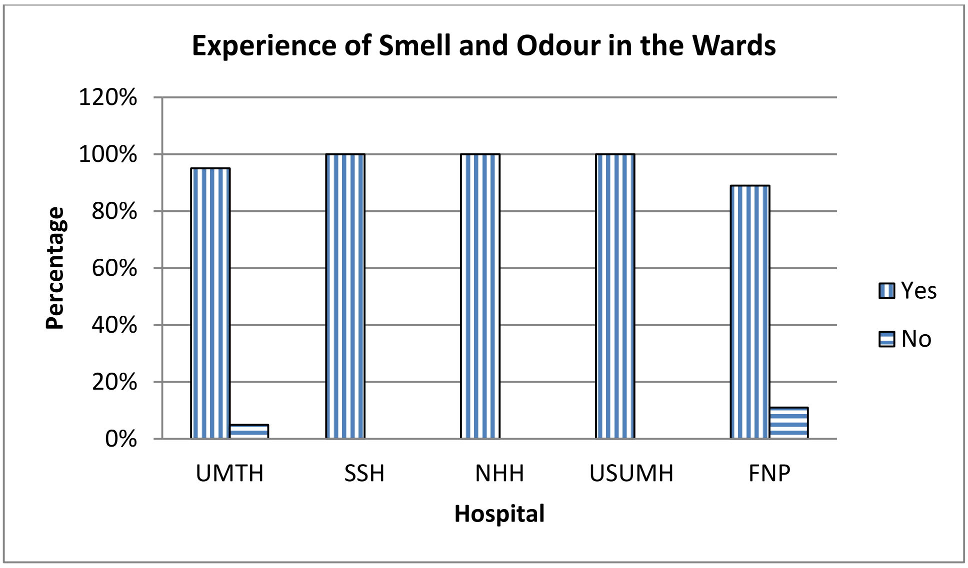


Figure 5.8: Experience of Smell and Odour in the Wards

Generally, smell and odours in hospital environment and especially multi-bed wards is as a result of many reasons either from the building fabric, patient body, disinfectants or inadequate ventilations. Patient wounds including infected wounds, septic wounds, offensive wounds, burns, traumas, cancers, depilating ailments, ulcers and bedsores remains the major source of smell and odour in the studied hospital wards. According to the survey, poor sanitation in and around the ward premises constitute another source of odour in the hospital wards. These odours usually emanate from poor drainage and soak away systems, lack of enough manpower and cleaning materials and accumulated patient properties indoors due to lack of enough storage. Apart from the accumulated patients' properties, dustbins, disposed waste and food remnant in the wards also constitutes another source of odour. Moreover, smell from dirty toilets and odour from various chemicals used in the wards contributes immensely to the contamination of indoor air in the wards. These chemicals are usually used in the wards as disinfectants, antiseptic, medications and for dressing wounds. However, apart from odours and smells, human waste from patients' body, secretions, spilling of bloods and blood products, and other body fluids also contributes to the smell and odour in the hospital multi- bed wards. The above mentioned problems are further aggravated by the congestion and overcrowd in the multi-bed wards resulting in compacted patients bed spacing and increased pressure on already inadequate resources in these wards. However, according to the survey, inadequate ventilation and stuffiness due to poor ventilation systems and inadequate openings in these spaces have further worsened the indoor air quality complications. Therefore, adequate ventilation system should be provided to remove all the odorous substances in the indoor environment. Table 5-14 shows various factors responsible for the smell/odour in the five hospital wards studied.

Table 5-14: Reasons for Smell and Odours in the Hospital Multi-Bed Wards

S/N		Frequency of responses in different Hospitals					
	Reasons for Smell and Odours	UMTH	SSH	NHH	USUMH	FNPH	Total
1.	Toilet Odour	7	5	2	1	1	16
2.	Wounds (Infected, septic, offensive, Burns, traumas, cancers, Infected operations, orthopaedic cases, Debilitating ailments, Ulcers and Bedsores)	20	3	4	1	-	28
3.	Chemicals (Disinfectants, Antiseptic, Medications	8	8	-	-	-	16
4.	Dustbins/disposed waste /Food Remnants	4	-	2	1	1	8
5.	Congestion and Overcrowd (Patient bed spacing)	5	-	1	-	1	7
6.	Stuffiness or inadequate ventilation (e.g. due to poor ventilation, inadequate openings)	3	2	2	5	1	13
7.	Poor Sanitation in and around the wards (Lack of manpower, cleaning materials, drainage and soak way, Patients properties due to lack of enough bedside storage)	3	12	10	1	1	27
8.	Human Waste (Patient body, secretions, Spilling of bloods, blood products, body fluids)	3	-	-	4	3	10
9.	When some medical procedures are done (e.g. Incision and Drainage of abscess)	1	-	-	-	-	1

5.4.2.2 Indoor Air Contaminants Sources within and around Wards

Airborne pathogens in healthcare environments originate from diverse sources mainly originating from the staff, patients and visitors within the hospital building (Ulrich *et al.* 2008). These sources are usually the product of those factors that are responsible for the pollution of indoor air in hospital wards including human sources, medications, cleaning agents, furniture, supporting facilities such as toilets and the surrounding environment. Some of these contaminant sources like furniture can be removed and changed with better ones, while others will be solved by improving on the ventilation. When the respondents were asked "Do you recognize some indoor air contaminants sources within/around the wards?" about 89% said that they usually see some contaminants source within and around the hospital wards and the remaining 11% don't recognize any contaminant sources as illustrated in table 5-15 and figure 5-9.

Table 5-15: Availability of Contaminant Sources in the Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	31	5	86%	14%	36
2.	*State Specialist Hospital (SSH)*	18	1	95%	5%	19
3.	*Nursing Home Hospital (NHH)*	12	2	86%	14%	14
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	10	1	91%	9%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	8	1	89%	11%	9
	Total Response	**79**	**10**	**89%**	**11%**	**89**

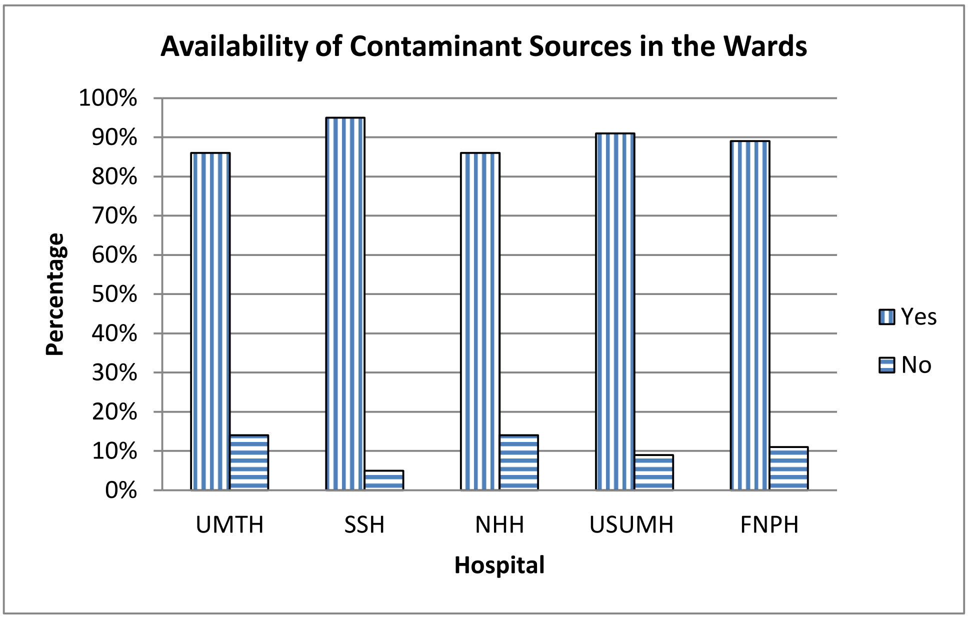


Figure 5.9: Availability of Contaminant Sources in the Wards

According to Ulrich *et al.* (2008) the common sources for outbreak of airborne infections in an environment is due to numerous environmental aspects and conditions including breakdown or contamination of ventilation sources and absence of proper cleaning and maintenance. Based on the result of the survey, various contaminants sources obtainable within and around hospital wards are responsible for the contamination of the multi-ward hospital wards. Major among these sources are environment related factors including toilets, pollutants in the surrounding environment and waste disposal areas such as dustbins and incinerators when unemptied. The patients and staff attitude of disposing waste improperly within and around the wards, poor sewages, soakaways and drainage systems and patient food remnants are among the key contaminant around hospital wards in the study area. Furthermore, apart from the environmental related factors; there are also patient related issues including contaminants associated with body wounds from dirty or undressed wounds, infectious and septic wounds, uncasing masses, and soiled linen.

Direct body smells especially from patients and human waste such as bloods, body fluids, un-emptied blood cloths and secretions also remain some of the major sources of indoor air contaminants. The smell and odour from patients bed sides, mainly due to lack of enough storage within the hospital wards also contributes to the contamination of the indoor environment. The application of chemicals (disinfectants) such as Halothane and Nitrous Oxide are also responsible for changing the natural odour in hospital wards and do affects people that are allergic to such chemicals. However, inadequate ventilation in these wards spaces according to the survey has made the indoor air problem even worse and hence many respondents have suggested that doors and windows should be open to allow fresh air into the building. But the opening of these doors and windows will also lead to the penetration of various unwanted substances such as Harmattan dust and mosquitoes. Table 5-16 presents the various sources of contaminants in the five hospitals surveyed in the study area with their frequency of response.

Table 5-16: Sources of Contaminants in Hospital Multi-Bed Wards in the Study Area

S/N		Frequency of responses in different Hospitals					
	Sources of Contaminants	UMTH	SSHM	NHHM	USUMH	FNPH	Total
1.	Toilets	8	8	4	4	4	28
2.	Contaminants around the wards (Improper disposal of waste Within and Around the wards, poor sewage/drainage system, soak-away and Patients Foods remnants)	7	12	1	4	4	28
3.	Dustbins/Waste Bins/incinerators	16	2	6	3	-	27
4.	Wounds (Dirty/undressed, infectious, septic, Uncasing Masses, Soiled Linen)	8	1	3	2	-	14
5.	Direct body smells and Human waste such as Bloods/body fluids/Un-emptied blood cloths e.g. secretions	4	-	-	2	1	7
6.	Inadequate ventilation (Doors and windows should be open)	2	1	1	-	1	5
7.	Chemicals (Disinfectants) e.g. Halothane, Nitrous Oxide	2	1	1		-	4
8.	Patients bed sides, (properties due to lack of enough storage)	1	1	-	-	2	4

The respondents to the survey including medical doctors, healthcare workers and nurses were asked regarding their general view about the indoor air quality in multi-beds wards of the five selected hospitals. They expressed diverse views about the IAQ, which has been categorised into four different classes. The first group of opinions is about issues related to indoor air quality such as odour and smell, and stuffing and the effects of IAQ in spreading infections in the hospital multi-bed wards. The smell and odours are usually from patients' wounds, food leftovers, stools, patients' spaces and odours from disinfectants. According to the respondents poor IAQ in the wards contributes in spreading infectious pathogens such as tuberculosis and causes inconvenience in breathing, which is detrimental to both patients and staff. Moreover, the respondents suggested that, patients with infectious diseases should be isolated to avoid cross infection in the multi-bed wards.

The second set of opinion expressed by the respondents relates to ventilation in the multi-bed wards. Ventilation in these wards according the survey was perceived as adequate in certain seasons and poor in others. This is due to the fact that in hot periods, thermal comfort is difficult to realize in the indoor spaces as they closely follow outdoor climatic trends which at times makes ventilation counterproductive by blowing hot air from the outside. However, in the cold season, thermal comfort in the indoor spaces was perceived as adequate, but the major problem is the effect of Harmattan dust which usually happens in the cold Harmattan season. Furthermore, lack of sufficient ventilation facilities such windows, fan, air-conditioning systems in these wards has been pointed as one of the major causes of indoor air quality problems. Though, the effects of installing insect screens on the amount of fresh air received in the wards have also been mentioned as one of the concerns. Therefore windows should be wide enough to provide the required ventilation when these screens have been used to prevent the infiltration of mosquitoes and Harmattan dust. Hence, cross ventilation should be encouraged to help dissipate odours and reduce risk of transmitting disease and at the same time window openings should have good orientation to enhance good ventilation, because according to the survey good ventilation hasten the cure of wound in patients.

The third group of respondents perceived inadequacy in infrastructures including congestion and overcrowds in the wards as a result of insufficiency in space and lack of stable electricity are the major contributors to IAQ problems. Many respondents have complains about the congested nature of the wards and suggested to reduce the congestion (overcrowding) especially by the patients relatives. Wards should be expanded to accommodate more patients and the bed capacity in the wards should be reduced and the bed spacing should be increased. The energy shortage in the study area has affected the level of ventilation (obtainable) in the hospital wards. Lack of reliable electricity supply has forced hospitals to rely on natural means of ventilations to improve indoor air quality in the multi-bed wards. Therefore, stable electricity should be provided or the natural ventilation systems should be optimized to improve air quality in the multi-wards.

The last sets of opinions about the indoor air quality in the multi-bed wards according to the outcome of the survey are issues related to cleaning and hygiene within and surrounding the multi-bed wards. The hospital surroundings should be kept clean and dustbins and other disposal areas should be provided and emptied to avoid odours and breeding of infectious pathogens and mosquitoes. Moreover, enough storage areas should be provided within the wards to store patient properties and help decongest the multi-bed wards. Ward toilets should be kept clean and hygienic. Because unclean toilets within the wards usually serves as breeding grounds for mosquitoes and contribute to the contamination of the indoor air quality by discharging odours. Table 5-17 shows the responses and suggestions of the interviewees about the indoor air quality in the investigated multi-bed wards.

Table 5-17: The Respondents Views about Indoor Air Quality in the Multi-Bed Wards in the Study Area

S/N		Frequency of responses in different Hospitals					
	Views about IAQ	UMTH	SSHM	NHHM	USUMH	FNPH	Total
1.	Unpleasant odour/smell (wounds, food leftovers, stools, patients spaces and odours from disinfectants)	3	4	-	-	-	7
2.	Poor IAQ contributes to the spread of infections like TB (isolation of infectious patients) and Cause Inconvenience in breathing and detrimental to both patients and staff	8	5	-	3	-	16
3.	The Ventilation and the indoor air quality are (IAQ is stuffing and the Ventilation allows dust)	7	1	3	-	-	11
4.	windows should be free from all the screens and have best orientation to enhance good ventilation (Wound must have good ventilation to cure)	3	4	4	1	-	12
5.	Encourage and improve cross ventilation as it helps dissipate odour and reduces risk of transmitting disease.	6	6	1	4	1	18
6.	Lack/provision of enough ventilation facilities fans, AC, and windows in the wards.	7	9	4	5	3	28
7.	The Ventilation and IAQ are Satisfactory in certain seasons	7		-	-	2	9
8.	Reduce congestion (Overcrowd) especially patients relatives and ward expansion is necessary (Reduce bed capacity and spacing to at least 2m apart).	4	15	6	-	1	26
9.	Stable electricity should be provided by the gov't to improve air quality.	2	3	3	4	2	14
10.	Provision of enough disposal and storage area	-	4	2	-	1	7
11.	The hospital surrounding should be kept clean and dustbins should be emptied to improve indoor air quality	4	3	3	3	-	13
12.	Ward toilets should be kept clean and hygienic	1	3	-	1	1	6

5.4.3 Dust problems in the Wards

The outdoor sources of indoor air contaminants could be the key contributors to indoor concentrations of some pollutants (Jones, 1999). The penetration of outside dust into the indoor environment in the buildings of semi-arid climates remains one of the major concerns that required special consideration when designing hospital wards. Dust particles are usually transported by the North-Easterly trade wind from the Sahara desert in the Harmattan season and also in the rainy season especially before rainfalls. These dusts are made of tiny particles that can find its way into the indoor spaces through any tiny opening in the buildings. The major entrances of these dusts remain the windows, doors and air-condition openings. The availability of dust particles within hospital wards has great consequences on the patients' health condition. According to the result of the survey conducted to ascertain the level of dust problem within the hospital wards in the study area, by asking the respondents "Do you normally experience dust problem in the wards?" about 97% have agreed they experience dust problems in the wards and the remaining 3% don't experience any dust problem as illustrated in table 5-18 and figure 5-10.

Table 5-18: Presence of Dust Problem in the Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	36	2	95%	5%	38
2.	*State Specialist Hospital (SSH)*	20	1	95%	5%	21
3.	*Nursing Home Hospital (NHH)*	15	0	100%	0%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	11	0	100%	0%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	9	0	100%	0%	9
	Total Response	**91**	**3**	**97%**	**3%**	**94**

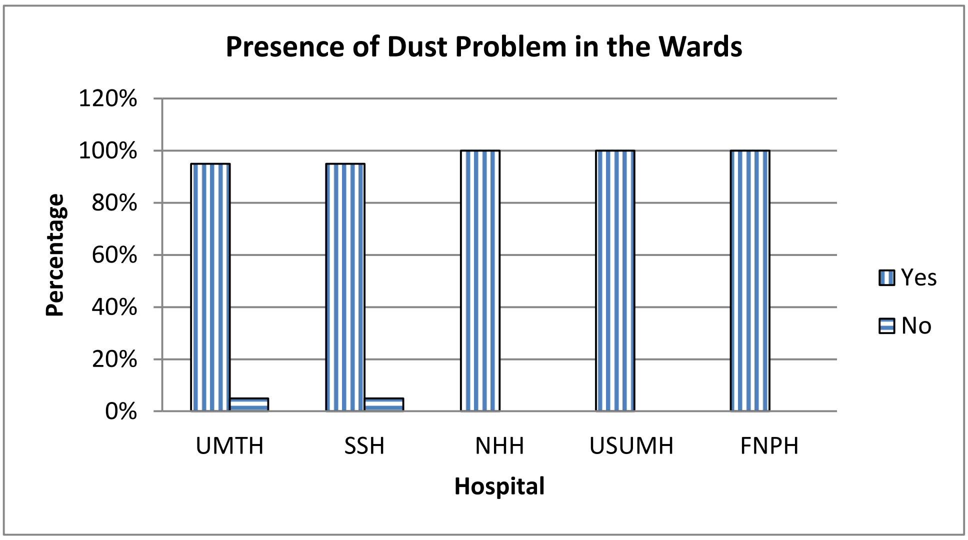


Figure 5.10: Presence of Dust Problem in the Wards

5.4.3.1 Sources of Dust in the Wards

Dust is one of the major indoor air pollutants in the semi-arid climates and it sources ranges from Harmattan dust, dust-storm to human activities that create dust like construction activities. The major entry points of dust in the multi-bed wards in the study area remains the openings including doors and windows. Apart from the outdoor sources of dust, there are indoor source including accumulation of dust on furniture and equipment and dust deposit on ceiling fans. These dusts are usually as a result of the climatic condition in the study area and inadequacy in vegetation cover.

When the respondents to the survey were asked “What are the possible sources of these dusts?” Table 5-19 presents the responses in order of frequency about the possible sources of dust in the hospital wards of the study area.

Table 5-19: Possible Sources of Dust in Hospital Multi-Bed Wards

S/N		Frequency of responses in different Hospitals					
	Sources of Dust in Wards	UMTH	SSHM	NHHM	USUMH	FNPH	Total
1.	Windows	15	8	4	4	2	33
2.	Sandstorm/wind (Wind from Desert encroachment, from Sahara, Rainy season Dust, Erosion, dry season dust, NE trade wind)	8	6	6	3	5	28
3.	Dust during sanitation and Surrounding environments (Sandy areas around the wards, Erosion, On floors)	8	7	3	1	1	20
4.	Doors	3	6	2	4	1	16
5.	Harmattan dust	7	4	1	2	1	15
6.	Nature of Weather and Inadequate vegetation cover in the area	4	1	-	1	1	7
7.	Furniture and equipment (Dust deposit on ceiling fans)	1	-	2	-	-	3

Some respondents have suggested on ways of reducing the penetration of dust into the wards spaces and managing the dust particles that are already indoors. Openings including doors and windows should be closed to avoid penetration of dusty wind especially when there is electricity and the mechanical ventilation systems are working. However, if there is no electricity it is extremely difficult to close the opening due to the fact that natural ventilation is the only source of ventilation at that time to manage the indoor air quality in the wards. The planting of vegetation in the wards’ surrounding environment is important because, vegetation does absorb and stop dust from penetrating into the wards. Moreover, the application of insect screen nets with lower porosity and heavy curtains to the openings also reduces the penetration of dust particles but at the same time decreases the amount of natural ventilation received in the wards. Therefore, alternative ventilation facilities such as fan and air-condition should be provided to be used especially in the dusty seasons. The alternative means of ventilation requires electricity for their operation and there is a huge shortage in electricity in the study area. The interior dust particles on the floors and the furniture should be cleaned especially by using damp dusting methods.

5.4.3.2 Noticeable Dust Particles

When the respondents were asked "Are their noticeable dust particles on the floor, furniture etc.?" about 87% agreed that there are some noticeable dust particles while the remaining 13% said they didn't see any dust particles on the floors and furniture as illustrated in table 5-20 and figure 5-11.

Table 5-20: Noticeable Dust Particles in the Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	27	11	71%	29%	38
2.	*State Specialist Hospital (SSH)*	20	1	95%	5%	21
3.	*Nursing Home Hospital (NHH)*	15	0	100%	0%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	11	0	100%	0%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	9	0	100%	0%	9
	Total Response	**82**	**12**	**87%**	**13%**	**94**

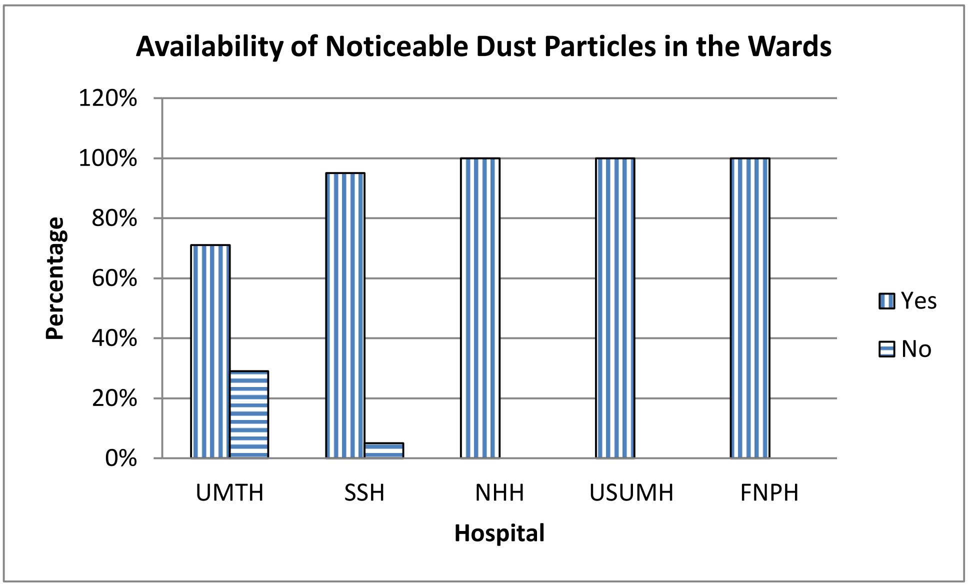


Figure 5.11: Noticeable Dust Particles in the Wards

5.4.3.3 Seasonality of the Dust Problem

When the respondent to the survey conducted to ascertain the seasonality or otherwise of dust in hospital multi be wards were asked "Is the dust problem worst in certain season?" about 94% of the respondents said dust problem is worst in certain season while the remaining 6% said it is not as illustrated in table 5-21 and figure 5-12. Dust has anonymously been recognised as a problem. Respondents related the increase in dust levels seasonally to the Harmattan storms.

Table 5-21: Seasonality of Dust Problem in the Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	34	4	89%	11%	38
2.	*State Specialist Hospital (SSH)*	19	1	95%	5%	20
3.	*Nursing Home Hospital (NHH)*	15	0	100%	0%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	11	0	100%	0%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	8	1	89%	11%	9
	Total Response	**87**	**6**	**94%**	**6%**	**93**

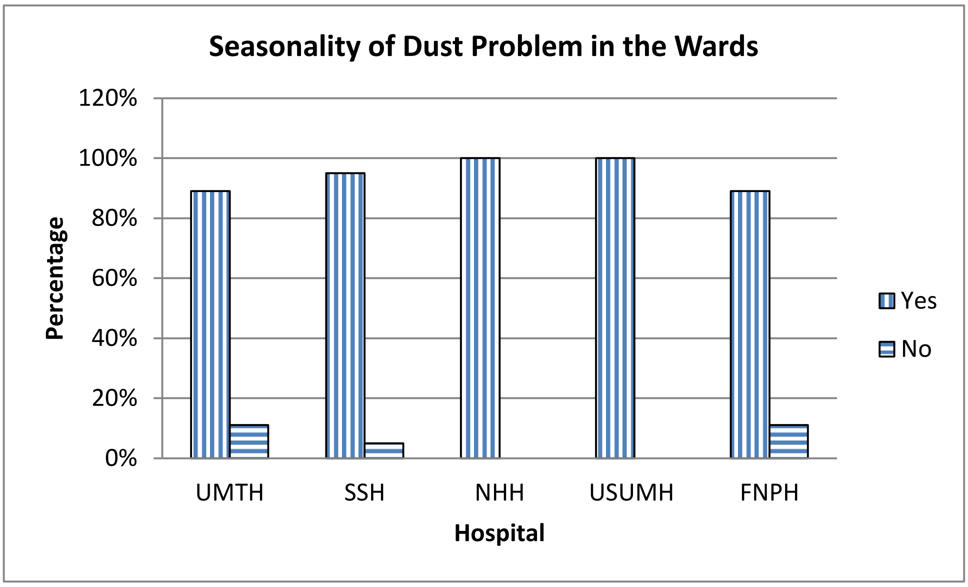


Figure 5.12: Seasonality of Dust Problem in the Wards

The problem of dust in the study areas is seasonal and some seasons are worse that the others. When the respondents to the survey to ascertain which season is worst among the three season of dry, wet and Harmattan. These respondents were asked if they have agreed the problem is seasonal "If yes which season?" about 73% said Harmattan season is the worst dust season, 22% said dry season is the worst and the remaining 5% said wet season is the worst as illustrated in table 5-22 and figure 5-13, while few respondents thick more than one season.

Table 5-22: Season with Highest Dust problem

s/n	Hospitals	Frequency			Percentage			Total Frequency
		Dry	Wet	Harmattan	Dry	Wet	Harmattan	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	8	3	29	20%	8%	72%	40
2.	*State Specialist Hospital (SSH)*	8	0	15	35%	0%	65%	23
3.	*Nursing Home Hospital (NHH)*	1	1	13	7%	7%	86%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	5	1	11	29%	6%	65%	17
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	1	0	7	12%	0%	88%	8
	Total Response	**23**	**5**	**75**	**22%**	**5%**	**73%**	**103**

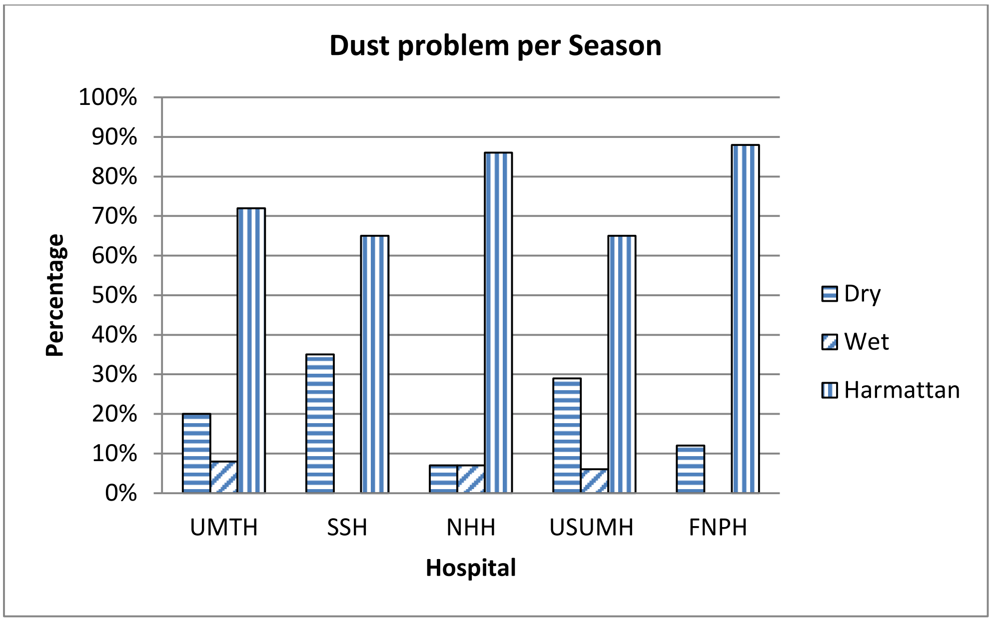


Figure 5.13: Season with Highest Dust problem

The dust problem is worst in the Harmattan season because, the season has the highest outdoor dust concentration throughout the year. Thus, indoor dust particle concentration increases with growing outdoor dust concentration. Since, the temperature in the Harmattan season is low, openings should be closed down to reduce dust particles concentration indoors.

5.4.4 Mosquito Problem in the Wards

Mosquitoes are an insect that causes Malaria fever especially in the tropical countries. Hence there prevention from entering into indoor spaces is essential especially in facilities such as hospitals. The effect of malaria on immunocompromised patients might be life threatening. The major constrains is how to provide acceptable indoor air quality through the optimization of natural ventilation strategies without allowing mosquitoes into the indoor spaces. When the respondents to the survey to ascertain the level of mosquito problem in the hospital wards were asked "Do you usually experience Mosquito problem in the wards?" 99% of the respondents said they experience mosquito problems in the multi bed wards of the study area, while the remaining 1% said they are not as shown in table 5-23 and Figure 5-14.

Table 5-23: Mosquito Problem in the Hospital Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	38	0	100%	0%	38
2.	*State Specialist Hospital (SSH)*	21	0	100%	0%	21
3.	*Nursing Home Hospital (NHH)*	15	0	100%	0%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	10	1	91%	9%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	9	0	100%	0%	9
	Total Response	**93**	**1**	**99%**	**1%**	**94**

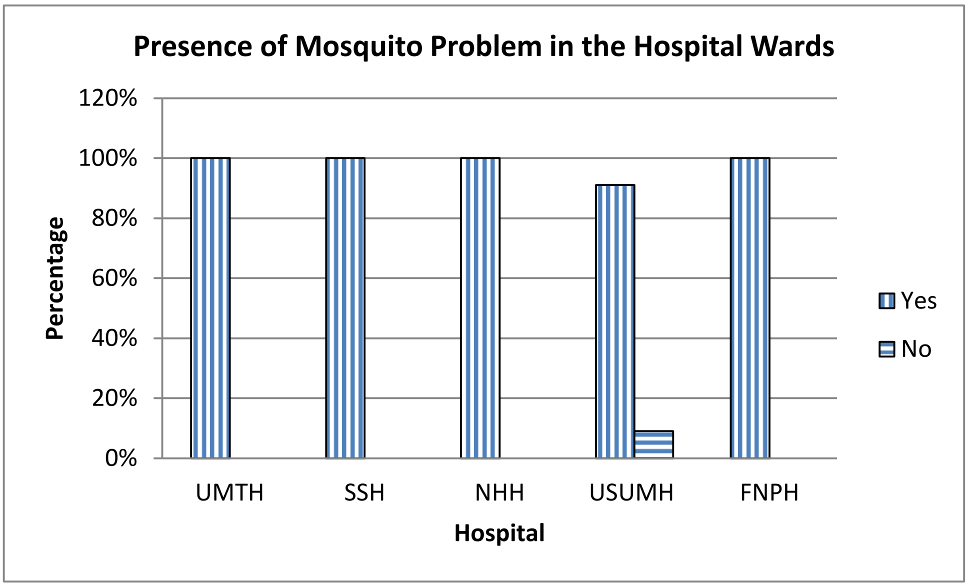


Figure 5.14: Mosquito Problem in the Hospital Wards

5.4.4.1 Sources of Mosquitoes in the Wards

The sources of mosquitoes are divided into indoors and outdoors sources. The outdoor sources of mosquitoes according to the survey outcome includes stagnant waters, poor drainages and gutters, vegetation cover such as grasses and flowers, refuse disposal centres. Mosquitoes can be stopped from entering from outside by netting the openings such as windows. But the problem is how to control the doors because people frequently go in and out which makes it easy for the mosquitoes to penetrate. In terms of indoor sources; dustbins, patient properties, toilets if not managed properly will serve as breeding ground for mosquitoes. The sources of mosquitoes indoors can be easily managed by removing the cause; however, the outdoor sources are difficult to manage. According to the survey, mosquitoes do normally enter through windows without insect screen or damaged insect screens and opened doors and rooftop openings, chambers and air-vents. Therefore, all opening should be properly treated to stop mosquitoes from getting access into the ward space. However, if netting is used, the total airflow should be measured to make sure that it has satisfied the required standards, as netting does reduce the amount of airflow in buildings. When the respondents to the survey conducted among medical doctors, nurses and other healthcare workers were asked “What are the possible sources of entrance of these mosquitoes?” their responses are summarized and illustrated in table 5-24.

Table 5-24: Sources of Entrances of Mosquito in the Multi-Bed Wards

S/N		Frequency of responses in different Hospitals					
	Sources of Entrances of Mosquito	UMTH	SSHM	NHHM	USUM H	FNPH	Total
1.	Windows(without Nets or scratched)	24	12	10	9	6	61
2.	Open doors (Due massive entrance and exits)	20	12	10	6	6	54
3.	Stagnant water outside/poor drainage/gutters	6	4	10	5	3	28
4.	Toilets	5	8	3	3	2	21
5.	Inappropriate disposal of refuse, nearby dustbins and patient properties	-	9	4	-	1	14
6.	Damage nettings/wire gauze	6	4	1	-	1	12
7.	Vegetation/flowers/grasses	2	3	-	-	-	5
8.	Open roof top/chambers and Air vents	2	-	1	-	-	3

The respondents to the survey have suggested various ways of preventing the entrance of mosquitoes to the multi-bed wards. These suggestions are useful in pinpointing the actual lapses that is leading to the penetration of mosquitoes to the indoor spaces. The first set of suggestions is related to openings operation and design. According to the respondents, doors and windows should be closed as much as possible without affecting occupants comfort and health. These doors and openings should also be protected with wire gauze or well fitted netting to prevent the penetration of mosquitoes. Moreover, the respondents have also suggested that, mosquito breeding grounds in the wards, toilets and surrounding environment should be removed and insecticides and fumigation should be applied periodically to avoid the multiplication of mosquito family in the indoor environment. Furthermore, patients should be enlightened on best practices that will prevent or repel mosquitoes in the multi-bed wards. The use of mosquito nets on individual patients’ beds has also been suggested by the respondents.

5.4.4.2 Seasonality of Mosquito Problem in the Case Study wards

When the respondent to the survey conducted to ascertain the seasonality or otherwise of the mosquito phenomenon in hospital multi-bed wards were asked “Is the mosquito problem worst in certain season?” about 96% of the respondents said mosquito problem is worst in certain season while the remaining 4% said it is not as illustrated in table 5-25 and figure 5-15.

Table 5-25: Seasonality of Mosquito Problem

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	34	3	92%	8%	37
2.	*State Specialist Hospital (SSH)*	20	0	100%	0%	20
3.	*Nursing Home Hospital (NHH)*	15	0	100%	0%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	10	0	100%	0%	10
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	8	1	89%	11%	9
	Total Response	**87**	**4**	**96%**	**4%**	**91**

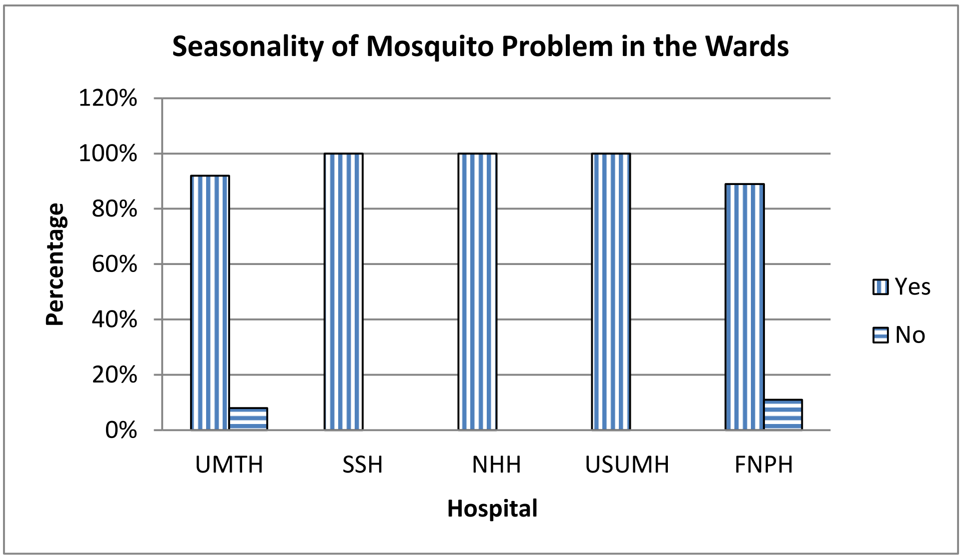


Figure 5.15: Seasonality of Mosquito Problem

Based on the outcome of the survey conducted to ascertain the extend of the mosquito problem per season, about 89% of the respondent said mosquito problem is worst in the wet season and the remaining 11% said it is worst in the dry season as shown in table 5-26 and figure 5-16. Mosquitoes usually breeds in wet environments such as stagnant waters, drainages, gutters, toilets, vegetation covers and refuse disposal sites. Its availability in an environment is largely dependent on the availability of its breeding grounds. Therefore, its consequences also follows the same pattern of worst in wet environment and even in dry seasons if they can get a breeding ground around, they can survive and multiply. That’s why few respondents have thick both dry and wet seasons.

Table 5-26: Extend of Mosquito Problem per Season

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Dry	Wet	Dry	Wet	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	5	29	15%	85%	34
2.	*State Specialist Hospital (SSH)*	2	19	10%	90%	21
3.	*Nursing Home Hospital (NHH)*	3	15	7%	83%	18
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	0	10	0%	100%	10
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	0	8	0%	100%	8
	Total Response	**10**	**81**	**11%**	**89%**	**91**

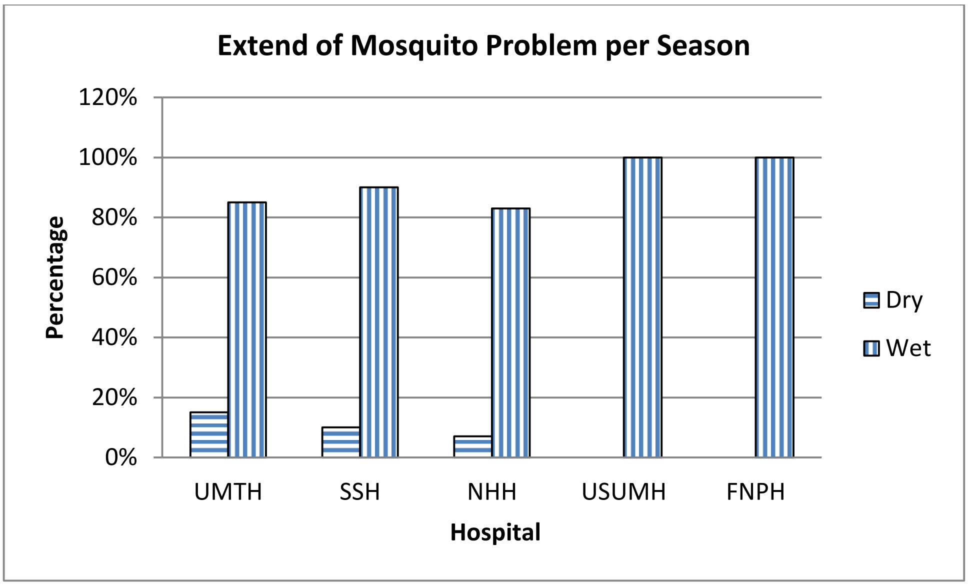


Figure 5.16: Extend of Mosquito Problem per Season

5.4.5 Thermal comfort in the Wards

The level of thermal comfort in indoor spaces in the study area has been an issue of concern due to the high temperatures as a result of direct solar radiation and the climatic context of Nigeria. In order to provide acceptable thermal comfort, temperature and relative humidity has to be regulated to meet the international standard requirement of less than 60% humidity and temperature range of 24.2 - 29.2^{o}C (the calculated neutrality temperature). When the multi-bed wards healthcare workers were asked about their satisfaction with the thermal comfort "Are you satisfied with thermal comfort (Temperature and Humidity) in the ward?" more than 70% of them were not satisfied with the level of thermal comfort in the studied hospital wards as shown in table 5-27 and figure 5-17. The result agrees with the physical measurement conducted in these hospitals wards which shows that, none of these wards have made the required temperature standards of 24.2 - 29.2^{o}C as shown in table 5.9.

Table 5-27: Thermal Comfort Satisfaction Level

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	11	26	30%	70%	37
2.	*State Specialist Hospital (SSH)*	7	13	35%	65%	20
3.	*Nursing Home Hospital (NHH)*	5	8	38%	62%	13
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	0	11	0%	100%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	3	5	38%	62%	8
	Total Response	**26**	**63**	**29%**	**71%**	**89**

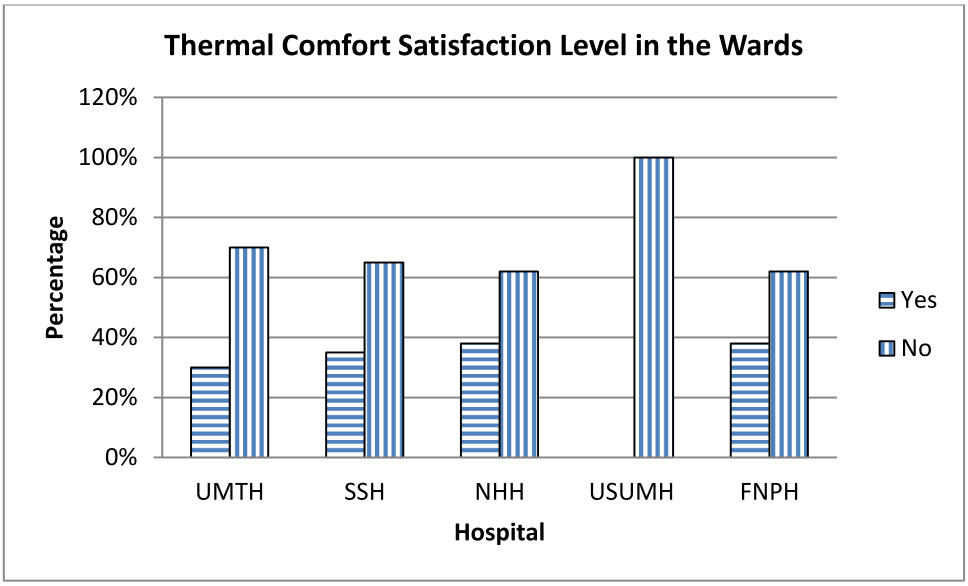


Figure 5.17: Thermal Comfort Satisfaction Level

5.4.5.1 Draughtiness

The intensity of draughtiness in any space is determined by the wind speed, temperature and humidity level. When the wind speed is high outdoors, it affects the amount of fresh air received indoors and at the same time changes the level of the temperature and relative humidity indoors. The level of draughtiness in the hospital wards of the study area depend largely on the season of the year. Draughtiest seasons usually occur in the months with high wind flow (March, April, May and June) in the study area. When the respondents were asked "Is the ward draughty?" 50% of them said they feel draughtiness in the multi-bed wards, while the other 50% said they are not, as illustrated in table 5-28 and figure 5-18.

Table 5-28: Draughtiness in the Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	12	15	44%	56%	27
2.	*State Specialist Hospital (SSH)*	13	6	68%	32%	19
3.	*Nursing Home Hospital (NHH)*	5	5	50%	50%	10
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	5	4	56%	44%	9
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	2	7	22%	78%	9
	Total Response	**37**	**37**	**50%**	**50%**	**74**

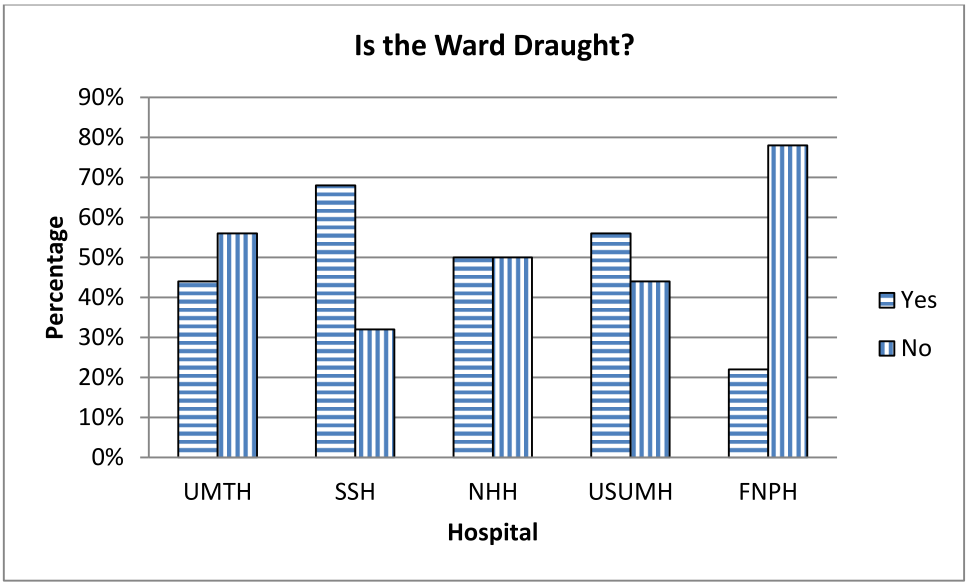


Figure 5.18: Draughtiness in the Wards

5.4.5.2 Humidity

Relative humidity is the quantity of water vapor obtainable in the air at any given time in an environment. ASHRAE Standard 62-2001 Ventilation for Acceptable Indoor Air Quality recommends that the lower and the upper boundaries of the relative humidity range in an interior space be limited to 25% and 60% respectively (Lstiburek, 2002). Moreover, according to the measurement conducted within some existing multi-bed wards in the study area, the relative humidity level range from 11% to 34.7% as illustrated in table 5-9. However, the outcome of the survey conducted to ascertain the perception of hospital ward users about the level of relative humidity, when the respondents were asked (Is the ward humid?). The result shows that, about 53% of the respondents said the wards are humid, while the other 47% said the wards are not humid as illustrated in table 5-29 and figure 5-19. Therefore, the result from the physical measurement have shown that the humidity level in the multi-bed wards is within the acceptable upper limit, but does not fulfil the lower limit requirement of up to 25%.

Table 5-29: Humidity in the Wards

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	14	18	44%	56%	32
2.	*State Specialist Hospital (SSH)*	13	6	68%	32%	19
3.	*Nursing Home Hospital (NHH)*	7	5	58%	42%	12
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	4	3	57%	43%	7
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	4	5	44%	56%	9
	Total Response	**42**	**37**	**53%**	**47%**	**79**

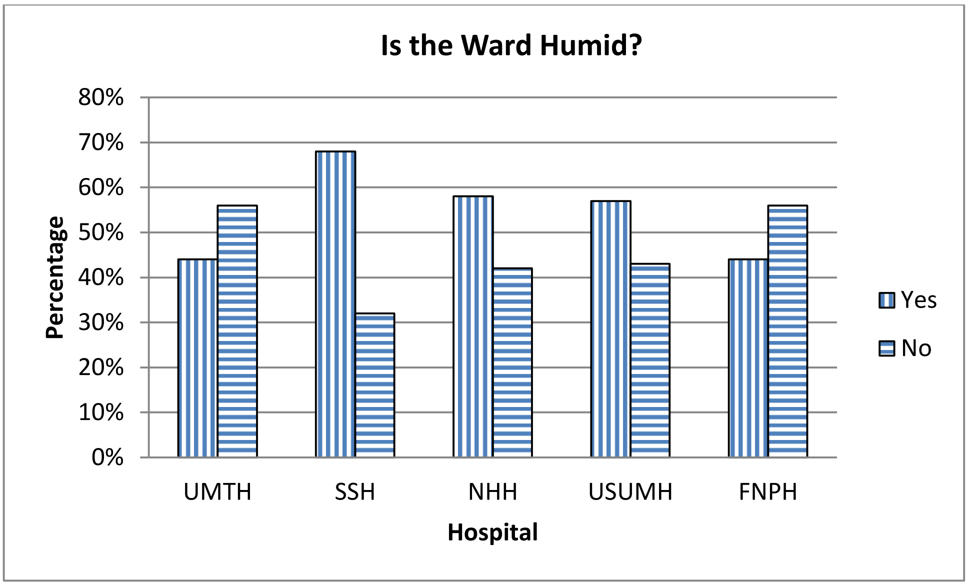


Figure 5.19: Humidity in the Wards

5.4.6 Ventilation in the Wards

Ventilation can be defined as a controlled movement or changing of air in an enclosed space (Naghman, et al. 2008). The ventilation system in the various multi-bed wards studied in the five hospital selected is hybrid, which is the combination of natural ventilation through the windows and the use of ceiling fans except in case of the Federal Neuro-Psychiatric Hospital where window type air-conditioning units has been used apart from the natural ventilation. But, the air conditioning units only operates when electricity is available or diesel generator is on and thus, natural ventilation is used most of the time. The mission of any effective ventilation system design in buildings is to; dilute the indoor air contaminants and concentration of carbon dioxide discharged by breathing, even distribution of air to ensure occupant's equal access to fresh air, and sustainability of air pressure balance between indoors and outdoors (Bas, 2003). When the respondent to the questionnaire survey conducted in the hospitals of the study area were asked "What is the nature of the airflow in the ward space?" about 62% said the airflow is fairly good, 21% said not so good, and the remaining 17% said the airflow in the wards is good, as shown in table 5-30 and figure 5-20.

Table 5-30: **Nature of the Airflow in the Wards**

s/n	Hospitals	Frequency			Percentage			Total Frequency
		Good	Fairly Good	Not so Good	Good	Fairly Good	Not so Good	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	10	20	7	27%	54%	19%	37
2.	*State Specialist Hospital (SSH)*	2	16	2	10%	80%	10%	20
3.	*Nursing Home Hospital (NHH)*	0	10	5	0%	67%	33%	15
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	2	4	5	18%	36%	46%	11
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	2	7	0	22%	78%	0%	9
	Total Response	**16**	**57**	**19**	**17%**	**62%**	**21%**	**92**

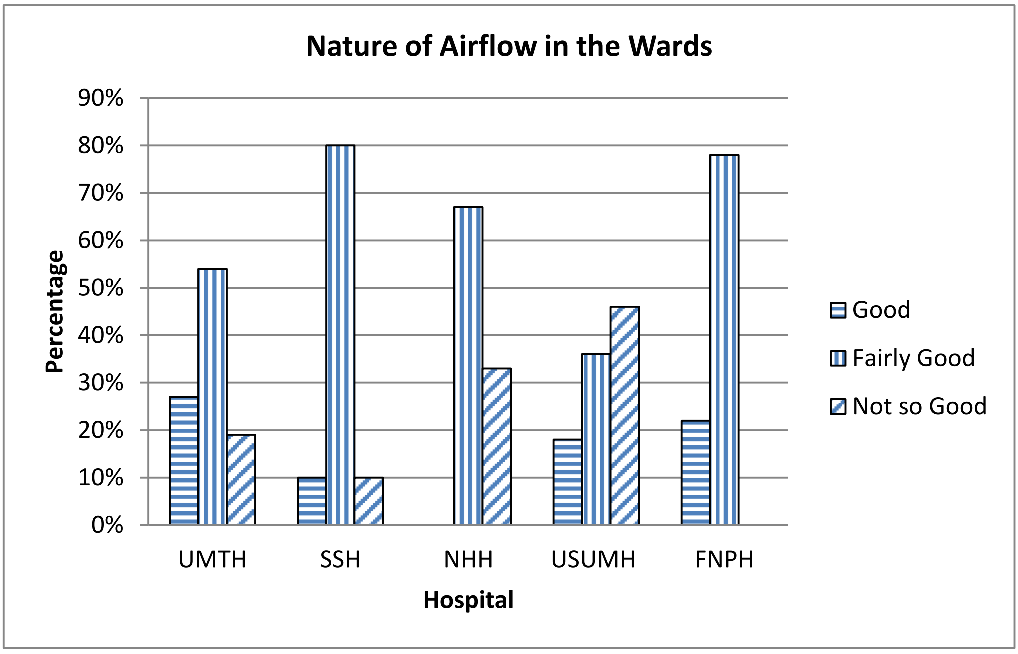


Figure 5.20: Nature of the Airflow in the Wards

5.4.7 Indoor Air Quality and Patients Health

The level of air pollution in an environment is associated with various health concerns. Various scientific studies have asserted that air contamination has great health consequences in the environment. According to the EEA (2011), air pollution is the major cause of damage to body organs such as respiratory system, cardiovascular system, nervous system, reproductive system and cause cancer. Weaker groups of people including older adults, children and people with pre-existing heart and lung diseases or diabetes, are the major casualties of air pollution-related health consequences (EEA, 2011). When the respondents to the survey including medical doctors, nurses and other healthcare workers were asked "Have you experienced any cases of deterioration in patient health due to indoor air quality problems in the wards?" about 43% responded that they have perceived a direct relationship between indoor air quality and deterioration in patients' health, while about 57% said they have not perceived such situation, as illustrated in table 5-31 and figure 5-21.

Table 5-31: Indoor Air Quality and Patient Health Deterioration

s/n	Hospitals	Frequency		Percentage		Total Frequency
		Yes	No	Yes	No	
1.	*University of Maiduguri Teaching Hospital (UMTH)*	10	24	29%	71%	34
2.	*State Specialist Hospital (SSH)*	5	11	31%	69%	16
3.	*Nursing Home Hospital (NHH)*	10	6	63%	37%	16
4.	*Umaru Shehu Ultra-Modern Hospital (USUMH)*	8	2	80%	20%	10
5.	*Federal Neuro-Psychiatric Hospital (FNPH)*	3	5	38%	62%	8
	Total Response	**36**	**48**	**43%**	**57%**	**84**

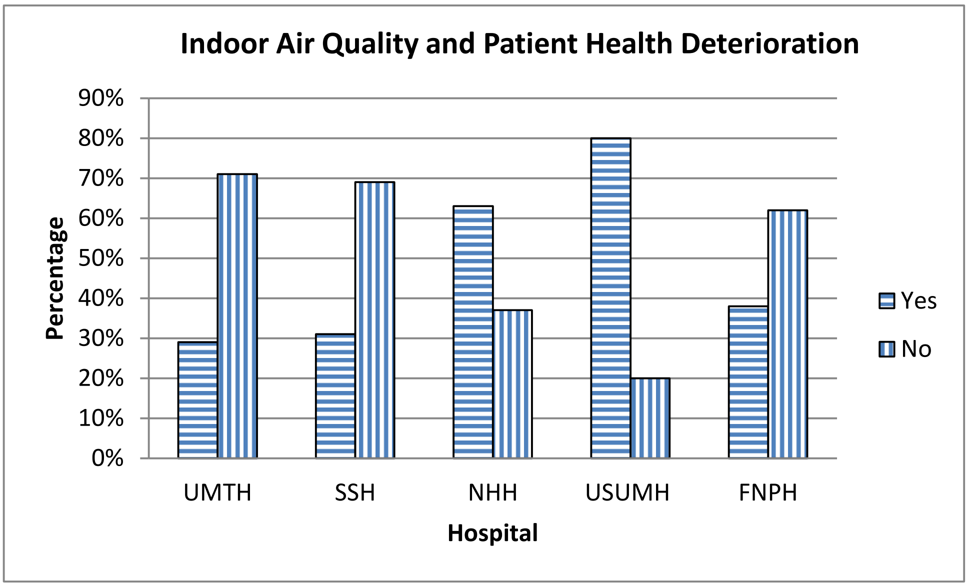


Figure 5.21: Indoor Air Quality and Patient Health Deterioration

5.5 Chapter Conclusion

This chapter presents the results of physical, environmental and social assessment of the existing hospital wards. The chapter also assessed and analysed the physical properties of the existing hospital wards and provides the required information to be used as an input in the subsequent part of this study. The chapter also presents the environmental parameters of the existing wards including temperature and relative humidity measurement in the existing hospital wards, to underpin subsequent assessment steps of natural ventilation in wards, including full-scale measurements and CFD modelling.

In order to confirm the indoor air quality and ventilation problems associated with the hospital wards from the immediate users of the facility, questionnaire survey has been conducted. The results of the survey show that, the respondents are not satisfied with the indoor air quality and ventilation in the wards. In terms of ventilation, only 17% of the respondents have well satisfied with the ventilation levels, while 97% of the respondents do usually experience odour/smell in the investigated hospital wards. Thus, the existing ventilation system needs to be optimised to provide the required ventilation rates and improve the indoor air quality.

However, the respondents have also confirmed the existence of dust and mosquito problems in the hospital wards. In terms of dust, about 97% of the respondents experience dust problem in the investigated wards, and the phenomenon increases seasonally with 73% of the respondents indicating that Harmattan season is the dustiest season. However, the results also indicate that, 99% of the respondents experience mosquito problems in the wards and they are more prevalent in the wet season compared to dry season. The study also established that poor indoor air quality is related to deterioration of patients' health in hospital wards. Thus, the outcome of this chapter has assisted in establishing and identifying the research problem and existing knowledge gap regarding indoor air quality and ventilation beyond the literature assertions.

Chapter Six

Measurement of Environmental Condition and Ventilation Rates Using Tracer Gas Techniques

Chapter Structure

6.1 Introduction

6.2 Measurement of Ventilation Rates using Tracer Gas Technique

6.3 Tracer Gas Measurement Procedures

6.4 Full-scale Measurement Results and Discussion

6.5 Section Conclusion

6 Chapter Six: Measurement of Environmental Condition and Ventilation Rates Using Tracer Gas Techniques

6.1 Introduction

In the previous chapter (chapter 5) results have confirmed the problems of indoor air quality in the hospital wards of the study area, based on social perception. The psychosocial perceptions are linked to a scientific methodology to relate ventilation rates to the wards design. Therefore, in the present study, full-scale ventilation measurements have been conducted using tracer gas techniques together with air temperature and relative humidity. The chapter (chapter 6) presents the results of the tracer gas techniques showing the air change rates, indoor air temperatures and relative humidity of the four (4) investigated hospital wards. Chapter 6 was intended as a response to objective number 3, which is *"To examine and analyse the performance of the existing ventilation strategies in relation to indoor air quality"*.

In this chapter, section 6.2 introduces the measurement of ventilation rates using tracer gas techniques, while section 6.3 of the chapter presents the measurement procedures. Finally section 6.4 presents the results analysis and discussion of the full-scale measurement including air change rates, temperature and relative humidity.

6.2 Measurement of Ventilation Rates using Tracer Gas Technique

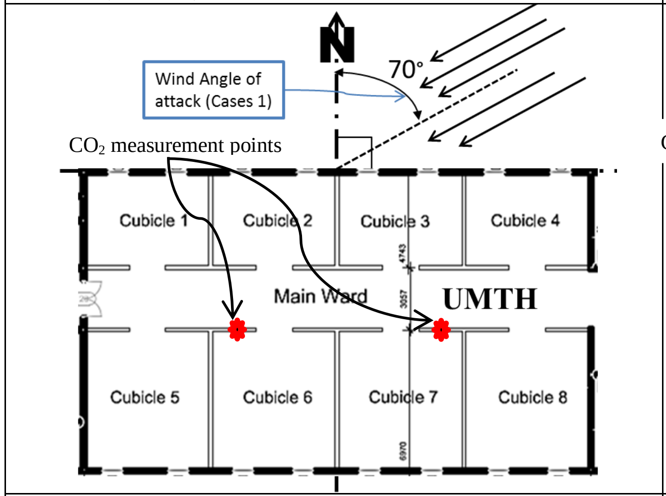
The total airflow rate including infiltration of outdoor air to building indoor space is mainly measured using tracer gas techniques. Tracer gas provides a direct method for measuring the total airflow rates in buildings. This is achieved by injecting a readily detectable tracer into the space/room and recording the history of its concentration (Etheridge and Sandberg 1996). The physical measurements of ventilation rates in existing hospital multi-bed wards of the study area (Maiduguri-Nigeria) were conducted to ascertain the actual ventilation rates obtainable in typical wards of the study area. The measurements were conducted in the months of November and December of 2012. The selection of these months is mainly due to accessibility, because patients need to be evacuated for tracer gas measurements to be carried out. Five different hospitals have been selected for the purpose of this study including University of Maiduguri Teaching Hospital (UMTH), Umaru Shehu Ultra-Modern Hospital Maiduguri (USUH), Federal Neuropsychiatric Hospital Maiduguri (FNPHM), Nursing Home Hospital Maiduguri (NHHM), and State Specialist Hospital Maiduguri (SSHM). But the measurements were conducted in only four hospital wards. The measurement in the fifth hospital ward (SSHM) was not conducted due to the unavailability of access at the time of the field work. This is because the measurements are required to be carried out in empty wards, meaning all patients need to be evacuated before any measurement is conducted. Hence, it was not possible to evacuate patients in the fifth hospital ward (SSHM) due to shortage in space in the hospital.

The assessment of airflow rate has been carried out in multi-bed wards within four (4) of the five hospital selected, including UMTH, USUH, FNPHM, and NHHM. The measured hospital wards with their respective prevailing wind directions or angle of attacks and positions of the CO_2 measurement devices are presented in table 6-1. Two CO2 detectors were used for a measurement and they are placed 0.8 to 1.0m above floor level. The interior view of the measured hospital wards describing the positions of fans, instruments and CO_2 bottles are shown in figure 6.1. Moreover, to assess other indoor air parameters in the selected hospital multi-bed wards, dry bulb indoor and outdoor temperature, indoor and outdoor relative humidity were measured, while the outdoor wind speed and direction data were obtained from the nearby meteorological station.

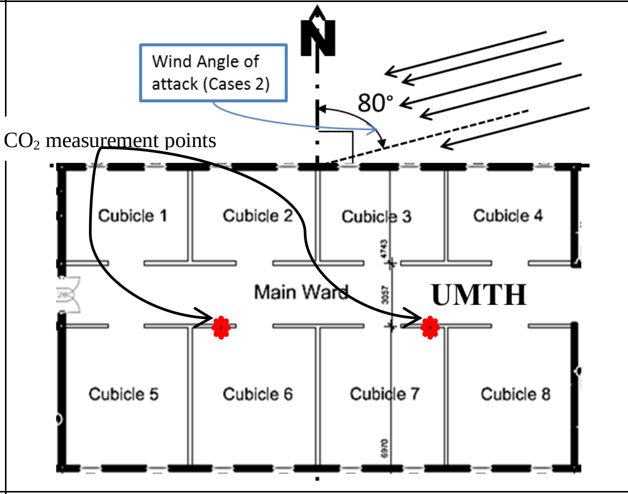
The CO_2 injection dates and time for all the measurements is presented in tables 6-4 and 6-5. The measurements periods are 30 minutes, 30 minutes, 30 minutes and 10 minutes for UMTH, USUHM, FNPHM and NHHM respectively. The measurement procedures for the above mentioned parameters are presented in sections 6.3.4 to 6.3.9.

Table 6-1: The measured hospital wards and their prevailing wind directions (angel of attack)

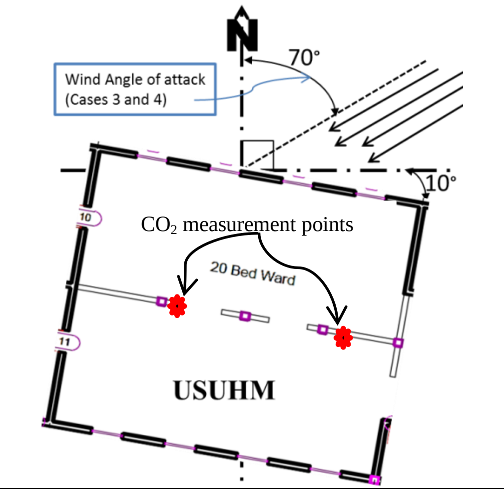
Case 1 (UMTH)



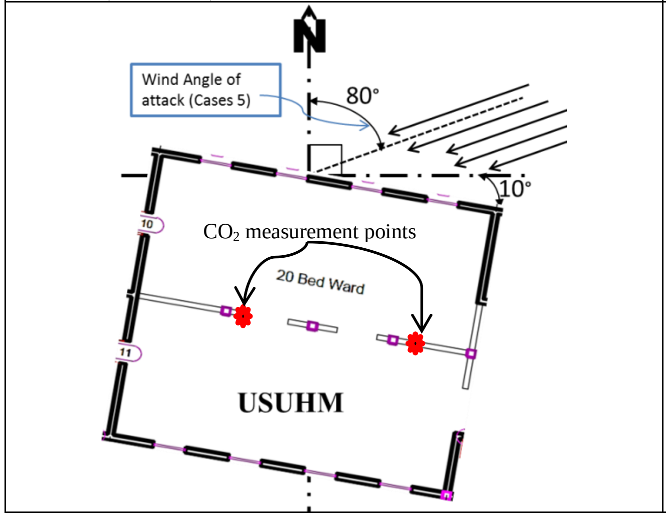
Case 2 (UMTH)



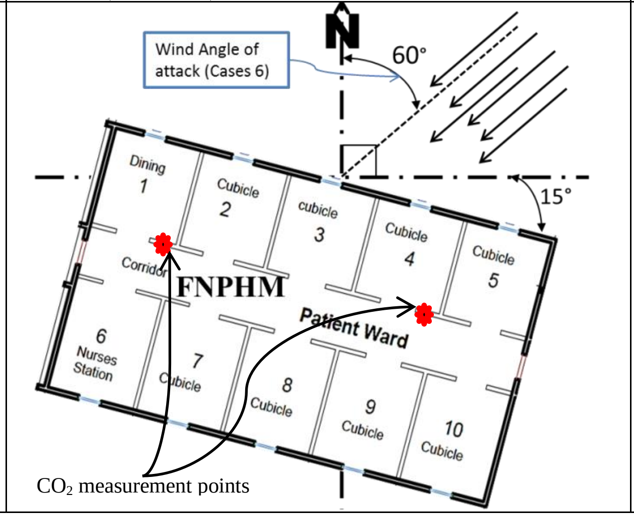
Case 3 and 4 (USUHM)



Case 5 (USUHM)



Case 6 (FNPHM)



Case 7,8 and 9 (NHHM)

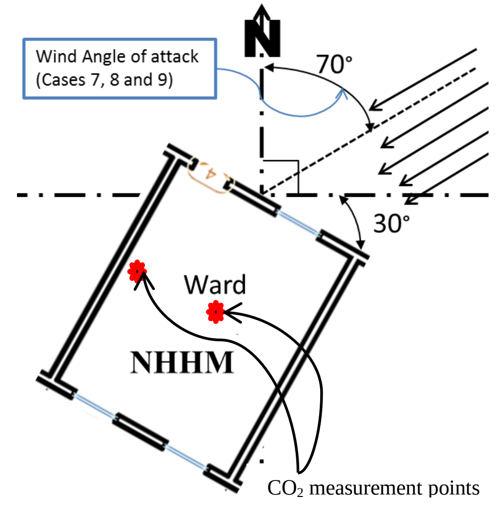


Figure 6.1: The interior view of the measured hospital wards showing Fans, instruments and CO_2 bottles

6.3 Tracer Gas Measurement Procedures

The measurement of air change rates, temperature, relative humidity and wind speed and direction require systematic methodology and state-of-the-art equipment and materials. The onsite measurements were made to obtain air change rates, temperature, relative humidity, while the remaining data were obtained from the nearby meteorological station.

6.3.1 Measurement Equipment

In this study, measuring equipment manufactured by Eltek Ltd. has been used for the assessment of air change rates. This equipment is capable of detecting and measuring CO_2, temperature and relative humidity simultaneously. The Squirrel 1000 Series Data Logger with serial number EL-10330 was used in conjunction with four (4) different transmitters including Gen-II Transmitters type GD-47(2 in Number) and Gen-II Transmitters type GD-10(2 in Number). A typical diagram illustrating the telemetry of the data logger and the transmitters is shown in Figure 6.2. The Eltek 1000 series data logger was used to receive CO_2, temperature and relative humidity from 8 transmitter channels.

The Gen-II Transmitters sensors are capable of measuring temperature ranging from -30 to 65ºC, relative humidity range of 0-100% and CO_2 from 0 to 5000 ppm. Moreover, the GenII radio data logging system records data from sensors positioned remotely from the Receiver Logger, where cables would be costly and impractical. With the logger it is possible to cover a radio range of over 2 km in an open ground (Eltek 2014; Eltek 2009). The logging sampling interval can be set from 1 second to 24 hours in 1-second increments. The sampling interval used in the present study is 30 seconds. The accuracy of the logger ranges from ± (0.1% of reading, +0.2% of range span).

Figure 6.2: Telemetry of Eltek data loggers/receivers and transmitters (Source: Eltek, 2014)

6.3.2 Data Logger Channels

6.3.2.1 Squirrel 1000 Series Data Logger (Type: RX250AL)

The Eltek SQ1000 Series Squirrel data logger usually receives transmission from different networked transmitters documenting parameters such as temperature, relative humidity (RH) and CO_2. It provides a flexible combination of channels, ranges, and memory sizes. A typical Squirrel Datalogger consists of one CPU module and at least one input module. The CPU module is divided into two including; one event input and one pulse input. One squirrel Datalogger is capable of combining up to 8 input modules for a maximum total of 250 input channels (Eltek, 2014). The eight (8) different channels that have been used in the current study are shown in table 6-2. A typical Squirrel 1000 Series Data Logger is illustrated in figure 6.3.

Table 6-2: Squirrel Data logger Channels Employed

Channels	*Channel's Serial numbers*	*Parameters tested*
Channels 1	TX 16665 A	Temperature in ºC
Channels 2	TX 16131 C	CO_2 in PPM
Channels 3	TX 16132 A	Temperature in ºC
Channels 4	TX 16132 B	Relative Humidity in %
Channels 5	TX 16132 C	CO_2 in PPM
Channels 6	TX 16666 A	Temperature in ºC
Channels 7	TX 16666 B	Relative Humidity in %
Channels 8	TX 16665 B	Relative Humidity in %

Figure 6.3: Squirrel 1000 Series Data Logger (Source: Eltek, 2014)

6.3.3 Transmitters

In this study, four (4) different transmitters have been used including Gen-II Transmitters type GD-47(2 in Number) and Gen-II Transmitters type GD-10(2 in Number), which transmits with eight channels. In this study, two GD47 transmitters were employed and were both placed inside the hospital wards to record CO_2 concentrations and corresponding temperature and relative humidity. The transmitters were placed into different positions and the average of the two was used as the room average values. Likewise, two GD10 transmitters were also used for the purpose of this study. One of these transmitters was placed inside the ward and the other outside recoding temperature and relative humidity in both outside and inside the ward.

6.3.3.1 Gen-II Transmitters type GD-47(2 in Number)

The GD47 transmitter is a self-sufficient air quality monitoring transmitter, with built in sensors for RH, temperature and CO_2 (0-5000 ppm). It is normally designed to be used with Gen-II Telemetry monitoring system, Wireless Sensor Receiver system (WSR) or Telemetry receiver system (RC250). The transmitter is integrated with built-in rechargeable batteries to withstand task for up to 100 hours in the event of AC mains supply disruption (Eltek, 2009). It is continuously monitored and presented as a channel at the Squirrel 1000 Series Data Logger. Typical Gen-II Transmitters type GD-47 is shown in Figure 6.4.

Figure 6.4: Gen-II Transmitters type GD-47

6.3.3.2 Gen-II Transmitters type GD-10(2 in Number)

The GD-10 transmitter is a self-sufficient air quality monitoring transmitter, with built in sensors for RH, and temperature with display. The sensors are capable of measuring temperature ranging from -30 to 65ºC and relative humidity range of 0-100%. It is equipped with built-in rechargeable batteries and it is constantly monitored and displayed as a channel at the Squirrel 1000 Series Data Logger. Typical Gen-II Transmitters type GD-10 is shown in figure 6.5.

Figure 6.5: Gen-II Transmitters type GD-10

6.3.4 Measurement of Ventilation Rates Using Tracer gas Techniques

Tracer gas assessment techniques are widely employed in ascertaining ventilation efficiency in buildings. The tracer gas is usually injected into the room/space using a gas bottle with pressure reducer or manually with filled gas tanks/cylinders, for a short period of time. The concentration is measured when the tracer gas is fully mixed with air in the room/space (Detlef and Dieter, 2011). In this study, the measurement was carried out using concentration decay techniques with CO_2 as the tracer gas. The concentration decay method is usually done by releasing a small amount of gas initially, after which there is no injection of gas throughout the measurement period (Etheridge and Sandberg, 1996). Once the injected tracer gas is mixed with the space air, the concentration is measured during the decay period at a regular time interval (Laussmann and Helm 2011). Concentration decay is the most commonly used method in practice, which provides a direct measurement of the nominal time constant or the air change rate and gives unbiased estimate of the mean airflow rate. It is a transient method which measures the air change rate by recording the change in tracer gas concentration (Roulet, 2008). However, this method has numerous limitations including:

a) Applicable only at that time for the prevailing weather and building configuration
b) Adequate mixing of the tracer gas is required
c) Measurement points are representative

d) ACR can change during the test period
e) May be unknown sources of tracer gas leaking in the space
f) The method does not give a continuous indication of the ventilation rate and is not suitable for long-term airflow measurements (Ogink et al. 2013), except through periodical repetition of the measurement at different time interval for the required period.

When using concentration decay methods to calculate the total flow rate, it is essential to be conversant with the total volume of the ventilated space and make sure that thorough mixing is established within the space (Etheridge and Sandberg, 1996). Typical procedure to be used for conducting concentration decay tracer gas measurement is illustrated in Figure 6.6. The measurements were conducted for both open and closed windows situations.

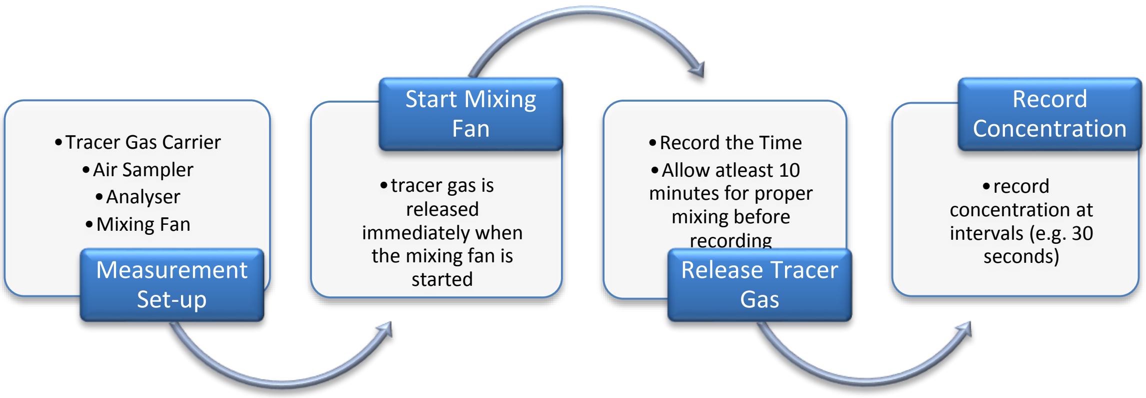


Figure 6.6: Procedures for conducting concentration decay tracer gas measurement

6.3.5 Measurement Procedure

In this study, the measurements were conducted in empty wards and the measurement periods vary from 20 minutes to 40 minutes, with measuring intervals of 30 seconds. All openings in the four hospital wards studied are closed before injecting the CO_2. Opening with installed closure devices such as doors and windows are closed with such devices, while openings without installed closing device such as corridors linking the ward to other departments in the hospital, were closed using polythene sheet cover as shown in Figure 6.7. Polythene sheet was selected due to it advantage of stopping the movement of gases from one zone to the other.

Figure 6.7: Corridor Covered with polythene Sheets

The injected CO_2 was allowed in the room for at least 15 minutes before the commencement of any measurement to allow proper mixing with indoor air. The mixing process was aided by standing fans that are placed in various positions of the room. The measurements were conducted for both closed and open windows scenarios, to enable the estimation of the infiltration and ventilation levels respectively. In each of the studied hospital wards, one to three different measurements on different days (9 days) were performed and the air change rates are determined for all the measurements and the two scenarios (closed and opened windows). In case of opened windows, both the inlet and outlet openings are fully opened to achieve cross ventilation in the period of the measurement. The sequence of events in the tracer gas measurement process is illustrated in table 6-3

Table 6-3: Sequence of events in the tracer gas measurement process

S/N	Events	Descriptions
1	Hospital ward evacuation	The selected hospital wards were emptied before the commencement of the tracer gas measurements.
2	Ward Sizes	The sizes of the selected wards were measured.
3	Inspection of openings	All openings in the selected wards were inspected to check for damages and those without covers.
4	Sealing of openings without covers	All openings without covers such as corridors linking the wards to other functions were covered with polythene sheets
5	Equipment set-up	Measuring equipment including CO_2 detectors, air temperature and relative humidity sensors and mixing fans were positioned accordingly.
6	Closed window measurement	The measurements were started with closed window scenario to enable the use of the same CO_2 in the opened window situation, because, the level of CO_2 escape with closed window is very low. Thus, all openings in the ward were closed.
7	CO_2 injection	CO_2 was injected to the empty ward simultaneously with the start of the mixing fans.
8	Mixing of the CO_2 in the ward	The injected CO_2 was allowed to mix for about 15 minutes before the commencement of the measurements.
9	Readings for closed window	The readings for the closed window scenario were taken after the elapse of the mixing period
10	Concentration records	The concentration readings were recorded at 30 seconds intervals
11	Opened window measurement	The opened window measurements commences immediately after completing the closed window scenario without injecting more CO_2 to the ward. All the openings in the ward was opened and measurement started immediately at 30 seconds interval
12	Measurement periods	The measurements lasted for 20 to 40 minutes depending on the hospital ward.

6.3.6 Carbon Dioxide (CO_2) as Tracer Gas

One of the gaseous organic compounds that are always detectable in the air is Carbon Dioxide (CO_2). It is widely used for measuring indoor air quality in buildings, owing to its simplicity in quantification, reasonably priced devices requirement, and ease in operation (Laussmann and Helm, 2011). The typical characteristics of an ideal tracer gas includes a substance that is; not a normal constituent of the investigated environment, easily measurable at low concentrations, non-toxic and non-allergic for use in occupied space, non-reactive, non-flammable, environmentally friendly and cost effective (Etheridge and Sandberg, 1996). The properties of some typical tracer gases are shown in table 6.4.

Table 6-4 properties of some typical tracer gases

Gas	Molecular weight	Boiling point (°C)	Density (15°) (kg/m³)	Analytical method (ppm)	Detection range (ppm)	Background concentration	Toxicity
Carbon dioxide	44	−56.6	1.98	IR	0.05–2000	Variable	Slight
Freon 12	121	−29.8	5.13	IR GC-ECD	0.05–2000 0.001–0.05		
Helium	4	−268.9	0.17	MS		5.24	
Nitrous oxide	44	−88.5	1.85	IR	0.05 – 2000	0.03	
Sulphur hexafluoride	146	−50.8	6.18	IR GC–ECD	0.05 – 2000 0.00002 – 0.5		
Perfluoro-n-hexane	338	57.0		GC–ECD	10^{-6}		

Source: (Etheridge and Sandberg, 1996)

As humans exhale metabolic carbon dioxide in substantial amounts, its concentration can rise to several thousand ppm within a short time. The understanding of CO_2 concentration is often used to evaluate the air quality of occupied rooms. At the present time CO_2 measurements are regularly used for the determination of the indoor Air Change Rate (ACR), because it can be easily quantified and it requires reasonably low cost devices and easy to operate. Furthermore, CO_2 satisfies a number of the above mentioned specifications of a good tracer gas (Laussmann and Helm, 2011). CO_2 is widely used as tracer gas for measuring ventilation especially by tracer decay methods, see (Zhang et al., 2005; Müller, et al. 2007a; Müller, et al. 2007b; Ngwabie et al. 2009; Laussmann and Helm, 2011; Ngwabie et al 2011; Samer et al., 2011; Wu, et al. 2012; Labat et al. 2013; Ogink et al. 2013). Studies about using a tracer gas that is already present in the atmosphere, Lambert et al. (2013) confirms that CO_2 is the best among such kind of gasses because of its less impact on the environment.

Moreover, any tracer gas that is employed in measuring airflow in buildings should ideally have the following properties (Roulet, 2008):

- Be easily analysable, if possible at low concentrations to reduce cost and side effects such as density changes or toxicity.
- Have low background concentration, permitting the use of low concentration in measurements.
- Be neither flammable nor explosive at practical concentrations, for obvious safety reasons.
- Be non-toxic at the concentration used, for obvious health reasons in inhabited buildings.
- Have a density close to the density of air (i.e. molecular weight close to 29 g/mole) to ensure easy mixing.
- Not be absorbed by furnishings, decompose or react with air or building components.
- Should be cheap in the quantity required for measurement.

The tracer gas used in the present study which is CO_2 has satisfied all the above mentioned requirements.

6.3.7 Tracer gas injection and Mixing

In concentration decay method the tracer gas is normally release or injected to the investigated environment as a short burst or pulse of gas in order to obtain the initial concentration (Etheridge and Sandberg, 1996). Mixing fans is used to improve the mixing capacity of the injected tracer gas with the air in the measuring space. To facilitate proper mixing, the tracer gas will be released into the space immediately when the mixing fan is started to follow the air stream created by the fan (Etheridge and Sandberg, 1996).The perfect tracer gas in the air of the measured space/room is vital when ascertaining airflow rates. In this study, the most commonly used method of accelerating tracer gas mixing which is to inject the tracer upwind of a mixing fan or instead using portable fans (Roulet, 2008) was used.

6.3.8 Tracer gas sampling

According to ASTM Standards E741-11, spatial sampling for the determination of uniformity in tracer gas concentration is mandatory. If the gas analyser is on site, it is recommended to conduct the spatial sampling at 15 minutes interval until uniformity of concentration is confirmed. Single storey buildings will be sampled at mid-height between ceiling and floors, while for multi storey buildings; the sampling is done at the equivalent of mid-height for each storey. In a sample zone with undifferentiated open space, the sampling is done at a minimum of three evenly spaced locations (ASTM Standard, 2011). As selection of the sampling position(s) to measure a representative average building concentration is crucial when using tracer decay method (Ogink et al. 2013). In this study two sampling points have been used, each located at different points in the room measured. The best representative sample location is normally considered to be near the outlet openings of the building. However, it is difficult and challenging to identifying a building opening as either inlet or outlet in a situation where the wind direction is rapidly changing. This fluctuating nature of the wind direction may result in lower tracer gas concentration at the sampling points and subsequently lead to over estimation of the ventilation rates (Ogink et al. 2013). Therefore, due to the fluctuating nature of airflow direction in the study area, the sampling points were selected at the centre of the ward.

6.3.9 The Tracer Gas Concentration Analysis and Estimation of Air Change Rates

The analysis of tracer gas concentration could be either done on site simultaneously with the sampling process or off site when the gas samples are collected in sealed containers (ASTM Standard, 2011). However, for the purpose of this study, the tracer gas concentration analysis was conducted on site concurrently with the sampling process. The measurement was carried out using tracer decay techniques with CO_2 as the tracer gas. The tracer gas concentration was analysed and recorded with the aid of CO_2 analyser and data loggers respectively and the results obtained from these measurements were used to estimate the air change rates of the hospitals wards.

The ventilation rate can be estimated by multiplying the air change rate and the room volume (Kiwan et al. 2012). The concentration of gas usually decreases once it is injected into a sealed enclosure or room, as air enters and leaves. The tracer gas concentration will decay exponentially against time, provided that the driving forces for air exchange in the room remain constant. Hence, plotting the natural logarithm of the exponential decay curve against time would produce a straight line, the slope of which is the Air Change Rates (ACR) in air changes per unit time. The air exchange rate (N) of a specific gas is determined by the difference in concentration of the gas inside and outside the room/enclosure (Calver et al. 2005). The general form of the equation for calculating air exchange per unit time is given in Equation (11):

$$N = [\ln(C_{int}t_0 - C_{ext}) - \ln(C_{int}t_1 - C_{ext})]/(t_1 - t_0) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Where

N = number of air changes

$C_{int}t_0$ = internal concentration of tracer gas in enclosure at start

C_{ext} = external concentration of tracer gas in room

$C_{int}t_1$ = internal concentration of tracer gas in enclosure at end

t_0 = time at start (seconds)

t_1 = time at end (seconds)

l_n = natural logarithm.

6.4 Full-scale Measurement Results and Discussion

6.4.1 Measurement of Air Change Rates

The air change rate measurements were conducted in multi-bed wards of four (4) different hospitals in the study area. These hospitals include the University of Maiduguri Teaching Hospital (UMTH), Umaru Shehu Ultra-Morden Hospital Maiduguri (USUHM), Federal Neuro Psychiatric Hospital Maiduguri (FNPHM) and Nursing Home Hospital Maiduguri (NHHM).These measurements were conducted once or twice and in some case three times in both closed and opened windows situations, depending on the availability of the wards. Because, occupants of the affected ward including patient and other healthcare workers must be evacuated prior to any experiment in the wards. The air change rate measurements were conducted together with other parameters including outdoor and indoor dry bulb temperature, outdoor and indoor relative humidity. The wind speed and direction data were collected from the nearest meteorological station. The air change rates measurement results and other important boundary conditions including temperature, relative humidity for closed and opened window cases and outdoor wind speeds at the time of the measurement are shown in table 6-5, 6-6 and figure 6.8a, 6.8b.

The first instance of measurement was the air change rates assessed when the hospital ward openings were closed, which are infiltration rates due to cracks in the envelope and gaps along the perimeters of the window and door frames. Infiltration is a major problem in buildings, especially when using mechanical ventilation systems, because it allows conditioned air to escape and loose energy to the outside. However, in naturally ventilated buildings like ones under investigation, the effect of infiltration is uncontrolled. The lowest and highest infiltration of 0.31 ach^{-1} and 1.56 ach^{-1} were recorded in Case-6 and Case-8 respectively, as illustrated figure 6.8[a].

It could be observed in figure 6.8[a] that, there is a large difference in infiltration rates between cases 7 and 8, which are measurements from the same ward (NHHM), but at different times. The orientation of wind flow direction in relation to the inlet openings is 90° in case 7 and 70° in case 8. Even though, the outdoor prevailing wind speed is higher in case 7 (3.1m/s) compared to case 8 (2.6m/s), but due to the variation in orientation, case 8 recorded higher air change rate compared to case 7, as illustrated in table 6-5 and figure 6.8[a]. This is due to the fact that the 20° differences between 70° orientation in case 8 compared to the 90° orientation in case 7, could result in case 8 allowing more air movement to the indoors. The variation in infiltration rates in the remaining cases is negligible, but follows the same pattern as in cases 7 and 8. Therefore, building orientation toward the prevailing winds plays an important role in determining air change rates in buildings. The effect of building orientation on ventilation rate has been simulated and discussed in detail in chapter 8, subsection 8.8.

Table 6-5: Infiltration Rates and other Climatic Parameters at measurement period for closed window in wards

Cases	Test No	Test dates	CO_2 Injection	Closed Window							
				Time	Infiltration rate	Wind (m/s)	Angle	$T_{outdoor}$	T_{indoor}	RH $_{oudoor}$	RH $_{indoor}$
UMTH	Case1	26/11/2012	12:00pm	12:26pm	0.42	3.6 m/s	120	32.1	29.3	26	31
	Case2	01/12/2012	11:40am	12:01pm	0.39	3.1 m/s	070	33.6	29.0	22	29
USUH	Case3	17/11/2012	10:42am	11:10am	0.31	3.1 m/s	070	31.9	28.3	22	28
	Case4	18/11/2012	9:00am	9:33am	0.32	3.1 m/s	070	31.0	28.2	25	32
	Case5	17/12/2012	10:25am	10:55am	0.38	6.7 m/s	070	26.0	24.9	29	28
FNPHM	Case6	24/11/2012	11:15 am	12:07pm	0.31	2.1m/s	060	33.1	27.8	21	32
NHHM	Case7	23/11/2012	09:10am	09:50am	0.91	3.1 m/s	090	30.2	27.6	28	32
	Case8	28/11/2012	11:25am	12:25pm	1.56	2.6 m/s	070	33.3	28.0	19	24

The air change measurements were also conducted in opened window situations to ascertain the ventilation rates of the hospital wards. These measurements were conducted by completely opening all the inlet and outlet openings. The results obtained for air change rates, indoor and outdoor air temperature and relative humidity are presented in table 6-6. The air change rates in all the 9 cases measured with open windows indicates that none have satisfied the ASHRAE requirements of 6 ach^{-1} in patient rooms except case number 7, as illustrated in figure 6-8[b]. The positive result in case 7 is probably as a result of high outdoor wind speed of 4.1 m/s at the time of the measurement, coupled with the small size of the ward. Hence, in situations with low outdoor wind speeds, the existing opening size and configurations does not provide the required air change rate to remove contaminants within the hospital wards. The window to floor area ration in all the hospital wards measured are above the 4% recommended by International Mechanical Code (IMC), except in FNPH where the window to floor area ratio is 2.35%.

Moreover, in an opened window situation, the variations in air change rates from measurements conducted in the same wards is either due to the difference in outdoor wind speed and/or building orientation in relation to wind flow direction. The measurements in cases 7, 8 and 9 (figure 6.8[b] and table 6-6) are from the same ward (NHHM) at different times, but there is variation in air change rates between the three. This is because, the outdoor prevailing wind speed of 4.1m/s in case 7 is higher than the wind speed in both case 8 and 9 with 2.6m/s. the difference in air change rates between case 8 and 9 is negligible because they have the same outdoor wind speed at the time of the measurements. Hence, adequate cross ventilation is achieved with high wind speeds.

Likewise, cases 3, 4 and 5 (figure 6.8[b] and table 6-6) were measured in the same ward (USUHM), but have different air change rates. The orientation of the wind flow direction in relation to the openings in cases 3, 4 and 5 are 70^o, 70^o and 80^o respectively. However, the outdoor prevailing wind speed for cases 3, 4 and 5 is 3.1m/s, 2.6m/s and 4.1m/s respectively. Hence, the high air change rate in case 5 is due to the higher outdoor wind speed of 4.1m/s compared to cases 3 and 4. Moreover, the second highest air change rates among the three cases is recorded by cases 3 which also has the second highest wind speed of 3.1m/s. hence, the effect of outdoor prevailing wind speed in determining air change rates is significant. However, there is a slight difference in orientation of 10^o between cases 3 and 4. Similarly, the situation is the same in cases 1 and 2 in which the higher the outdoor wind speed, the higher the air change rates recorded as illustrated in figure 6.8[b] and table 6-6. Finally, in cases with closed windows, orientation is more important, while in cases with opened windows outdoor wind speed is more important than orientation in deciding air change rates. Hence, the existing design is not sufficient for natural ventilation.

Table 6-6: Air Change Rates and other Climatic Parameters at measurement period for opened window in wards

Cases	**Test No**	**Test dates**	**CO_2 Injection**	**Opened Window**							
				Time	ACR	Wind (m/s)	Angle	$T_{outdoor}$	T_{indoor}	RH $_{oudoor}$	RH $_{indoor}$
UMTH	Case1	26/11/2012	12:00pm	13:00pm	3.63	1.5 m/s	070	31.5	29.7	28	28
	Case2	01/12/2012	11:40am	12:23pm	4.07	3.1 m/s	080	32.8	30.2	23	24
USUH	Case3	17/11/2012	10:42am	11:30am	2.93	3.1 m/s	070	31.5	29.1	32	25
	Case4	18/11/2012	9:00am	9:56am	1.84	2.6 m/s	070	30.8	28.9	28	29
	Case5	17/12/2012	10:25am	11:36am	4.21	4.1 m/s	080	27.8	25.5	26	27
FNPHM	Case6	24/11/2012	11:15 am	12:33pm	2.61	2.1m/s	060	33.8	28.6	18	31
NHHM	Case7	21/11/2012	11:40am	12:26pm	6.75	4.1 m/s	070	36.9	30.3	14	18
	Case8	23/11/2012	09:10am	10:07am	2.46	2.6 m/s	070	30.7	28.0	27	29
	Case9	28/11/2012	11:25am	12:48pm	2.62	2.6 m/s	070	33.8	28.7	19	22

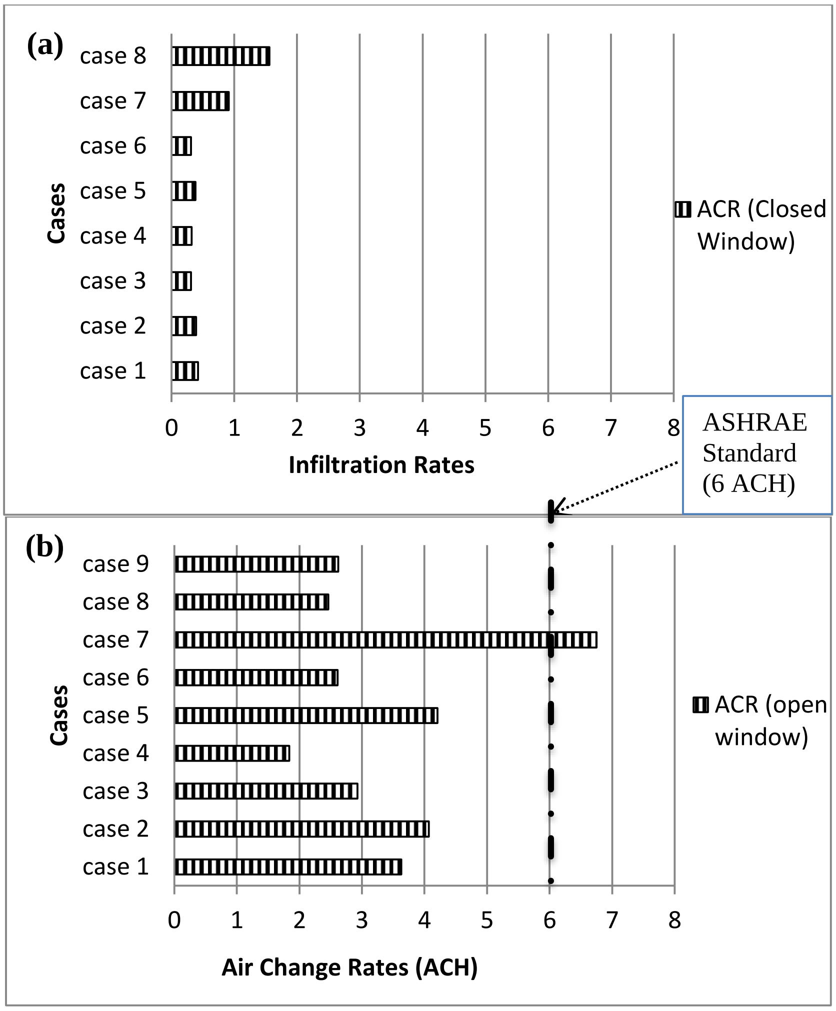


Figure 6.8: Infiltration rates and air change rates in closed and opened windows respectively

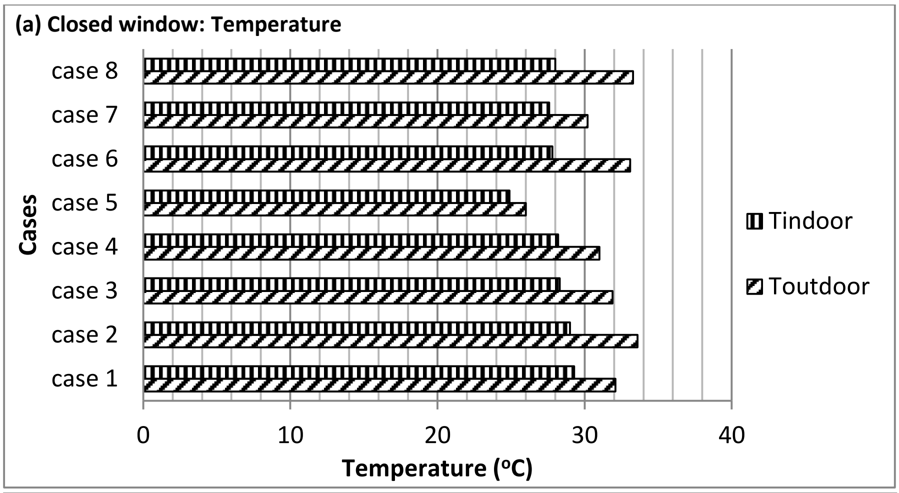
6.4.2 Air Temperature Measurements

In closed window situation, the indoor and outdoor air temperature measurements have been carried out simultaneously with the air infiltration rate measurement. The temperatures outdoors are higher than indoors for all the eight cases studied as illustrated in figure 6.9. The result indicates that the outdoor air temperature ranges from 26°C to 33.6°C and the indoor air temperature falls between 24.9°C and 29.3°C at the measurement period in closed window situations. The lowest outdoor and indoor temperature was recorded by case 5, and the highest outdoor and indoor temperature is recorded by cases 2 and 1 respectively.

The differences in temperature in the measurements are mainly due to the impact of outdoor weather condition at the time of the measurement and the thermal mass of the building envelope. Since, the thermal comfort and human preferences are related to acclimatisation to local conditions, Mohammed et al. (2013a) have estimated the neutrality temperature of the study area (Maiduguri) using the outdoor average ambience temperature with the $T_n = 17.8 + 0.31T_{oav}$ correlation established by Szokolay (2008). The thermal neutrality temperature of Maiduguri is found to be 26.7^{o}C, and considering a temperature band of ±2.5 as recommended in Szokolay (2008), the thermal comfort zone will fall between 24.2^{o}C and 29.2^{o}C. Hence, the indoor air temperatures of 24.9^{o}C to 29.3^{o}C obtained from these measurements have fulfilled the comfort requirements of the study area based on the estimated thermal neutrality temperature.

Moreover, the results for temperature in the opened window situation are similar to the closed one. The temperatures outdoors are higher than the temperatures indoors. The result indicates that the outdoor air temperature ranges from 27.8^{o}C to 36.9^{o}C and the indoor air temperature falls between 13.8^{o}C and 30.3^{o}C at the measurement period in opened window situations. The indoor air temperatures measured falls between 13.8^{o}C and 30.3^{o}C. Some of these temperatures have fulfilled the comfort requirements of the study area based on the estimated thermal neutrality temperature, while the others did not.

The similarity between the temperatures in the two cases of opened and closed windows could be due to the low wind speed at time of the measurement. However, the indoor air temperature is higher in opened window situation compared to the closed window as observed by comparing figures 6.9[a] and 6.9[b]. In a full-scale measurement study at semi-arid climate reported by Givoni (1981), the lowest temperatures in the indoor space were obtained when the building openings are closed. Moreover, the study indicated that, opening one window increased the room temperature with about 0.5^{o}C and opening two windows resulted in 1.0^{o}C increase in temperature.



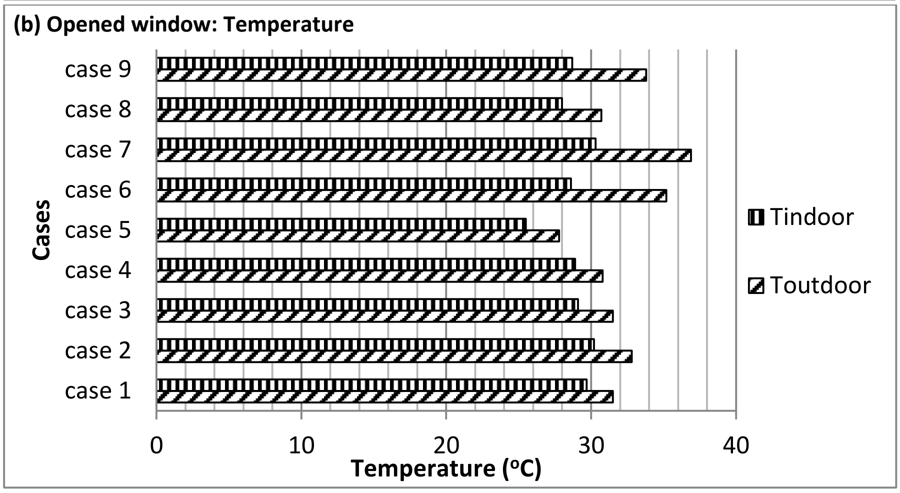


Figure 6.9: Air temperature of all the cases measured in (a) closed and (b) opened window situations

However, in most cases the difference between the outdoor and indoor temperature is higher in closed window situations as shown in table 6-7 and figure 6.10. This is because of the trapping of heat from various sources indoors due to little contact between indoor and outdoor air. The possible explanation for the case 5 and 8 in which the difference in opened windows is higher than closed window might be due to low ambience air temperatures outside the building. According to Givoni (1981) compared with unventilated buildings, ventilation reduces the temperature of internal surfaces closer to that of the outside, however the influence is less pronounced with indoor air temperature.

Table 6-7: The difference in air temperature between closed and opened window wards

Cases	Closed Window	Open Window
Case-1	2.8 °C	1.8 °C
Case-2	4.6 °C	2.6 °C
Case-3	3.6 °C	2.4 °C
Case-4	2.8 °C	1.9 °C
Case-5	1.1 °C	2.3 °C
Case-6	5.3 °C	5.2 °C
Case-7	-	6.6 °C
Case-8	2.6 °C	2.7 °C
Case-9	5.3 °C	5.1 °C

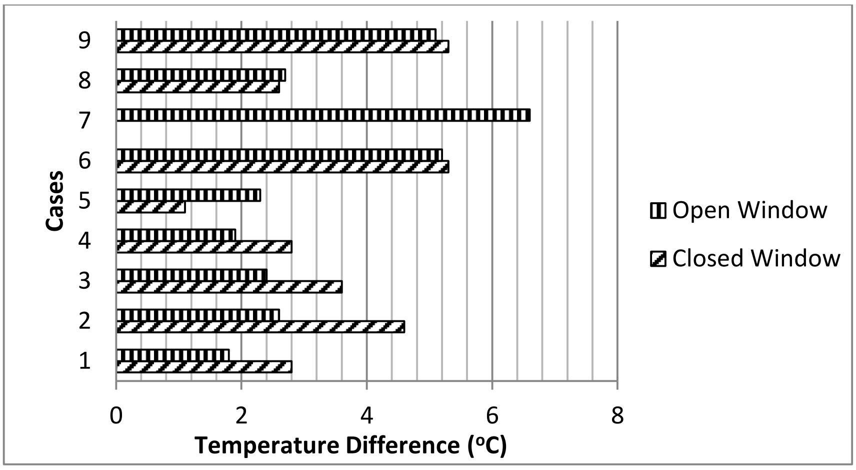


Figure 6.10: The difference in temperature between closed and opened window wards

6.4.3 Relative Humidity Measurements

To achieve maximum comfort, the relative humidity level in patient room should be between 30 and 50% (ASHRAE, 2007; Centre Point Energy, 2006). In indoor spaces, the acceptability of air decreases considerably with increasing air temperature and relative humidity at a constant pollution level (Fang et al. 1998). In this study, the relative humidity measurements were also made simultaneously with the air change rates. The result indicates that, in a closed window situation, the relative humidity is higher indoors compared to the outdoors except in case 5 in which the outdoor relative humidity is slightly higher than indoors as illustrated in Figure 6.11a. Moreover, the highest outdoor relative humidity was recorded in case 5 and the highest indoor relative humidity was recorded by cases 4 and 7. Similarly, both the lowest outdoor and indoor relative humidity was recorded in case 8. Thus, the indoor relative humidity in closed door situations in all the cases are within the acceptable limit of 20% to 50% except in case 8 (see Figure 6.11a.).

Likewise, the measurement of the indoor and outdoor relative humidity in opened window situation was conducted simultaneously with the air change rates showing similar results to the closed window situation. The result indicates that, the indoor relative humidity is higher than the outdoors except in case 3, as illustrated in Figure 6.11b. This is because the level of relative humidity in the ambience air is low in the study area (semi-arid climates). Desirable humidity according to ASHRAE Handbook of fundamentals is 30% in winter and 50% in summer (ASHRAE, 2007). ASHRAE manual give a range of 30 to 60% as the desirable relative humidity in indoor environment (ASHRAE 2003). CIBSE guide B prescribed 40 to 70 % relative humidity for hospital wards (National Health Service, 1994). HTM 2025 guideline prescribed 40 to 60 % as desirable relative humidity in patient rooms (The Chartered Institution of Building Services Engineers, 2004).

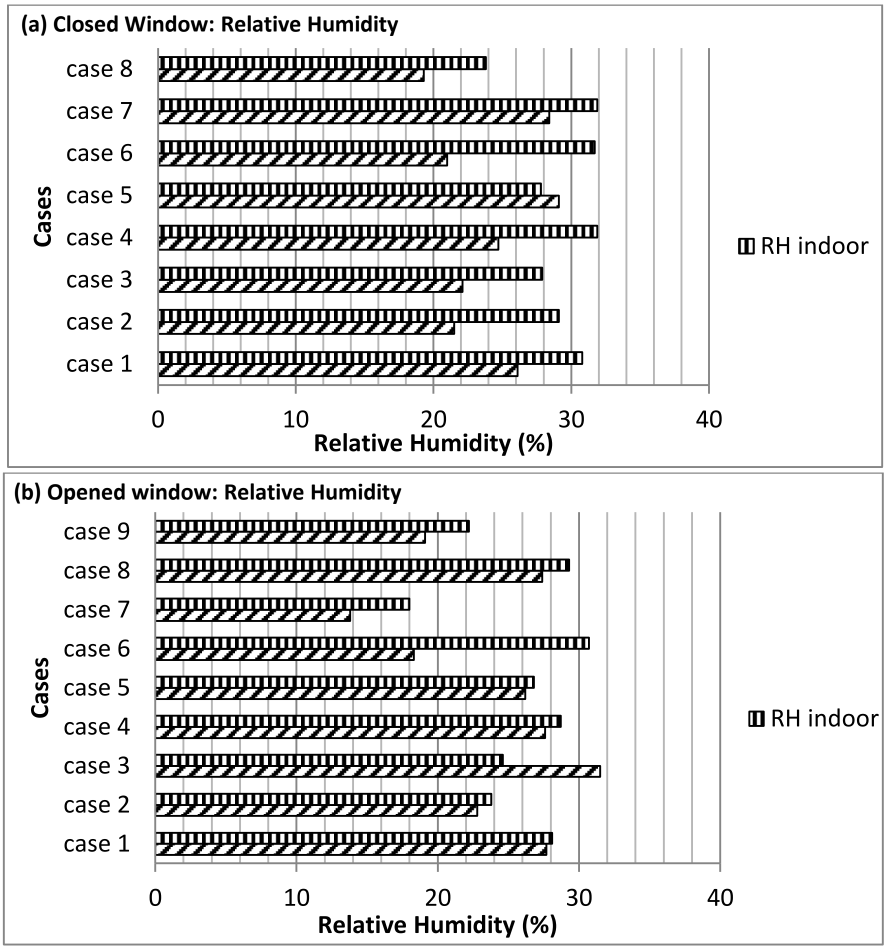


Figure 6.11: Relative Humidity of all the cases measured in closed and opened window situation

Furthermore, the relative humidity difference between outdoor and the indoor environment is higher in closed door situation compared to opened door cases in all the measurements except in case 6, as illustrated in table 6-8 and figure 6.12. This result follows the same trend as with the temperature difference.

Table 6-8: The difference in relative humidity between closed and opened window wards

Cases	RH in Closed Window (%)	RH in Open Window (%)
Case-1	5	0
Case-2	8	1
Case-3	6	-7
Case-4	7	1
Case-5	-1	1
Case-6	11	12
Case-7	0	4
Case-8	4	2
Case-9	5	3

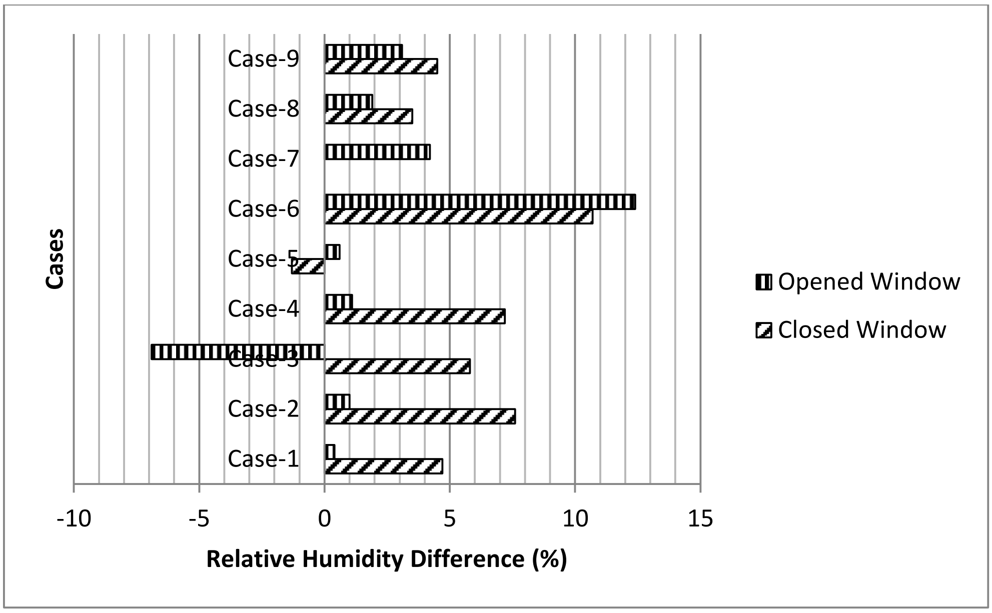
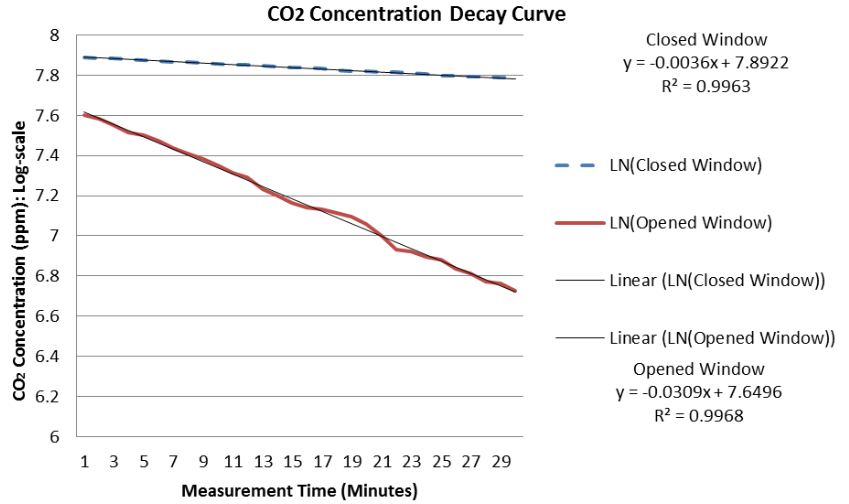
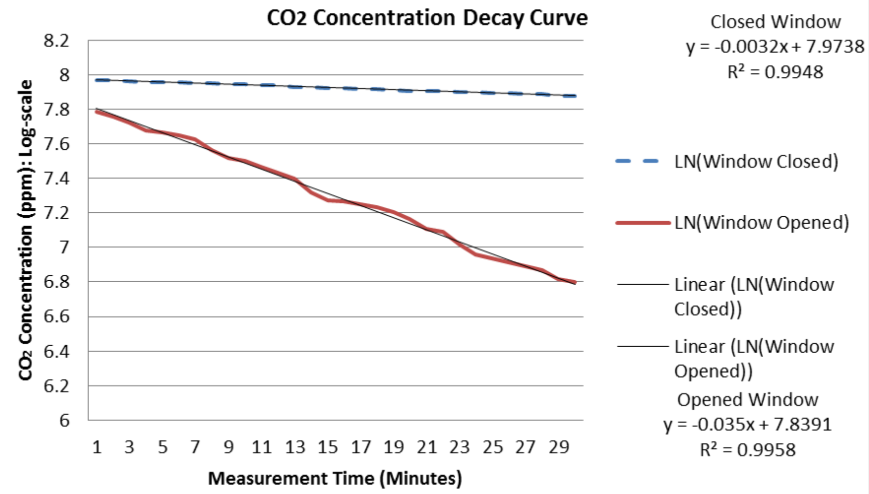
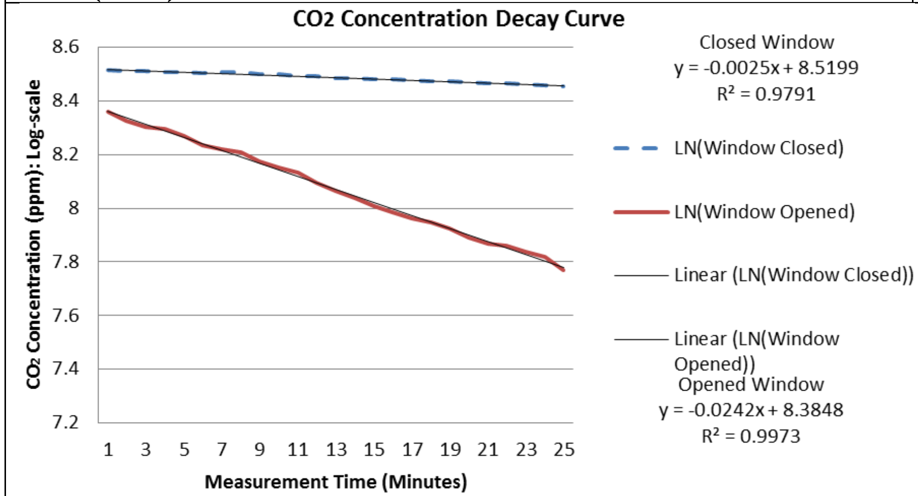
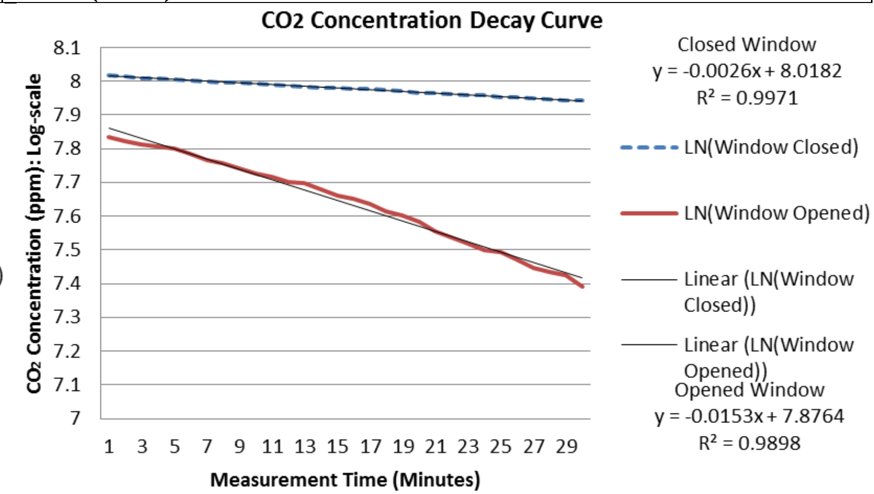


Figure 6.12: The difference in relative humidity between closed and opened window wards

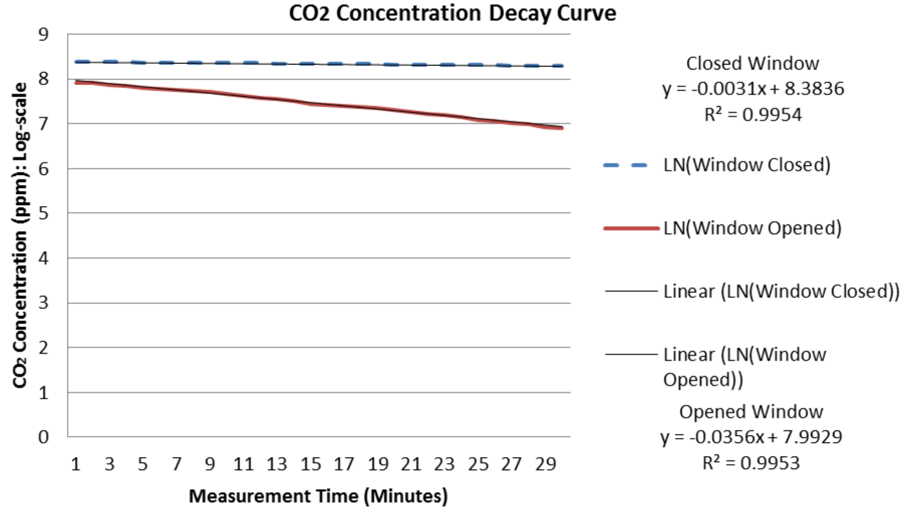
However, the logarithmic CO_2 concentration decay curve of the nine (9) cases investigated in the four (4) hospitals is illustrated in table 6-9, while the complete CO_2 decay curve in ppm showing data points used for the calculation of air change rates is illustrated in table 6-10 . The vertical axis in the graphs represents CO_2 concentration (ppm), while the horizontal axis represents the decay time/period (minutes). The difference in gradients between the opened and closed window scenarios has been clearly demonstrated with continuous and dotted lines respectively. The level of decay in the wards with opened windows is faster than those with closed windows. The little decay in the closed window situations is as a result of infiltration through cracks and gaps on the envelope and openings.

Moreover, significance level in terms of regression coefficient (R^2) computed for all the cases are above 97% showing strong correlation and reliability of the measurement results. Thus, the linear curves presented for both opened and closed window situations with R^2 greater than 97% have explained all the variability of the response data around its mean.

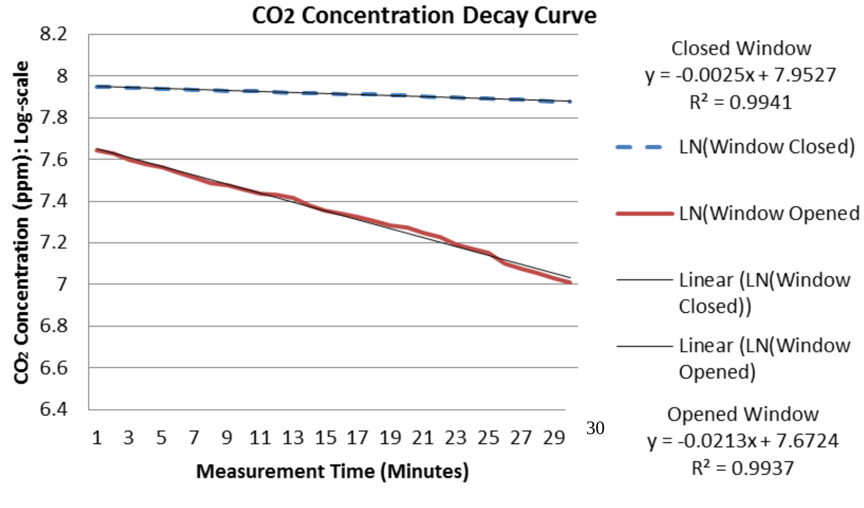
Table 6-9: The logarithmic CO_2 concentration decay curve for all the cases studied

Case 1 (UMTH)	Case 2 (UMTH)
	
Case 3 (USUH)	**Case 4 (USUH)**
	

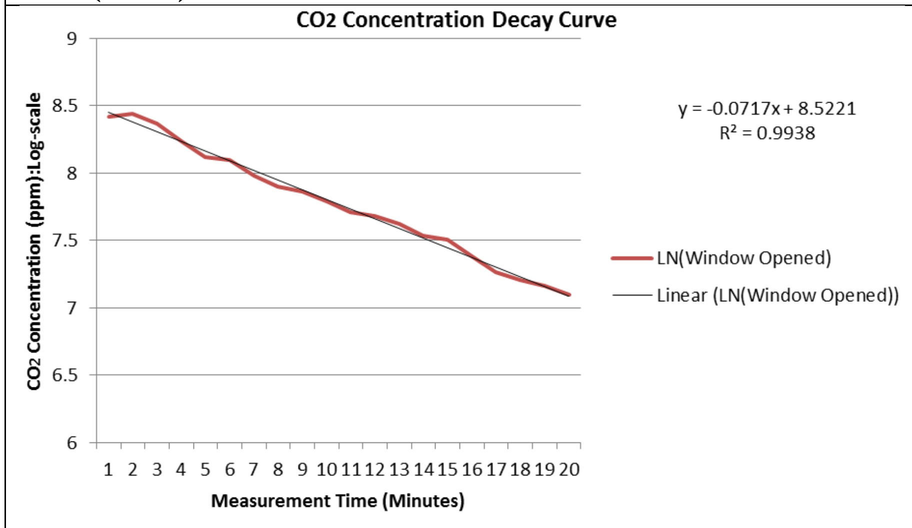
Case 5 (USUH)



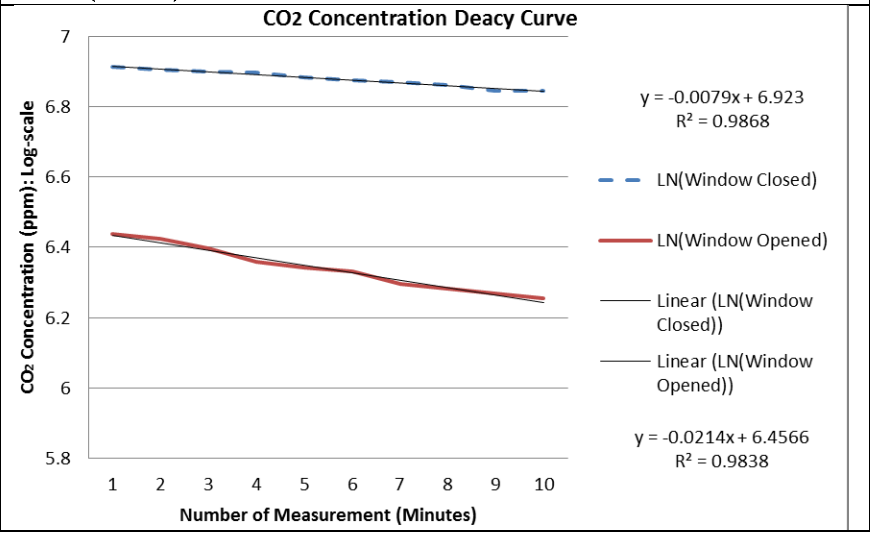
Case 6 (FNPHM)



Case 7 (NHHM)



Case 8 (NHHM)



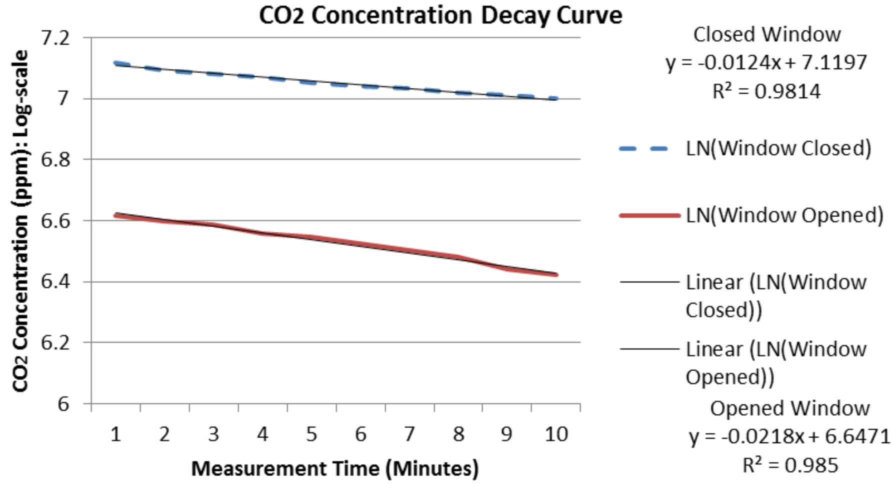
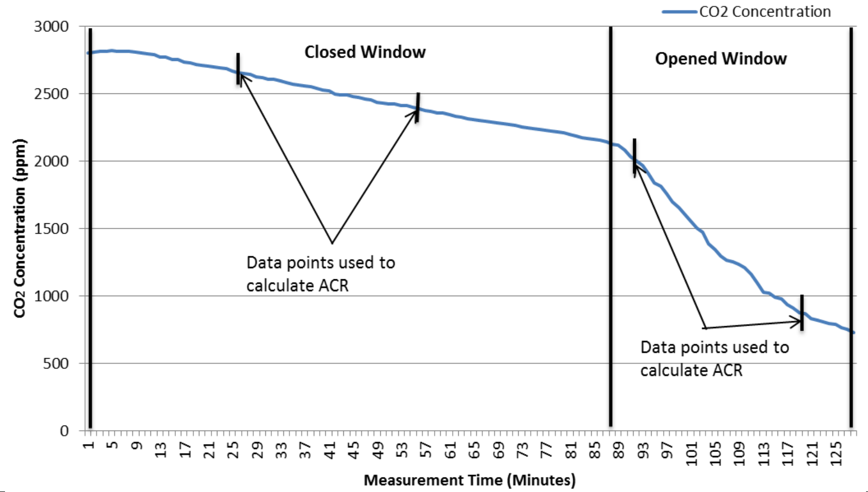
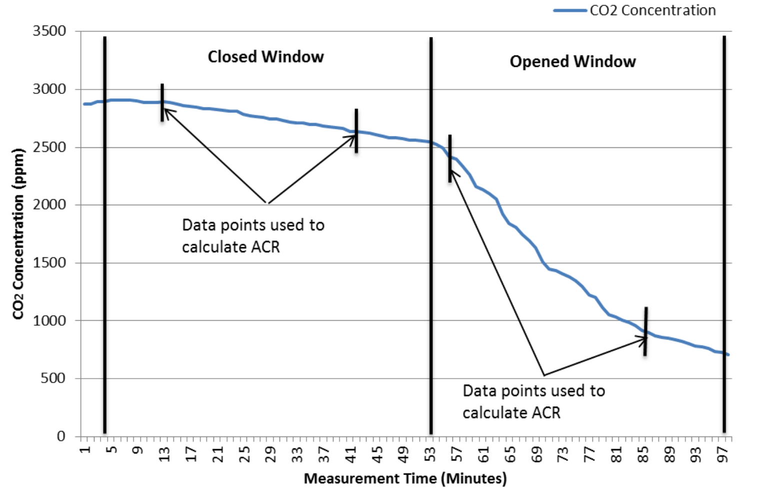
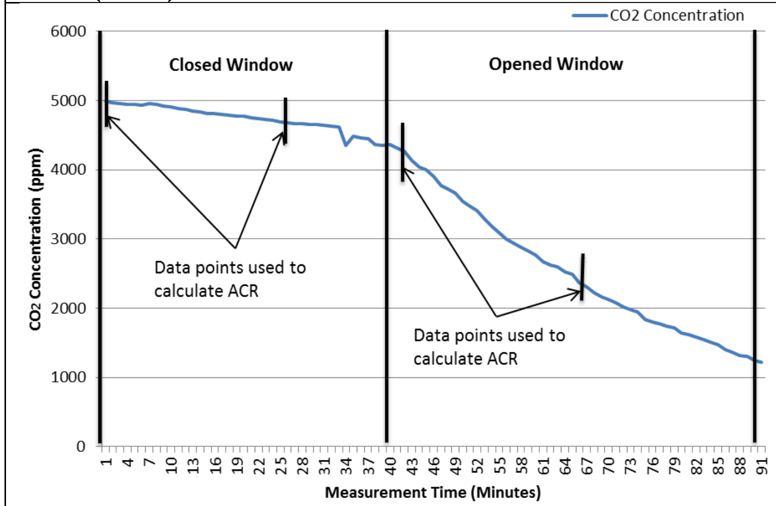
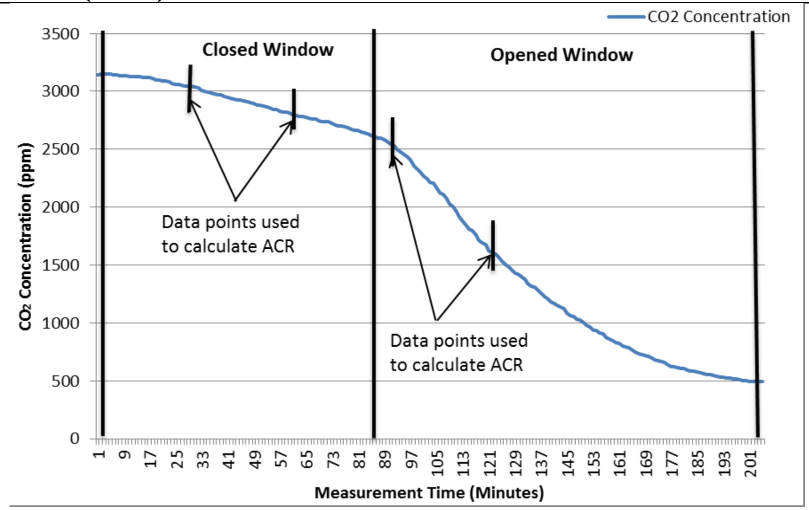
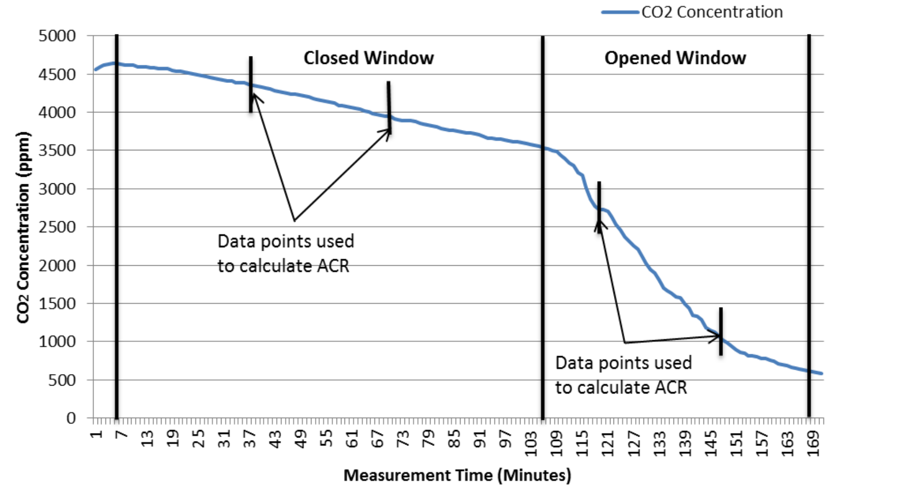
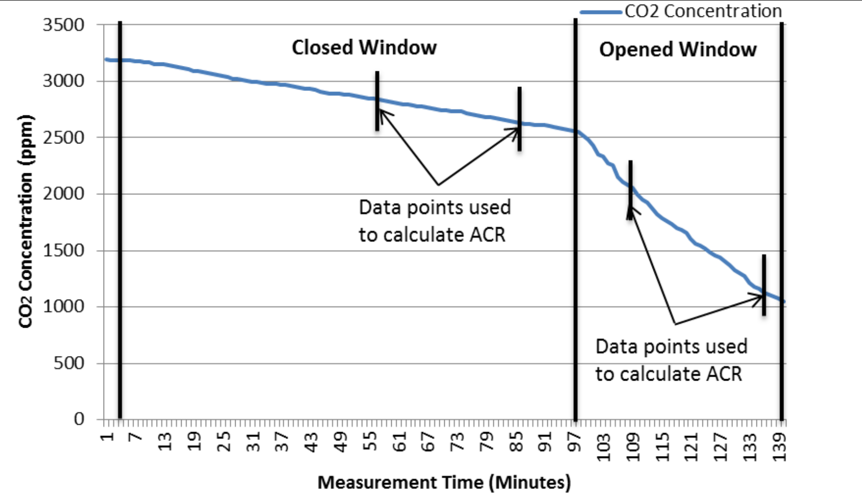
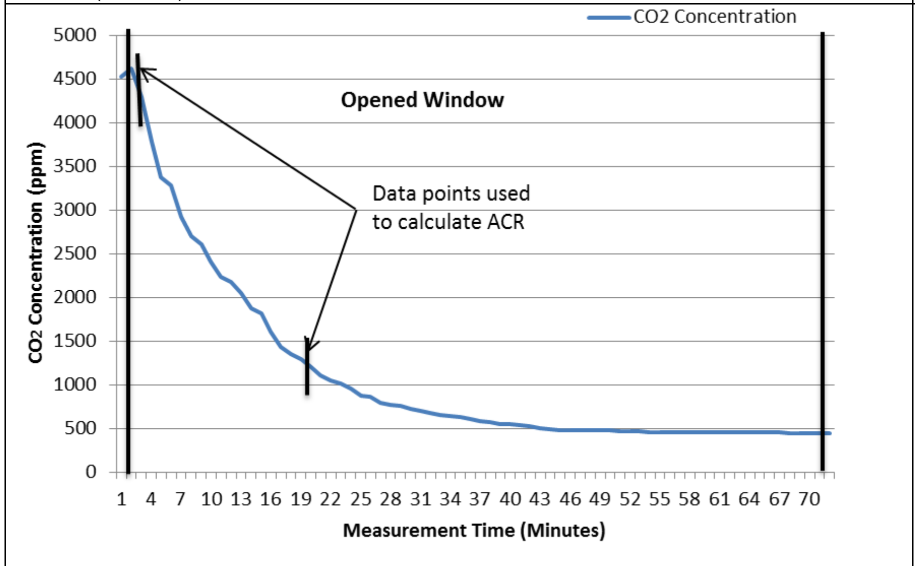
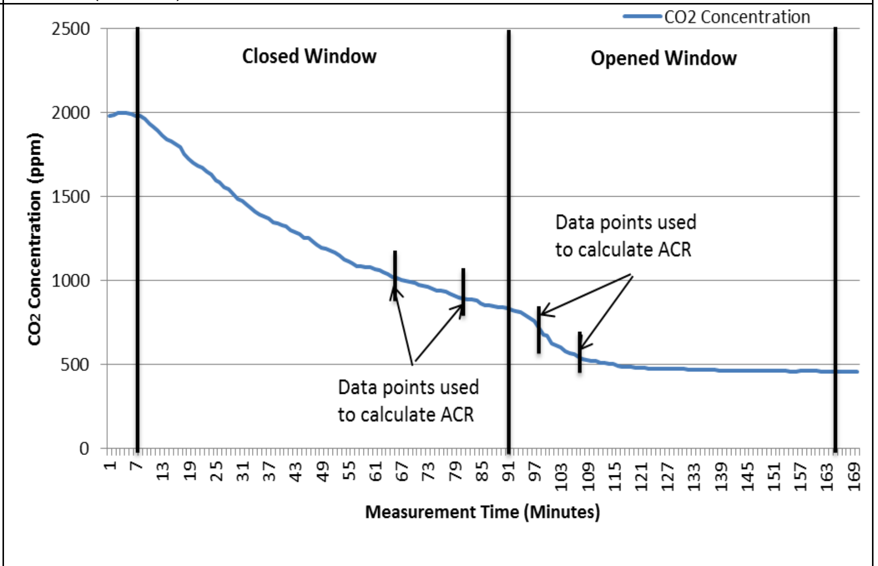
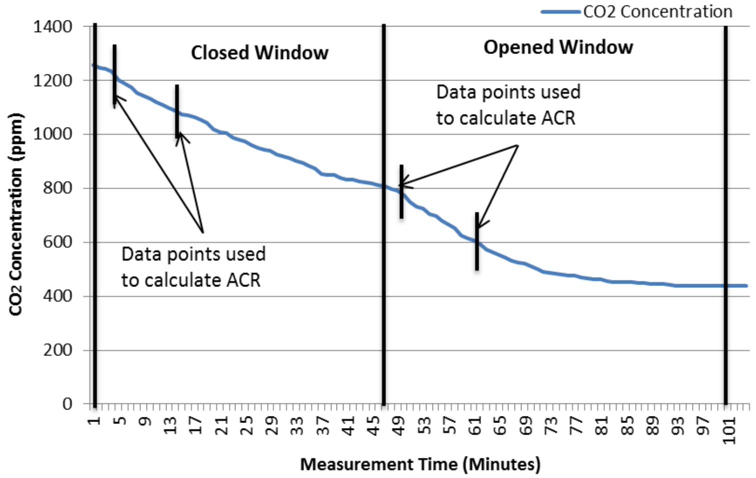
Case 9 (NHHM)	
CO2 Concentration Decay Curve 7.2 7 6.8 6.6 6.4 6.2 6 CO2 Concentration (ppm): Log-scale 1 2 3 4 5 6 7 8 9 10 Measurement Time (Minutes) Closed Window y = -0.0124x + 7.1197 R² = 0.9814 LN(Window Closed) LN(Window Opened) Linear (LN(Window Closed)) Linear (LN(Window Opened)) Opened Window y = -0.0218x + 6.6471 R² = 0.985	

Table 6-10: The CO_2 concentration (ppm) decay curve for all the cases studied showing data points used

Case 1 (UMTH)	Case 2 (UMTH)
	
Case 3 (USUH)	**Case 4 (USUH)**
	

Case 5 (USUH)	Case 6 (FNPHM)
	

Case 7 (NHHM)	Case 8 (NHHM)
	

Case 9 (NHHM)	
CO2 Concentration Closed Window Opened Window Data points used to calculate ACR Data points used to calculate ACR CO2 Concentration (ppm) Measurement Time (Minutes) 0 200 400 600 800 1000 1200 1400 1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101	

6.5 Chapter Conclusion

The psychosocial perception of the hospital wards' occupants has been presented in the previous chapter (chapter 5). Based on the occupants' perception, the hospital wards occupants are generally not satisfied with the indoor air quality and ventilation in these wards. The ventilation rate measurements taken during the test periods show relatively low rates of air flow and would confirm Chapter 5's assertion that ventilation rates are too low in these hospital wards, and this would account for poor indoor air quality highlighted by the wards permanent occupants.

In this chapter, the ventilation rates in four (4) different hospital wards in the study area were measured using tracer gas decay method. These measurements were divided into nine (9) cases depending on the number of measurements in each ward (2 in UMTH, 3 in USUHM, 1 FNPHM, and 3 in NHHM). The result shows that, the air change rates in the eight of the nine measurements taken from the four hospitals fall short of the ASHRAE standard of 6 ach^{-1} prescribed for hospital wards during the periods of the measurements as illustrated in table 6-11.

Table 6-11: The Air Change Rates and Indoor Air Temperature of the measured hospital wards

Cases	Test No	Air Change Rates
UMTH	Case1	3.63
	Case2	4.07
USUH	Case3	2.93
	Case4	1.84
	Case5	4.21
FNPHM	Case6	2.61
NHHM	Case7	6.75
	Case8	2.46
	Case9	2.62

Moreover, the results from the tracer gas measurements affirm the occupants' response showing their dissatisfaction with the indoor air quality and ventilation in the hospital wards. The measurement results will be validated using CFD simulation by replicating the hospital wards and their measurement conditions in the virtual CFD environment. The hospital ward in the USUHM has been selected as the base-case for further CFD analysis in chapters 7, 8 and 9.

The results from the full-scale measurements also highlight the effects of building orientation in relation to wind flow direction and outdoor prevailing wind speed on the ventilation rates. Thus, based on the outcomes of both psychosocial perception and full-scale measurement, the indoor air quality and ventilation rates in the hospital wards of the semi-arid climates are not adequate and need to be optimised to satisfy the standard requirements and subsequently provide the required comfort for the occupants.

Chapter Seven

The Process of CFD Simulation and Software Validation

Chapter Structure

7.1 Introduction

7.2 Ventilation performance prediction using Computational Fluid Dynamics (CFD)

7.3 Computational domain

7.4 Atmospheric Boundary Layer (ABL)

7.5 Turbulence model -Reynolds-Averaged Navier-Stokes (RANS) equations

7.6 Boundary Conditions

7.7 Model Calibration

7.8 Validation Studies

7.9 The CFD Validation results

7.10 Simulation Convergence

7.11 Chapter Conclusion

7 Chapter Seven: The Process of CFD Simulation and Software Validation

7.1 Introduction

The accurate prediction of ventilation systems required a state-of-the-art tool that is reliable, cost effective, easy to use and readily available. The simulation of hospital ward models using the selected Computational Fluid Dynamics (CFD) simulation software Fluent 13.0 requires validation. In this study the accuracy of the CFD simulated hospital wards was validated against the full-scale measurement results of ventilation rates using tracer gas techniques that are presented in the previous chapter (Chapter 6). Moreover, apart from the validation results, this chapter (Chapter 7) also presents the processes and guidelines followed in conducting the CFD simulation together with the boundary conditions employed. The guidelines consist of the processes right from model construction, computational mesh, atmospheric boundary layer profile, turbulence model and convergence criteria. The Fluent 13.0 software was used to study various natural ventilation strategies to improve indoor air quality in hospital wards.

7.2 Ventilation performance prediction using Computational Fluid Dynamics (CFD)

The fundamental fluid motion equations that formed the basis of Computational Fluid Dynamics (CFD) techniques exist since the 19th century. Moreover, over four decades ago engineers and mathematicians used these techniques in solving flow problems in the area of industrial engineering. However, effective numerical solution techniques and the capacity to execute those on computers is required to employ these methods for the resolution of problems with complex geometries and boundary conditions (Blocken and Gualteri, 2012). It is generally acknowledged that earlier prediction and analyses of future building behaviour is far more efficient and cost-effective than resolving problems when the building is in its occupancy period (Hensen and Lamberts, 2011). CFD is a tool for predicting airflow in buildings right from the design stages. Other prediction tools such as wind tunnel and full-scale measurements are costly and very difficult for comparative studies.

CFD is widely used in building design and the choice of a CFD solution is often determined by several factors. These factors include the complexity of the building system being considered, unavailability of other suitable methods, cost and time implications, promoting the design feasibility, and the confidence in the use of CFD

(Nielsen et al. 2007). CFD simulation models can furnish researchers with detailed information on the interested indoor environment design parameters such as air velocities, temperatures, and contaminant concentrations. These models are suggested as an economical approach compared to full-scale measurements/wind tunnel and the outcomes are more detailed compared to the multi-zone airflow network models. CFD model usually splits the interior space into a number of cells, in which the conservation of mass is satisfied for each cell, in order to balance the sum of mass flows into or out of a cell from all its neighbours to zero. Likewise the momentum exchange from the flow into or out of a cell have to be balanced in each direction with pressure, gravity, viscous shear, and energy transport by turbulent eddies (Srebric, 2011). In the present study, the Fluent 13.0 CFD code was used by implementing the pressure based solver, with absolute velocity formulation and steady state simulation time. The typical process implemented in using CFD Fluent is illustrated in figure 7.1.

Although, ventilation performance can be evaluated through experimental techniques such as analytical or semi-empirical formulae, zonal and multi-zone network models simulations, but computational fluid dynamic (CFD) models (Ramponi and Blocken, 2012) are the easiest, cost effective, practical, flexible and reliable. CFD has been used extensively in research on natural ventilation of buildings (e.g. Jiang and Chen, 2002; Jiang et al., 2003; Heiselberg et al., 2004; Wright and Hargreaves, 2006; Cook et al., 2005; Chen, 2009; Norton et al., 2009, 2010; Hensen and Lamberts, 2011; van Hooff and Blocken, 2010a, 2010b; van Hooff et al., 2011; Blocken et al., 2011; Ramponi and Blocken, 2012). In this study CFD was used to evaluate the performance of natural ventilation strategies in reducing the effects of mosquitoes and Harmattan dust in hospital multi-bed wards of semi-arid climates of Nigeria. This is attributable to the fact that Computational Fluid Dynamics simulations have greater advantages over other methods such as theoretical models and experimental measurements when evaluating ventilation performance, particularly for sophisticated buildings within a complex built environment. Some of the key advantages of CFD include the permission of full control over the boundary conditions, simultaneous data provision in every point of the computational domain, allows simulation in full scale thereby eliminating any scaling limitations and enable effective parametric analysis of different configurations under different conditions (Blocken and Gualteri, 2012). Moreover, CFD can offer exhaustive information about fluid behaviours such as indoor air flow patterns, temperature, air movement, indoor pollutants, local draught distribution and pressure drops (Yang et al, 2006). This is attributable to the significant enhancements of computer facilities and computational fluid dynamics software in the recent years (Tominaga et al. 2008).

The input data were obtained from various sources including published literatures and physical (full-scale) measurements. The typical stages of CFD simulation process is illustrated in figure 7.1.

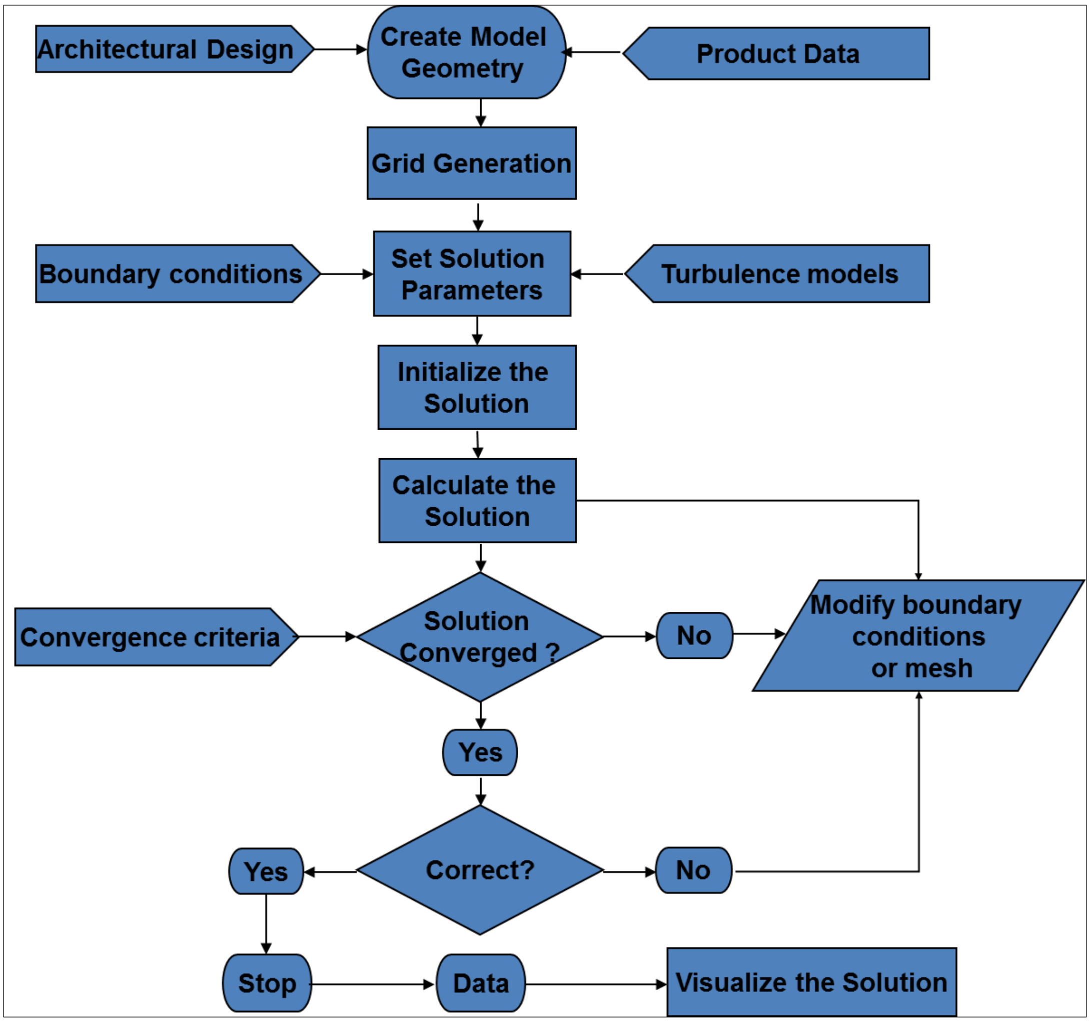


Figure 7.1: The CFD Simulation Process

7.2.1 *Model Geometry Creation*

The Model creation is the first stage of the simulation which involves the building of the geometry to be simulated. The geometry is either created from scratch or through adapting Computer Aided Design (CAD) or similar standalone geometry design programs such as Rhino etc. This geometry should be simplified to enable effective CFD solutions. However, the simplification and adjustment of geometry has to be handled carefully, with proper knowledge of the physical process that can affect the flow, to avoid unnecessary error in the final simulation outcome (Nielsen et al. 2007). In this study, the model was created using the ANSYS design modeller software. This is because model created from

ANSYS design modeller is more compatible with Fluent 13.0 simulation software compared to other modelling programs.

7.2.2 Computational Mesh Creation

Meshes are basically divided into structured and unstructured meshes. The structured consisting of horizontal and vertical lines crossing orthogonally at intersections called nodes, while in unstructured meshes, a 2-D physical domain is discretised by a set of apparently randomly placed nodes that are coupled to other nodes by triangular or quadrilateral elements. These elements are either linear three-noded triangles or linear four-noded quadrilaterals. Moreover, unstructured mesh generation involves additional consideration and effort compared to structured meshes. They are better suited for complex geometries because they can be adapted to any shape (Pepper, 2009).

The computational mesh must be fine enough to allow sufficient resolution of the flow. Generating an appropriate mesh depends upon the anticipated flow and transport behaviour. Producing an acceptable mesh may involve a number of attempts with further perfections as the calculations progresses in time. Therefore, it is essential to create a mesh-independent solution, which does not considerably vary with mesh refinement. This involves several solutions with finer meshes until consistent solution is achieved (Pepper, 2009). In this study, the computational grids were generated using state-of-the-art meshing software called Harpoon. Harpoon software has advantage over many other grid generation tools because, it gives the investigator greater control to manipulate and refine the mesh at the area of interest easily. The geometry produced with ANSYS design modeller were exported as 'STEP' (stp) files to Harpoon meshing software, where the computational meshes were created. Generally, structured grids used in this study are 'Structured Cartesian' grids encompass continuous grid lines across the domain with quadrilateral or hexahedral grid cells.

Owing to the considerable influence of cells size on the solution, careful selection of cell sizes in meshing is essential. Ideally, a cell should be smaller than the length scale of the key flow feature (Pepper, 2009). The key floor features in the context of this research are the openings (windows).

7.2.3 Solution boundaries

The selection and setting of appropriate solution boundaries such as solution methods, solution controls and solution initialization is important and sometimes affects the convergence of CFD simulations. In the present study the ‘Coupled’ algorithm was applied for pressure velocity coupling; together with ‘PRESTO’ pressure interpolation scheme and the ‘Second Order’ upwind discretisation schemes were used for momentum, turbulent kinetic energy, turbulent dissipation rate and energy. However, in terms of solution control, the default flow courant number of 200 was maintained. The explicit relaxation factors of 0.2 and 0.5 for momentum and pressure has been used. The default under-relaxation factors of 1 were maintained for density, body forces, turbulent viscosity and energy. However, the under-relaxation factors of 0.5 were used for turbulent kinetic energy and turbulent dissipation rate.

Moreover, the standard initialization was used, with relative to cell zone reference frame. The initial values were determined by the boundary conditions set. These includes the User Defined File (UDF) for velocity, turbulent kinetic energy, turbulent dissipation rate and roughness constant Cs, and the temperature which was directly imputed at the inlet boundary condition. In addition, prior to running the calculation, the ‘Fluent’ inbuilt case check button was used to check the case for errors such as skewedness. The numbers of iteration were set at 10000, and the calculation/simulation was initialised and started.

7.3 Computational domain

The computational domain usually encloses only portion of the entire control volume and environment (Zigh and Solis, 2013). It surrounds the physical boundaries designated within the urban environment for the application of the required boundary conditions. The area that will be represented and the boundary conditions that will be used, determines the whole size of the computational domain in the vertical, sides and flow directions. The range of the building area that is represented in the computational domain is subject to the influence of the features on the region of interest (Franke et al. 2007). The domain size should be carefully chosen to avoid interference with the fluid flow, while considering the availability of computer memory and processor speed (Hou and Ma, 2008). The larger the computational domain the more computer memory and processor speed it requires for calculation. Hence, the selection of the location of the limits of the computational domain influences the simulation results (Zigh and Solis, 2013).

The computational domain is generally divided into three different sections as illustrated in Figure 7.2. The first section is the domain’s central region, where the real obstacles (buildings, trees, stack etc.) are explicitly modelled with their geometric shape. The second and the third sections are the upstream and the downstream regions of the domain, where the real obstacles are modelled implicitly. In this section, only the effect of the geometry on the flow in terms of roughness characteristics rather than the actual geometry is modelled in the computational domain. The roughness characteristics are set through the application of wall functions to the bottom of the domain (Blocken, et al. 2007).

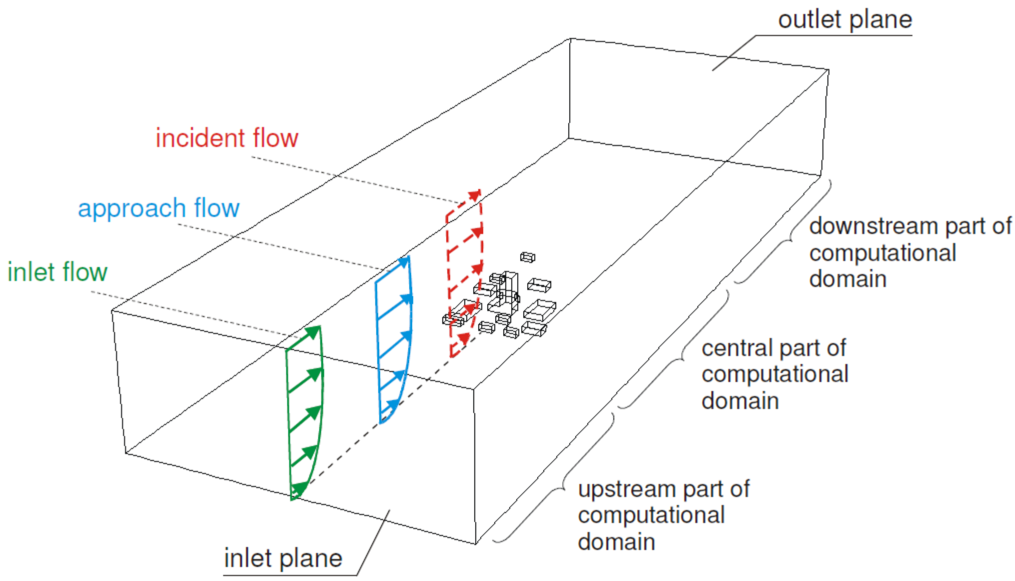


Figure 7.2: Computational domain with building models for CFD simulation of ABL showing inlet flow, approach flow and incident flow

In this study, the computational domain was designed based on the recommendation of Franke et al. (2007) for single building. The computational domain height should be at least 5H (H is the building height which is 3.3 metres) above the roof of the building and similarly the lateral or side extensions should be 5H as well. Moreover, regarding the longitudinal extension of the domain, the front region (approach flow) and the region behind (wake) of the building area have to be distinguished. The distance between the inlet boundary and the building is recommended to be at least 5H, if the approach flow profile is well-known. The region behind the building extending up to the outlet boundary should be positioned at least 15H after the building to permit flow re-development behind the wake region. Moreover, fully developed flow is usually used as a boundary condition in steady RANS calculations (Franke et al. 2007). In the present study, the fully developed flow was achieved by initially performing the simulation in an empty domain repeatedly until the homogeneous fully developed flow is achieved. The outlet pressure boundaries of the empty domain were then used as inlet boundary conditions. A computational domain of dimension 44.8 m x 75.86 m x 19.80 m (l x w x h) was used according to the guideline suggested by Franke et al. (2007) and Tominaga et al. (2008) as described earlier to avoid domain size interference on the numerical simulation results.

7.3.1.1 Coupled Computational Geometry Approach

Coupled approach has single computational geometry and computational domain comprising both outside and inside environment of the building. However, decoupled approach has two different computational geometry and computational domains, for outdoor and indoor environments in each case (Ramponi and Blocken, 2012). In this study, the coupled approach has been adopted. In this approach the ventilation openings are presumed open and the outdoor wind flow and indoor airflow are solved inside the same computational domain. The major reason for the widespread use of the coupled approach is the realization that, it doesn’t introduce important errors like decoupled approach in case of large ventilation openings (Ramponi and Blocken, 2012).

7.4 Atmospheric Boundary Layer (ABL)

Atmospheric Boundary Layer (ABL) is the lowest part of the earth’s atmosphere with characteristics that are directly influenced by the contact with earth’s surface (Zhang, 2009). In order to achieve accurate and reliable predictions of the atmospheric processes in the lower part of the atmosphere, accurate simulation of the ABL flow in a computational domain is essential (Blocken, et al. 2007).

ABL can be largely divided vertically into three parts. The lowest part is referred to as *laminar bottom layer* with a thickness equal to aerodynamic roughness length z_0. The second layer after the laminar bottom is a layer where turbulence is fully developed, known as *Prandtl* or surface layer with vertical length ranging from 20 to 100 meters, subject to the thermal stratification of the air. The third layer of the ABL above Prandtl layer is called *Ekman* layer reaching a height beyond 1000m, subject to the Coriolis parameter, ground roughness height and air surface stability (Zhang, 2009). The typical description of the ABL is illustrated in Figure 7.3.

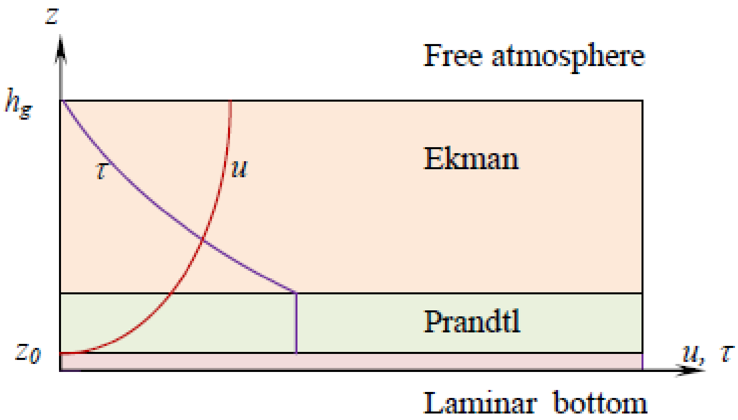


Figure 7.3: Subdivision of the Atmospheric Boundary, with conceptual illustration of vertical distribution of horizontal velocity and shear stress within the boundary layer (Zhang, 2009)

The generally used terrain surface roughness classifications are shown in Table 7-1 and 7-2 for different terrains. Both tables are describing roughness length (z_o) in metres, but the second classification (Table 7.2 is more detailed and specific with more categories compared to the first classification (Table 7.1). Thus the second classification was employed in the present study.

Table 7-1: Surface roughness lengths

Type of terrain	Roughness length z_0
Cities, forests	0.7
Suburbs, wooded countryside	0.3
Villages, countryside with trees and hedges	0.1
Open farmland, few trees and buildings	0.03
Flat grassy plains	0.01
Flat desert, rough sea	0.001

Source: Zhang (2009)

Table 7-2: Davenport classification of effective terrain roughness (Wieringa et al, 2001)

S/N	Z_0 (m)	Landscape Description
1.	**0.0002** "Sea"	Open sea or lake (irrespective of wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometres.
2.	**0.005** "Smooth"	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g. beaches, pack ice without large ridges, marsh and snow-covered or fallow open country.
3.	**0.03** "Open"	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g. grazing land without wind breaks, heather, moor and tundra, runway area of airports. Ice with ridges across-wind.
4.	**0.10** "*Roughly Open*"	Cultivated or natural areas with low crops or plant covers, or moderately open country with occasional obstacles (e.g. low hedges, isolated low buildings or trees) at relative horizontal distances of at least 20 obstacle heights.
5.	**0.25** "Rough"	Cultivated or natural area with high crops or crops of varying height, and scattered obstacles at relative distances of 12 to 15 obstacle heights for porous objects (e.g. shelterbelts) or 8 to 12 obstacle heights for low solid objects (e.g. buildings).
6.	**0.5** "Very Rough"	Intensively cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 8 obstacle heights. Low densely-planted major vegetation like bush land, orchards, young forest. Also, area moderately covered by low buildings with interspaces of 3 to 7 building heights and no high trees.
7.	**1.0** "Skimming"	Landscape regularly covered with similar-size large obstacles, with open spaces of the same order of magnitude as obstacle heights; e.g. mature regular forests, densely built-up area without much building height variation.
8.	**≥ 2.0** "Chaotic"	City centres with mixture of low-rise and high-rise buildings, or large forests of irregular height with many clearings.

Accurate interpretation of the flow close to the ground surface is necessary in virtually all CFD simulation of the lower part of the ABL. In a circumstances where an equivalent sand-grain roughness k_s is used in expressing the wall roughness in the wall functions; four conditions should be simultaneously fulfilled. This set of conditions has been extracted by Blocken et al. (2007) from different sources including CFD literature and software manuals as follows:

- An adequate high mesh resolution in the vertical direction close to the bottom of the computational domain (e.g. height of first cell < 1m);
- A horizontal homogeneous ABL flow in the upstream and downstream region of the domain;
- A distance y_p from the centre point P of the wall-adjacent cell to the wall (bottom of domain) should be greater than the physical roughness height k_s of the terrain ($y_p > k_s$); and
- Understanding the relationship between the equivalent sand-grain roughness height k_s and the corresponding aerodynamic roughness length z_0.

According to Blocken et al. (2007), with the k_s-type wall function, it is generally impossible to comply with all the above four requirements. This is simply because the fourth requirement of knowing the relationship between k_s and z_0 ($k_s = \frac{9.793 z_0}{C_s}$), combined with the third condition ($y_p > k_s$) suggests that enormous control volumes should be employed, which is in contradiction with the first requirement of high mesh resolution that will yield small y_p. Thus, in this study, coarse grid resolution was used in the computation domain and fine ones are employed in and around the building, which allows the achievement of both the first and fourth requirement.

The wind velocity in the lower parts of the earth's atmosphere is characterised by random fluctuations and their average over a fixed period of time, produces mean values of speed and directions. Since wind data are usually acquired from meteorological stations situated outside the urban environments. These wins speeds must be corrected for terrain conditions considering the building height relative to the wind measurement altitude, usually 10m above ground level (CIBSE, 2006). The approximate adjustment method proposed by BS 5925 is given as follows (equation 12):

$v_z = v_m \, k \, z^a$ ……………………………………………………………………………(12)

Where:

v_z = wind speed at the building height (m/s)

v_m = wind speed measures in open country at a height of 10 (m/s)
z = building height (m)
'k' and 'a' = constants dependent on the terrain

The terrain coefficient for wind speed as deduced from (CIBSE, 2006) is illustrated in Table 7.3

Table 7-3: Terrain coefficients for wind speeds

S/N	*Terrain*	*k*	*a*
1.	Open, flat country	0.68	0.17
2.	Country with scattered wind breaks	0.52	0.20
3.	Urban	0.35	0.25
4.	City	0.21	0.33

In the present study, since the meteorological data were obtained from a nearest meteorological station located outside the city, and these data should be corrected for terrain conditions. The wind speed at the city ($U_{city} = U_{ref}$) was calculated based on the expression of the vertical wind speed profile by the logarithmic law (Eq. 13) (Blocken et al. 2004) and the formula derived by simiu and scanlan (1986) (Eq 14) is used for the purpose of this study and is given as.

$$\frac{U_{10}}{U_{pot}} = \frac{U_{City} \cdot (z=10m)}{U_{meteo} \cdot (z=10m)} = \frac{u^*_{city} \cdot ln\left(\frac{10m}{z_{0,city}}\right)}{u^*_{meteo} \cdot ln\left(\frac{10m}{z_{0,meteo}}\right)} \quad \ldots\ldots (13)$$

$$\frac{u^*_{city}}{u^*_{meteo}} = \left(\frac{z_{0,city}}{z_{0,meteo}}\right)^{0.0706} \quad \ldots\ldots (14)$$

Where:

U_{10} = inlet wind speed in computational domain at 10m height (m/s)
U_{pot} = potential wind speed (m/s)
U_{city} = wind speed for city terrain (m/s)
U_{meteo} = wind speed at meteorological station (m/s)
u^*_{city} = friction velocity for city terrain (m/s)
u^*_{meteo} = friction velocity at meteorological station (m/s)
z_0 = aerodynamic roughness length (m)
$z_{0,\ city}$ = aerodynamic roughness length for the city terrain (m)
$z_{0,\ meteo}$ = aerodynamic roughness length for the terrain of the meteorological site (m)

The corrected wind speeds at the city (building positions) estimated using equation (19) and (20) has been presented in tables 7-4, 7-5 and 7-6 for the validation, velocity differences and monthly differences respectively. These velocities are used for the generation of the inlet velocity boundary conditions. Important factors such as the aerodynamic roughness length for the city terrain (m), wind speed and wind flow directions have been carefully considered.

Table 7-4: The corrected velocities at the building positions (city) for different cases validated

Wards	Cases	$Z_{0,\ city}$ (m)	Velocity at the meteorological station (m/s)	Corrected velocity at the city (m/s)	Wind flow direction
UMTH	Case 1	1.0	1.5	0.8	070
	Case 2		3.1	1.6	080
USUHM	Case 3	0.5	3.1	2.0	070
	Case 4		2.6	1.6	070
	Case 5		4.1	2.6	080
FNPHM	Case 6	0.1	2.1	1.8	060
NHHM	Case 7	1.0	4.1	2.1	070
	Case 8		2.6	1.3	070
	Case 9		2.6	1.3	070

Table 7-5: The corrected velocities at the building positions (city) for Different Velocities investigated

Cases	$Z_{0,\ city}$ (m)	Velocity at the meteorological station (m/s)	Corrected velocity at the city (m/s)
Velocity 7.0	0.5	7.0	4.40
Velocity 6.0	0.5	6.0	3.78
Velocity 5.0	0.5	5.0	3.15
Velocity 4.0	0.5	4.0	2.52
Velocity 3.0	0.5	3.0	1.89
Velocity 2.0	0.5	2.0	1.26
Velocity 1.0	0.5	1.0	0.63

Table 7-6: The corrected velocities at the building positions (city) for the 12 months investigated

Cases	$Z_{0,\ city}$ (m)	Velocity at the meteorological station (m/s)	Corrected velocity at the city (m/s)
January	0.5	4.94	3.11
February	0.5	5.90	3.72
March	0.5	6.10	3.84
April	0.5	5.80	3.65
May	0.5	5.81	3.66
June	0.5	6.06	3.82
July	0.5	5.66	3.57
August	0.5	4.62	2.91
September	0.5	4.49	2.83
October	0.5	4.55	2.87
November	0.5	5.10	3.21
December	0.5	4.68	2.95

7.4.1 Horizontal homogeneity

In order avoid unnecessary errors; the simulation of a horizontal homogeneous ABL over evenly rough terrain is very much essential in the upstream and the downstream region of the computational domain. "*The term 'horizontal homogeneous' refers to the absence of streamwise gradients in the vertical profiles of the mean wind speed and turbulence quantities, i.e. these profiles are maintained with downstream distance"* (Blocken et al. 2007). Therefore, horizontal homogeneity infers that the inlet profiles, the approach flow profiles and the incident profiles are identical (Blocken et al. 2007). To avoid profiles changes within the computational domain in front of the built area while generating the inflow profiles, begin the simulation with an empty domain with similar grid and periodic boundary conditions to acquire constant profiles that are equal to the velocity measurements at the meteorological station (Franke et al. (2007). This is because homogeneity can only happen in regions faraway from any obstacles, suggesting that the streamwise gradient of all variable should be zero (Richards and Hoxey, 1993). Hence, any horizontal inhomogeneity as a result of unintended differences between inlet profiles and incident profiles can affect the success of the CFD simulation, as slight variations to the incident flow profiles is capable of causing substantial changes in the flow field (Blocken et al. 2007).

Many researchers have reported problems in achieving homogeneous ABL profile. Richards and Younis (1990) observed in the computational modelling work of Matthews (1987) that by employing empirical equations for the inflow boundary conditions, such as power law for velocity, a circumstance leading to rapidly varying approach flow in the inlet region of the computational domain was created. In order to prevent such problems, it is critical that the inlet velocity and turbulence profiles, the ground shear stress and the turbulence model should be in equilibrium (Richards and Hoxey, 1993).

In this study, horizontally homogeneous inlet profiles for velocity, turbulence parameters (Kinetic energy, dissipation rate, intensity) were achieved through the simulation of an empty domain with the required grid (0.48 x 0.48m) and periodic boundary conditions to acquire constant profiles that are equal to the velocity measurements at the meteorological station as suggested by Blocken et al. (2007) and Franke et al. (2007). The process of using the outlet profile of the empty computational domain as an inlet profile of similar domain was repeated continuously until homogeneous profiles were achieved in all the parameters of interest. The homogeneous profiles comparing velocity magnitudes, turbulence kinetic energy, turbulence dissipation rates and turbulence intensity in the inlet, building position and the outlet of the empty studied domain is illustrated in Figures 7.4 – 7.7.

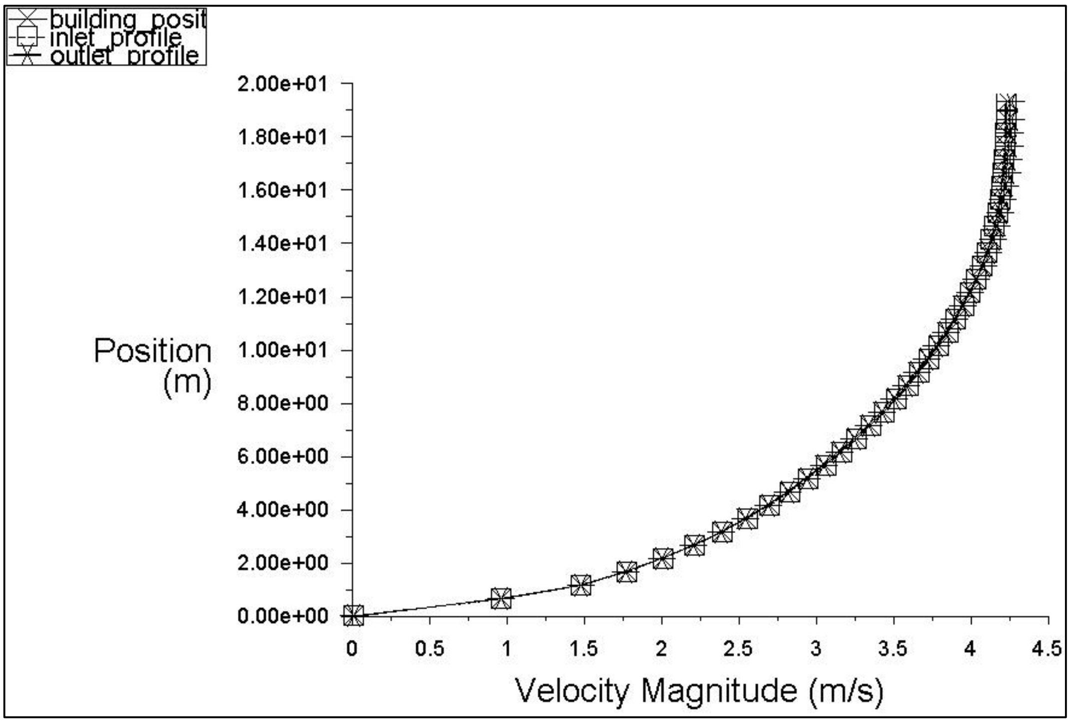


Figure 7.4: Vertical profiles of Mean wind speed at the inlet, outlet and the building positions of the computational domain showing homogeneity of the ABL profile

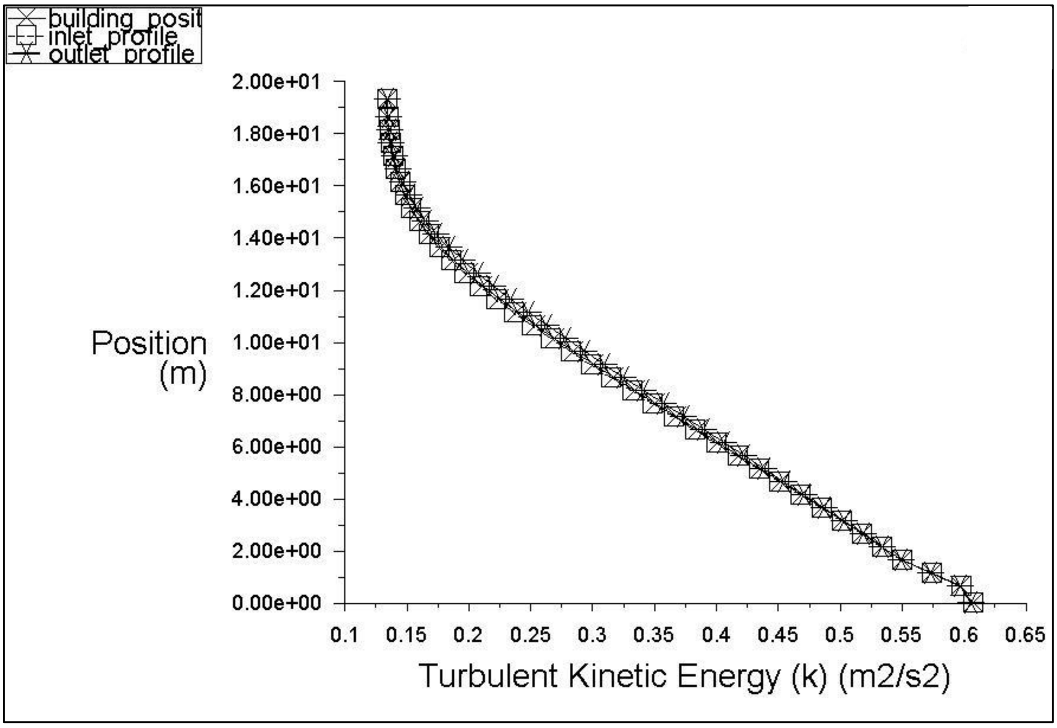


Figure 7.5: Vertical profiles of turbulent kinetic energy at the inlet, outlet and the building positions of the computational domain showing homogeneity of the ABL profile

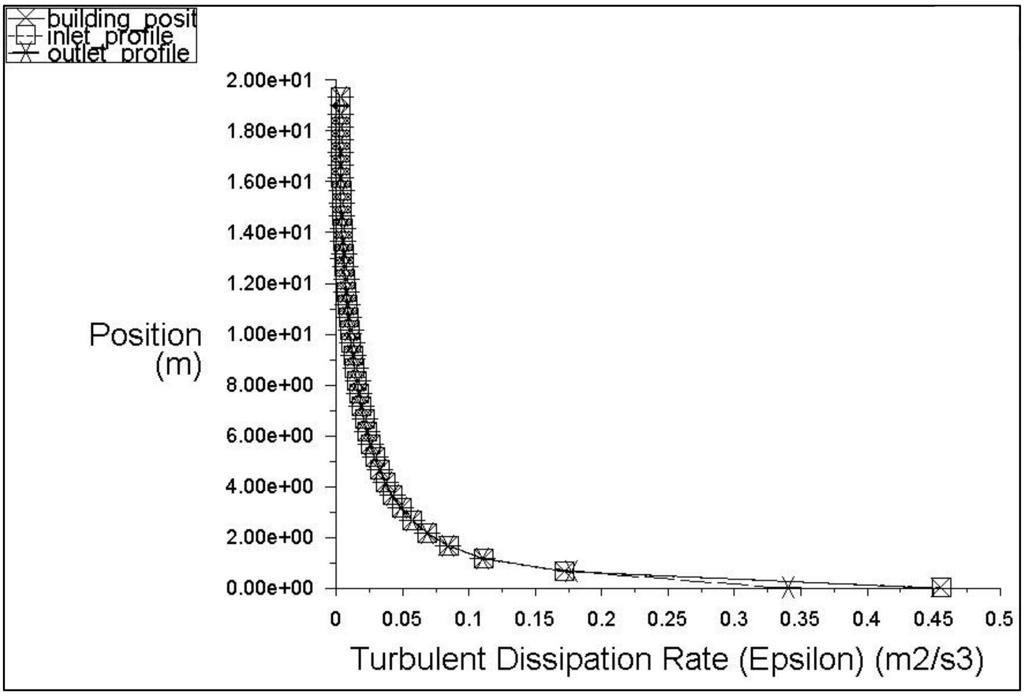


Figure 7.6: Vertical profiles of turbulent dissipation rate at the inlet, outlet and the building positions of the computational domain showing homogeneity of the ABL profile

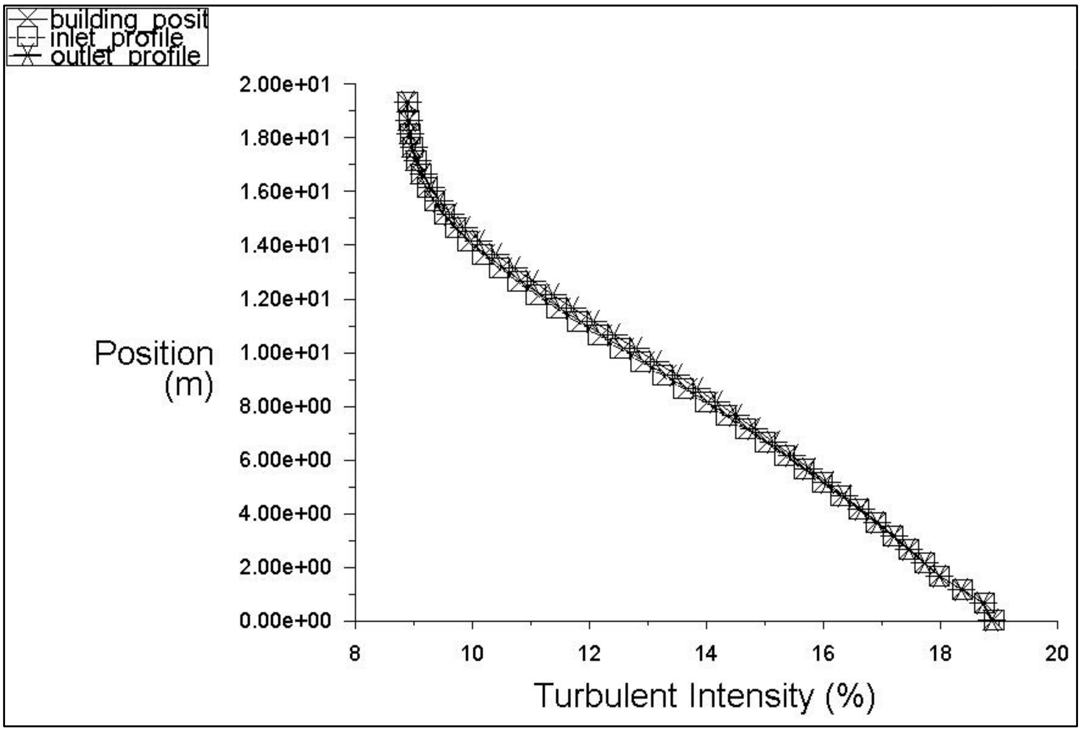


Figure 7.7: Vertical profiles of turbulent intensity at the inlet, outlet and the building positions of the computational domain showing homogeneity of the ABL profile

7.4.2 Wall Functions

Wall functions are usually applied to replace the actual obstacle, such as buildings and trees within the computational domain in CFD simulation of the ground roughness. They should have the same overall effect on the flow as the original obstacles. This roughness is expressed in terms of aerodynamic roughness length $z_{0,}$ or less frequently, in terms of the equivalent sand-grain roughness height for the ABL, $k_{S,\,ABL}$ (Blocken et al. 2007). The $k_{S,\,ABL}$ for large scale roughness (z_0) according to Wieringa, (1992) is quite high normally ranges from 0.03 m to 2 m, while the $k_{S,\,ABL}$ ranges from 0.9 m to 60 m (Blocken et al. 2007). Owing to the significance of the surface roughness and the high Reynolds numbers attached with ABL flows, the application of wall functions is usually essential for near-wall modelling. In most CFD codes, wall functions are normally based on the universal near-wall velocity-distribution (law of the wall), which is usually amended in accordance with the influence of rough surfaces (Blocken et al. 2007).

In this study, the standard wall function by Launder and Spalding (1974) was implemented together with sand-grain based roughness modification by Cecebi and Bradshaw (1977). This combination has been used in many researches (van Hooff and Blocken 2010b; Ramponi and Blocken 2012). The values of the factors, i.e. the sand-grain roughness k_s (m) and the roughness constant C_s in the roughness modification as required in Fluent CFD software, are defined based on their suitable relationship with the roughness length z_0 (m), as derived by blocken et al. (2007) for Fluent in eq. 15.

$$k_s = \frac{9.793 z_0}{C_s} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (15)$$

Where:
k_s = Sand-grain roughness height
C_s= roughness constant
z_0 = roughness length

In an attempt to take into account the roughness type, C_s which is the value of roughness constant was applied. But, owing to the absence in specific guidelines, the C_s value is generally prescribed at its default value of 0.5, which is originally aimed at sand-grain roughened pipes and channels. The required user inputs in most commercial CFD codes including Fluent are the values of the parameters k_s and C_s. but the value of C_s is restricted to remain between the interval of (0 and 1) in both Fluent 6.1 and 6.2 (Blocken et al. 2007). The graphical representation of fitting the mean-velocity ABL log-law inlet profile to the wall function for mean velocity in the centre point P of the wall-adjacent cell is illustrated in Figure 7.8.

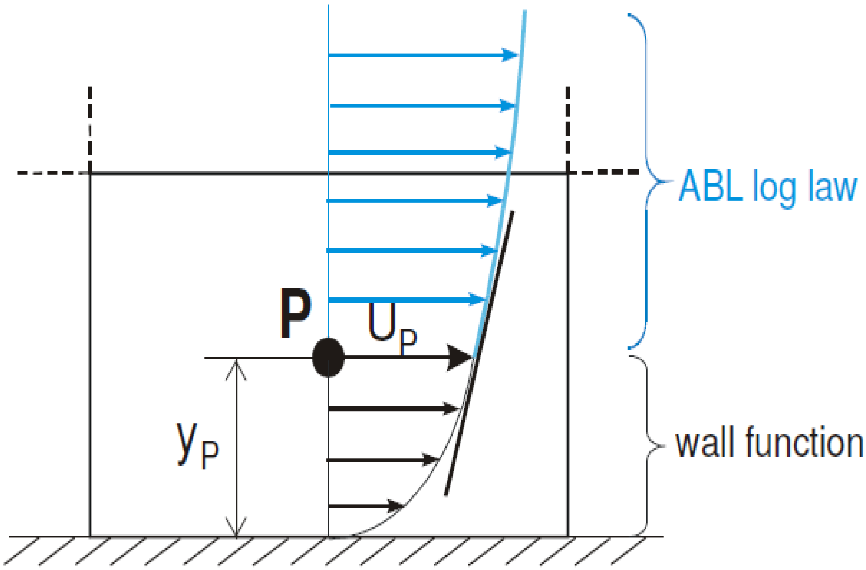


Figure 7.8: Graphical representation of fitting the mean-velocity ABL log-law inlet profile to the wall function for mean velocity in the centre point P of the wall-adjacent cell (Blocken et al. 2007)

7.5 Turbulence model -Reynolds-Averaged Navier-Stokes (RANS) equations

Owing to the high computational demands of more efficient turbulence models such as Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS), it is essential to select the approximate forms of the Reynolds-Averaged Navier-Stokes (RANS) equations, where a degree of physical modelling is used to decrease the physical complexity and the related computational demand. In RANS, turbulence model is used to model the influence of all or most of the turbulence scales on the mean flow and only the mean (time-averaged or ensemble-averaged) flow is resolved (Blocken and Gualteri, 2012. Moreover, according to Yang et al (2006), the reliability of RANS model predictions are more accurate in cases where the directions of wind are near normal to the ventilation openings.

In the present study, the 3D steady RANS equations were solved in combination with the realizable k-e turbulence model by Shih et al., (1995) using the commercial CFD code ANSYS Fluent 13.0. The k–ε model was selected due to its generally good performance in predicting indoor air flows in buildings (Linden, 1999; Sorensen and Nielsen, 2003). And the realizable k-ε turbulence model was chosen due to its good performance in predicting wind flows around buildings (Franke et al., 2004; Blocken et al., 2008; Blocken and Persoon, 2009; Van Hooff and Blocken 2010b; Blocken and Gualtieri , 2012; Teppnera et al. 2014). Moreover, Bacharoudis et al. (2007) used realizable k–ε model in their study after confirming its superior performance in flows boundary layer under strong pressure gradients using experimental data. Their simulation results indicate the ability of the realizable k–ε model to realistically predict the behaviour of different environmental conditions and subsequently support the assessment of airflow rates. However, various studies have established that other turbulence models such as Large Eddy Simulation and Reynolds Stress Methods are more accurate than the RANS, but require significant computational power or resources (Seifert et al. 2006), which makes them difficult to use in this study.

7.6 Boundary Conditions

Boundary conditions employed in computational model of any airflow problems should be capable of producing a homogeneous boundary layer flow in the absence of the object of interest, which is usually a building. This is achieved by locating the boundaries sufficiently remote from the object (building), in order to reduce the effect of these boundaries on the region of interest. Additionally, flows through a rectangular computational domain with inlet through one face, the inlet boundary should provide velocity (v), turbulence kinetic energy (k) and turbulence dissipation rate (ε) profiles (Richards and Hoxey, 1993).

The inlet velocity boundary conditions were set based on available wind speed information from the nearby meteorological station in the study area and other parameters that are estimated based on the wind speed including turbulent kinetic energy and dissipation rates. This information is based on the corrected incident vertical profile wind speed, computed turbulent kinetic energy and turbulence dissipation rate. The standard way of determining the mean velocity profile is through the logarithmic profile corresponding to the upwind terrain using the roughness length (z_0) (Franke et al. (2007). The equations used in determining the vertical velocity profile (U), the friction velocity (u*), the turbulent kinetic energy (k) and the turbulent dissipation rate (ε) are presented in equations 16, 17, 18 and 19 respectively.

$$U(z) = \frac{u^*_{ABL}}{\kappa} ln\left(\frac{(z + z_0)}{z_0}\right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (16)$$

$$u^* = \frac{\kappa U_{ref}}{\ln\left(\frac{z_{ref}}{z_0}\right)} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (17)$$

$$k = \frac{u^{*2}_{ABL}}{\sqrt{C_\mu}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (18)$$

$$\varepsilon = \frac{u^{*3}_{ABL}}{\kappa(z + z_0)} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (19)$$

Where:
U_{ref} = reference wind speed at reference height z
u^* = friction velocity
ƙ = 0.42(the von Karman constant)
z_0 = ground roughness height
z_{ref}= reference height 3.3m
C_μ= 0.09 (the model constant of the standard k-ε model)
ε= turbulence dissipation rate
z= height above ground level

The vertical profiles of the velocity, turbulent kinetic energy and the turbulent dissipation rates are presented in Figure 7.9, 7.12 and 7.11.

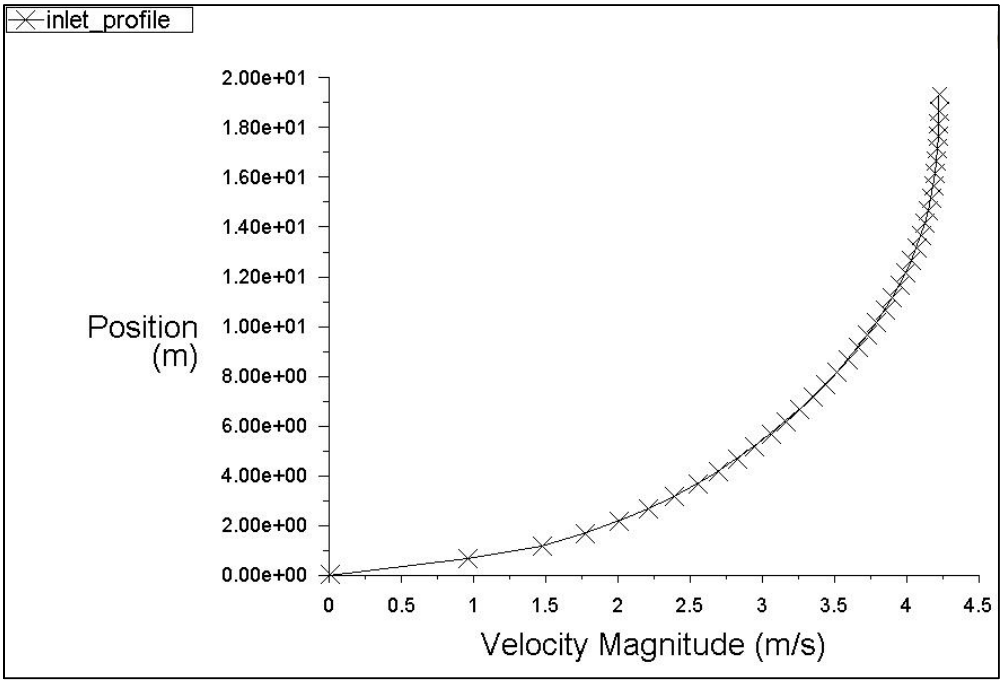


Figure 7.9: Inlet velocity magnitude profile

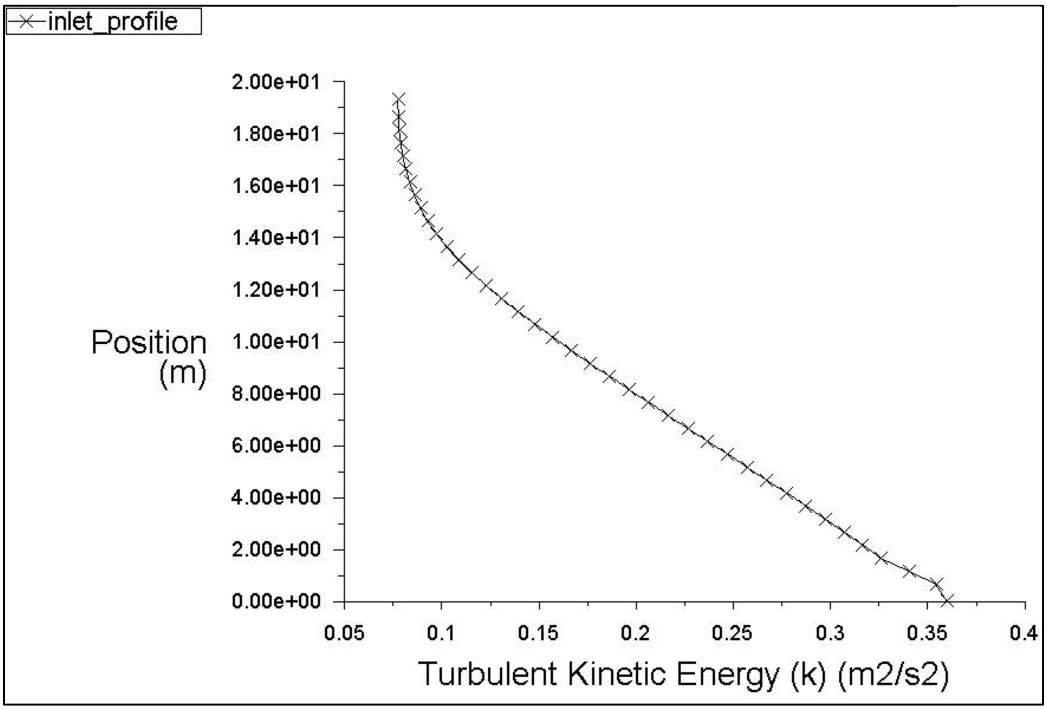


Figure 7.10: Inlet Turbulence Kinetic Energy Profile

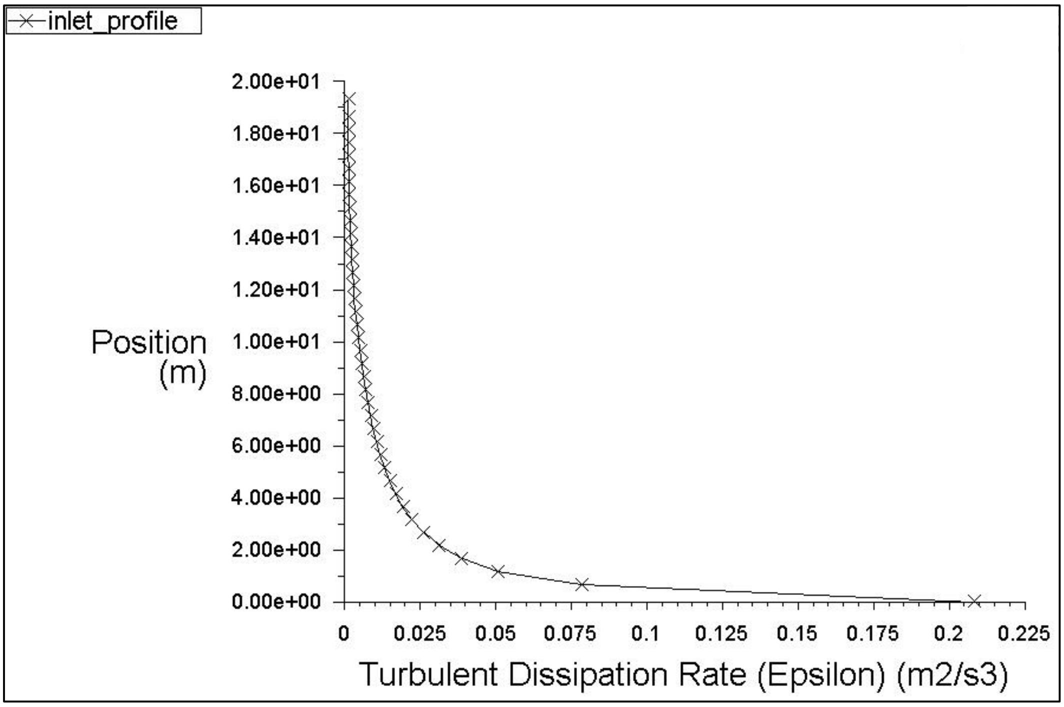


Figure 7.11: Inlet Turbulent Dissipation rate Profile

7.7 Porous Media Boundary Condition

In CFD simulation of openings with installed insect screens, information on the characteristics of the screen is required including screen permeability (K), inertial factor (Y) and the screen thickness. Cook et al. (2005) used porous medium boundary condition in modelling fine wire gauze used for absorbing momentum from incoming air, to enable the imposition resistance to airflow. The prescription of resistance while using porous medium boundary is done using volume porosity and the resistance vector of the flow. Moreover, in order to evaluate the characteristics of the window screen material to determine their permeability K, and inertial factor Y, the correlation derived by Miguel et al. (1997) relating the screen permeability and inertial factor to the porosity has been adopted as shown in equations 20 and 21 respectively.

$K = 3.44 \times 10^{-9}\alpha^{1.6}$ ………………………………………….…………………. (20)

$Y = 4.3 \times 10^{-2}\alpha^{-2.1}$ ………………………………………….………………….. (21)

Where α is the screen porosity

A typical insect screen of porosity 0.66 and porous medium thickness 0.36mm was used for the calculation of the screen permeability and inertial loss factor. The calculated face permeability (K) is 1.77×10^{-9}, while the pressure jump coefficient (C_2) of 297.5 was estimated by dividing the inertial factor with the porous media thickness. The insect screen was simulated as a porous jump boundary condition. All the Air Change Rates (ACR) results obtained are simulated with insect screen installed as obtainable in the existing hospital wards of the study area.

7.8 The Selected Hospital Wards Building Materials and Indoor air Properties

7.8.1 Building Envelope (Wall)

The material used for the construction of the building envelope (Wall) in the existing Multi-bed wards studied is concrete hollow block wall of thickness 150 mm and 230 mm for internal and external wall respectively. The properties of the hollow concrete block wall that are required as input to the simulation of the thermal characteristic of the multi-bed wards including thermal conductivity, density, absorptivity, specific heat emissivity and heat transfer coefficient. The properties of the above named parameters are presented in table 7-7.

Table 7-7: Properties of Concrete Hollow Block

S/N	Parameters	230 mm Hollow block wall
1	Density	1922 kg/m^3
2	Thermal Conductivity	0.86 W/m-k
3	Specific Heat	840 J/kg-k
4	Absorptivity	0.56-0.69
5	Emissivity	0.94
6	Heat Transfer Coefficient	2.46

7.8.2 Concrete Slab and sand

The properties of the concrete slab and sand that are required as input to the simulation of the thermal characteristic of the multi-bed wards including thermal conductivity, density, and specific heat are presented in table 7-8.

Table 7-8: Properties of Concrete slab and Sand

S/N	Parameters	Concrete Slab	Sand
1	Density	2000 kg/m^3	1500 kg/m^3
2	Thermal Conductivity	1.13 W/m-K	0.3 w/m-K
3	Specific Heat	1000 J/kg-K	800 J/kg-K

7.8.3 Indoor Air Properties

Air is the most important element in ventilation studies. A comprehensive property of air is required to setup a simulation case for natural ventilation and indoor air quality studies. Parameters such density, thermal expansion coefficient, specific heat capacity and gravitation force of attraction were considered for setting up the computational model. The values for the above mentioned parameters are shown in table 7-9.

Table 7-9: Properties of Air

S/N	Parameters (Air)	Properties
1	Density	1.1842 kg/m^3
2	Thermal Expansion Coefficient	3.20 x 10^{-3} (t = 40^{o}C)
3	Specific Heat Capacity	1004.99
4	Gravitation Force	-9.81m/s^2

7.9 Model Validation and Calibration Studies

Roache, (2009) defines Validation as: *"The process of determining the degree to which a model and its associated data is an accurate representation of the real world from the perspective of the intended uses of the model."* However, Roache, (1997) citing disagreements on the interpretations of the previous meaning, defines validation more precisely as the process of ensuring that, the right equation is solved in a calculation. Blocken and Gualteri, (2012) defines validation as the process of evaluating uncertainties in simulation modelling with benchmark experimental data and, when required estimating the sign and extent of the modelling errors. Moreover, Roache, (1997) in distinguishing validation from verification, affirmed that, *verification* means solving the equation right, while *validation* denotes solving the right equation. Logically, a code cannot be validated, but a calculation or range of calculations with a code can be validated. In other word, it is only model that is validated, and codes are only verified (Roache, 2009).

Computational Fluid Dynamic studies need to be validated due to the possibility of error from different sources including the CFD code errors, and user errors. The results obtained from CFD simulation is widely accepted to be very sensitive to the various computational parameters that is being set by the user. According to Blocken and Gualteri, (2012), some of these computational parameters for typical simulation include; *"the target variables, the approximate form of the governing equations, the turbulence model, the computational domain, the computational mesh, the boundary conditions, the discretization schemes, and the convergence criteria"*. The confident of users in ensuring that the results obtained are reasonable when running numerical simulations is essential. It is ideally recommended to compare predictions with high-quality measurements (Pepper, 2009).

However, Calibration is a process of modification or tuning of free parameters in a model to match with experimental data (Roache, 2009). Calibration is different from validation. It is also defined as the 'de facto' modification of physical and numerical model input parameters to adjust the agreement between model results and corresponding experimental data (AIAA G-077, 1998). According to Hajdukiewicz et al. (2013) the rationale behind systematic calibration of CFD models in indoor environments studies is;

(i) To reliably predict the environmental conditions that meets the agreement with the full-scale measurements; and
(ii) To enhance the prospect of accurately simulating the indoor environment with varying input parameters.

The model is considered as a true representation of the real environment, when it satisfied the specified validation criteria. A parametric analysis would be implemented if the criteria were not fulfilled, which assists in establishing the most influential boundary conditions to the results (Hajdukiewicz et al. 2013)

7.10 The CFD Validation results

The air change rates (ACR) were estimated with insect screen installed in all openings to mimic the existing buildings in the study area and the models are duplication of the existing wards, simulated in a virtual environment of CFD to validate the CFD models of the base-case. Moreover, the results of the full-scale measurement and the simulations were compared. In this study, wind induced cross ventilation strategies with different opening positions were tested using different reference wind speeds depending on the time of the measurements. The wind speed data was collected from the nearest meteorological station. The results obtained have been analysed in relation to the requirement of providing acceptable ventilation rate to achieve the ASHREA standard of 6 ach^{-1} (ASHRAE 2011; Ninomura and Bartley, 2001).

The validation study was carried using Fluent 13.0 Computation Fluid Dynamic (CFD) software, using the results from the full-scale measurements of nine (9) different cases from four hospital wards. The difference between these two measurements was found to be ≤15% (Willemsen and Wisse, 2002), which is within the acceptable error margin. The volumetric air flow rates of the individual openings and the total volumetric for rates and air change rates of the wards has been presented in table 7-10. The meaning of the W_Screen in table 7-10 is window with installed insect screen (Window Screen). The number of openings varies from one hospital ward to the other as illustrated chapter 5 (Figures 5.1 to 5.6). The number of openings for UMTH, USUHM, FNPHM and NHHM are 16 (8 inlets and 8 outlets), 8 (4 inlets and 4 outlets), 10 (5 inlets and 5 outlets) and 3 (1 inlets and 2 outlets) respectively as illustrated in table 7-10 and 7-12.

Table 7-10: Volumetric airflow rates of individual openings and air change rates of cases 1 to 9

Openings	**Volumetric airflow rates**								
	UMTH		**USUHM**			**FNPHM**	**NHHM**		
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**
W_Screen_1	-0.09	-0.10	-0.13	-0.09	-0.14	-0.14	-0.08	-0.031	-0.031
W_Screen_2	-0.13	-0.20	-0.12	-0.07	-0.13	-0.12	-0.08	-0.032	-0.032
W_Screen_3	-0.15	-0.20	-0.10	-0.06	-0.11	-0.11	0.16	0.063	0.063
W_Screen_4	-0.16	-0.20	-0.07	-0.04	-0.10	-0.10	-	-	-
W_Screen_5	-0.18	-0.20	0.14	0.10	0.10	-0.10	-	-	-
W_Screen_6	-0.18	-0.19	0.12	0.07	0.10	0.10	-	-	-
W_Screen_7	-0.19	-0.11	0.09	0.05	0.13	0.10	-	-	-
W_Screen_8	-0.17	-0.10	0.07	0.04	0.20	0.11	-	-	-
W_Screen_9	0.30	0.04	-	-	-	0.12	-	-	-
W_Screen_10	0.24	0.01	-	-	-	0.14	-	-	-
W_Screen_11	0.19	0.02	-	-	-	-	-	-	-
W_Screen_12	0.13	0.09	-	-	-	-	-	-	-
W_Screen_13	0.12	0.10	-	-	-	-	-	-	-
W_Screen_14	0.09	0.25	-	-	-	-	-	-	-
W_Screen_15	0.08	0.30	-	-	-	-	-	-	-
W_Screen_16	0.10	0.49	-	-	-	-	-	-	-
Volumetric airflow rates	**1.25**	**1.30**	**0.42**	**0.26**	**0.48**	**0.57**	**0.16**	**0.063**	**0.063**
Air Change Rates	**4.18**	**4.34**	**3.31**	**2.05**	**3.78**	**2.23**	**6.32**	**2.49**	**2.49**

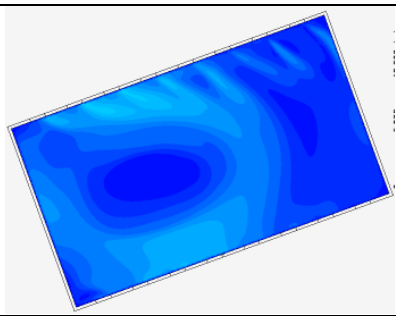
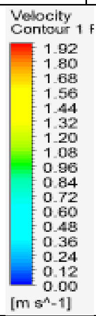
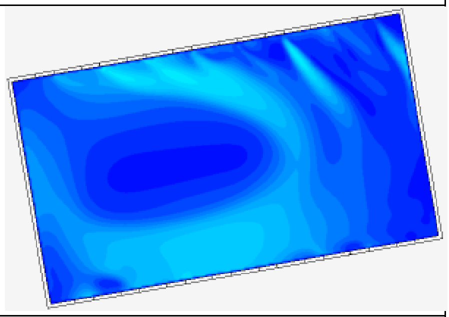
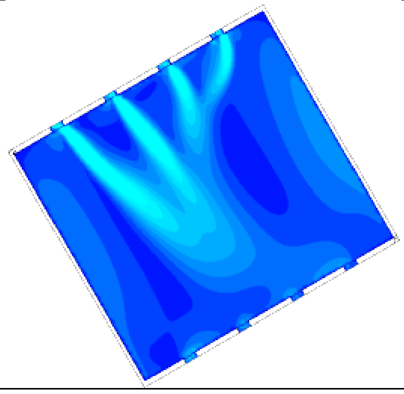
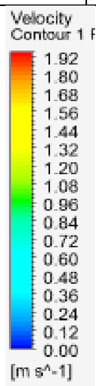
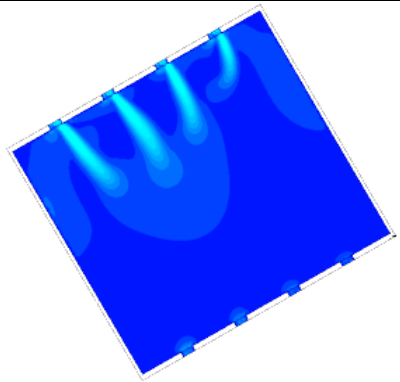
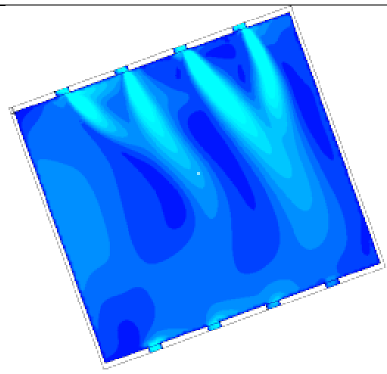
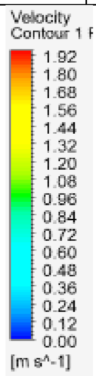
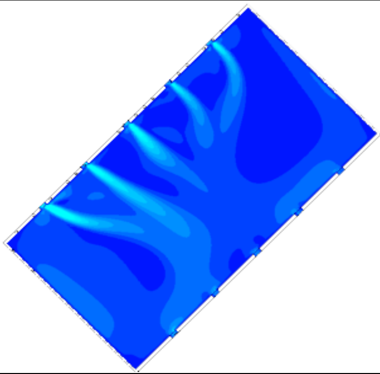
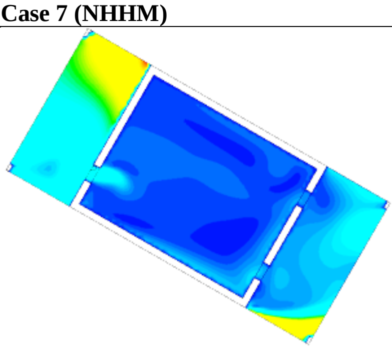
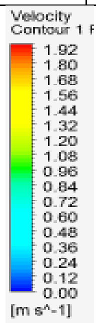
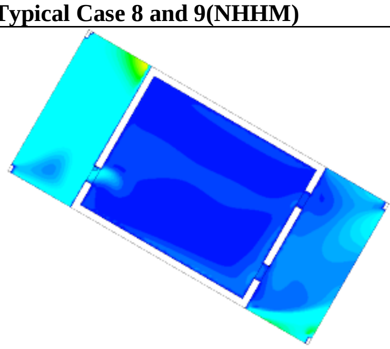
The hospital wards were modelled considering important factors that could affect ventilations rates. These factors include building orientations, outdoor wind speeds and surrounding terrain conditions. The outdoor prevailing wind speeds and direction data at the time of the full-scale measurements were obtained from the nearby meteorological station. Moreover, the terrain roughness conditions were estimated using the Davenport roughness classification adopted from Wieringa, et al. (2001).

In order to replicate the existing opening configuration, an insect screen with porosity of 0.66 (porosity of the insect screens installed on the existing hospital wards openings) has been installed on all the openings. The installation of these insect screens on the openings of the multi-bed ward to prevent mosquitoes has been associated with the reduction in ventilation rates. The horizontal section of the nine (9) simulated wards showing velocity magnitudes is illustrated in table 7-12. The building orientations in relation to the outdoor wind flow direction in all the nine (9) cases are not normal to the inlet openings. In table 7-12, Cases 1 and 2 are UMTH, Cases 3, 4 and 5 are simulations for USUHM, Case 6 is simulation from FNPHM and Cases 7, and 8 and 9 are simulations from NHHM. The two Cases 8 and 9 are presented with one diagram because they have the same ward and boundary conditions. The summary of the various boundary conditions used in the CFD simulation process are presented in table 7-11.

Table 7-11: Summary of boundary conditions used for the simulations

S/N	Boundary	Settings
1	Inlet profiles (U, u^*, k and ε)	Equations 16, 17, 18 and 19 (These equations were used as user-defined functions)
2	outlet	Relative static pressure is zero
3	ground	No slip rough wall (roughness heights: 0.1, 0.5, 1)
4	Building surfaces	No slip rough wall with zero roughness
5	Upper and side domains	Free slip symmetry
6	Domain size	44.8m x 75.86m x 19.80m
7	Mesh type	Hex-dominant structured grids
8	Turbulence model	k-ε Realizable
9	Discretization schemes	Second order upwind
10	Algorithm (pressure velocity coupling)	COUPLED
11	Pressure interpolation scheme	PRESTO
12	Time	Steady state simulation
13	Near wall treatment	Standard wall functions
14	Total number of cells (Average)	1.6 million
15	Reference height	10m
16	Roughness length (z_o)	See tables 7-4; 7-5 and 7-6
17	Reference mean wind speed inlet	2.6 m/s (4.1 m/s airport value): See tables 7-4; 7-5 and 7-6 for other wind speed values
18	Insect screen permeability (K)	1.77×10^{-09} (see equation 20)
19	Insect screen inertial factor (Y)	297.5 (see equation 21)
20	Insect screen porosity	0.66
21	Gravity	-9.81
22	Air density	1.842
23	Air temperature	27.8°C (Monthly averages were used for monthly simulations - see figure 2-1)
24	Ground roughness constant (Cs)	5
25	Ground roughness height (Ks)	0.98
26	Wall motion	Stationary wall
27	Heat transfer through walls/roof	adiabatic

Table 7-12: Contours of Velocity Magnitudes for the 9 Cases Validated

<table>
<tr><th>Wind flow direction</th><th>Case 1 (UMTH)</th><th></th><th>Case 2 (UMTH)</th></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>Case 3 (USUHM)</td><td></td><td>Case 4 (USUHM)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>Case 5 (USUHM)</td><td></td><td>Case 6 (FNPHM)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>Case 7 (NHHM)</td><td></td><td>Typical Case 8 and 9(NHHM)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>

The total volumetric airflow rates of the hospital wards obtained from the CFD simulation were compared with those obtained for the full-scale measurements. The result indicates that the CFD software over predicted cases 1, 2, 3, 4, and 8, while under predicts cases 5, 6, 7 and 9. The air flow rates for both full-scale measurement and the CFD simulation has been presented in table 7-13 and figure 7.12. These under prediction or over prediction of the volumetric airflow rates are mainly due to the fluctuations in the outdoor wind speeds and directions at the time of the measurement. Since, outdoor wind speed and direction data at the time of the measurements are hourly average data obtained from the nearby meteorological station and the period of the tracer gas measurements are less than an hour, the actual wind speed and direction at the time of the measurement might be slightly higher or lower than the average values used in the simulation. According to Lo et al. (2013), the basic assumption when using steady state simulation is that, there is a static condition in the inlet and outlet, however airflow characteristics in wind-driven ventilations are dynamic and unsteady.

Table 7-13: The Validation of the Measured Volumetric Flow Rates with CFD Simulation

Cases	Ward Location	Volumetric Flow Rates		Difference between CFD & Full Scale
		Full Scale Measurement	CFD Simulation	
Case 1	UMTH	1.10	1.25	13.8%
Case 2	UMTH	1.22	1.30	2.4%
Case 3	USUHM	0.37	0.42	7.5%
Case 4	USUHM	0.23	0.26	5.6%
Case 5	USUHM	0.53	0.48	7%
Case 6	FPHM	0.66	0.57	15%
Case 7	NHHM	0.17	0.16	6.7%
Case 8	NHHM	0.062	0.063	1.6%
Case 9	NHHM	0.067	0.063	4.6%

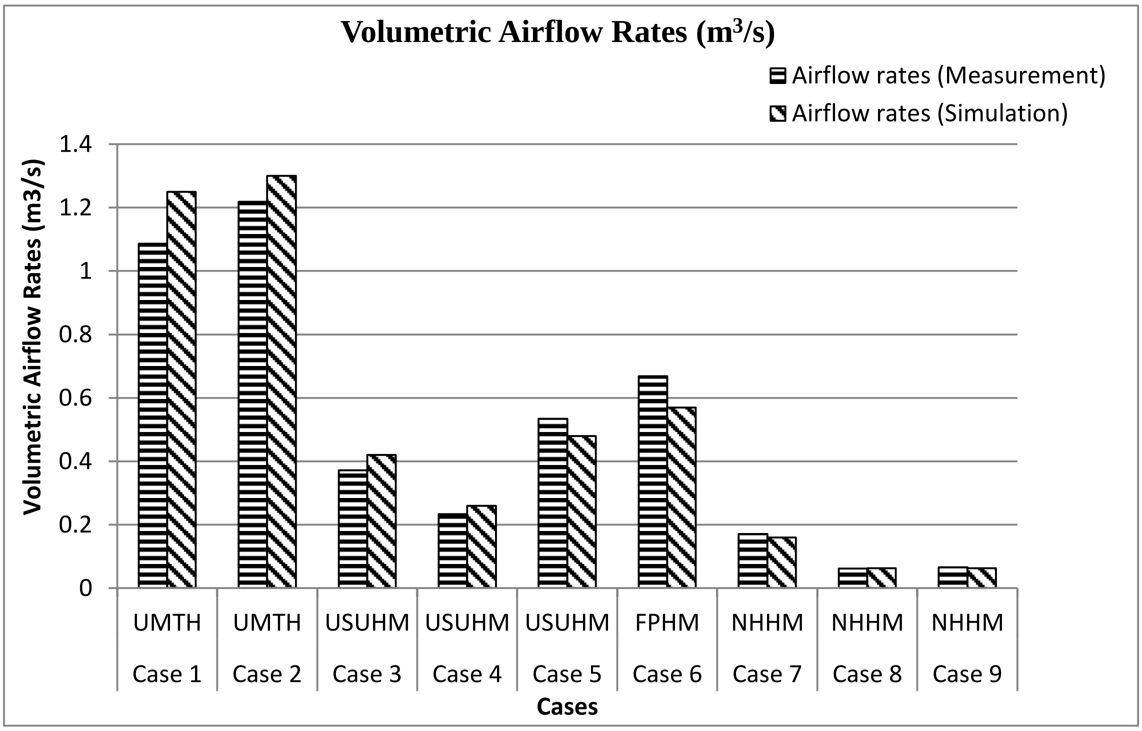


Figure 7.12: The Validation Results Comparing Air Flow Rates of Full-Scale Measurement and CFD Simulation

Consequently, the Air Change Rates (ACR) of the nine (9) cases were estimated using the simulated air flow rates and the results were also compared with the air change rates directly obtained from the full-scale measurements. The results of the validation comparing the ACR of the full-scale measurement and the simulation are illustrated in table 7-14 and figure 7-13.

Table 7-14: The Validation of the Measured Air Change Rates with CFD Simulation

Cases	Ward Location	Air Change Rates		% Difference between CFD & Full Scale
		Full Scale Measurement	CFD Simulation	
Case 1	UMTH	3.63	4.18	13.8%
Case 2	UMTH	4.07	4.34	2.4%
Case 3	USUHM	2.93	3.31	7.5%
Case 4	USUHM	1.84	2.05	5.6%
Case 5	USUHM	4.21	3.78	7%
Case 6	FPHM	2.61	2.23	15%
Case 7	NHHM	6.75	6.32	6.7%
Case 8	NHHM	2.46	2.49	1.6%
Case 9	NHHM	2.62	2.49	4.6%

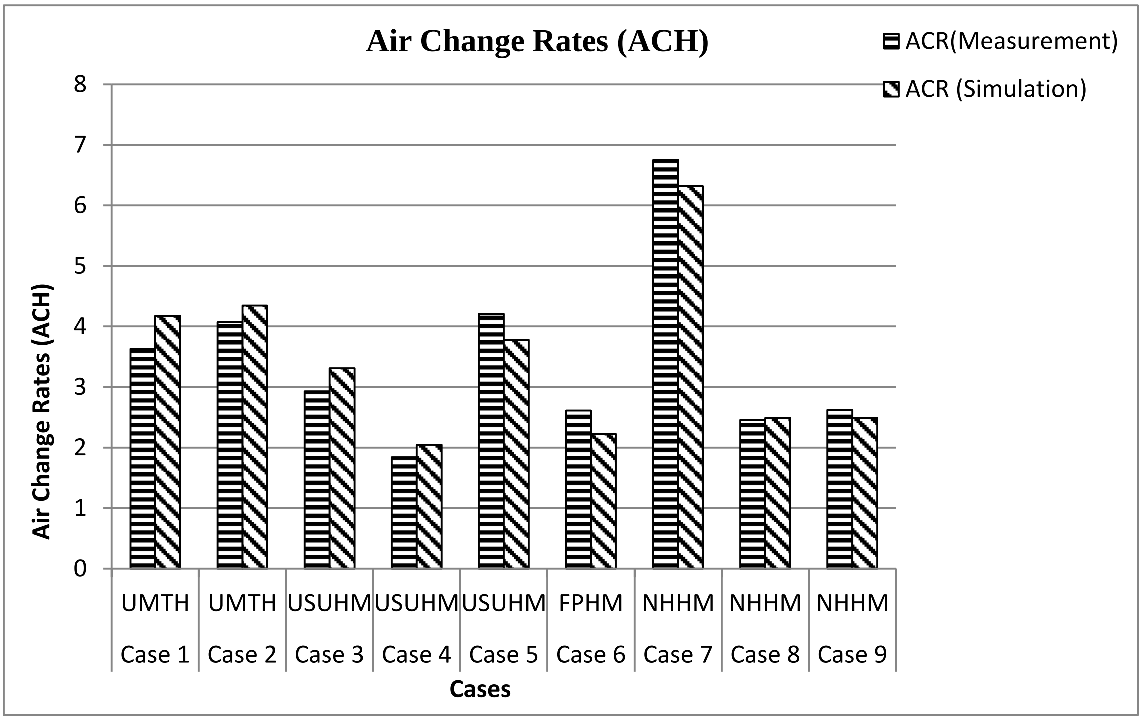


Figure 7.13: The Validation Results Comparing Air Change Rates of Full-Scale Measurement and CFD Simulation

7.10.1 Acceptable Error limits between CFD simulation and Full-scale Measurements

The errors realised between the full-scale measurements and the simulation results are possibly acquired from the full-scale measurement, as researchers have agreed with the possibilities of experiencing errors in this type of measurements. The errors obtainable from full-scale measurements could be larger than well controlled wind tunnel test (Easom, 2000). According to Yang (2004), the error range obtainable with full-scale measurement could reach 10 – 15%, while Willemsen and Wisse (2002) affirm that, errors implanted in full-scale measurements can extent up to 20%. Therefore, the 15% error experienced between the full-scale measurement and the simulations results in this study is within the acceptable error limit and could possibly be from the full-scale measurement.

Moreover, many factors could be responsible for the difference recorded between the full-scale measurement and the CFD simulation. The first factor is the measurement errors incurred during the full-scale measurements such as density difference between the air and the tracer gas, mixing errors, sampling position errors, blockages on the installed insect screens and fluctuation in wind speed and direction at the time of the measurement. The second factors that could be responsible for the errors between the full scale measurement and the CFD simulation are the assumptions in applying CFD boundary conditions. These assumptions include ground roughness length/height, computational grids, inlet velocity and homogeneity of the atmospheric boundary layer profile. Moreover, the simplification of the building model due to easy convergence and computational power restriction is also one of the major sources of error in simulation. The third factor responsible for errors between full-scale measurements and CFD simulation is measuring equipment and instruments.

7.10.2 Grid Independency Test

The Computational grids should be designed with fine resolution to represent important physical phenomena such as shear layers and vortices and to exclude too enormous errors. A local grid refinement should be employed especially in the regions of main interest, when systematic global refinement of the grid is unfeasible owing to limitations in computational power (Franke et al. (2007). When determining mesh resolutions, a compromise between accuracy and computational power should be handled wisely. Hirsch et al. (2002) recommended hexahedra shapes of computational cells compared to tetrahedral, because the former is known for its introduction of smaller truncation errors, while displaying better iterative convergence. In the present study, ‘Hex dominant’ mesh type with about 77% hexahedral cells was employed.

However, to ensure that simulation results are not sensitive to grids, a grid independency test is essential. Jiang et al. (2003) in their study realised that the disparity between two different grid resolutions in terms of the computed ventilation rates is less than 3%, and they consequently adopted the coarser mesh in their study. In the present study the grid independency test was carried out by refining the mesh until there is no change in the result of the simulation. Three different grid alternatives were used ranging from about 1 million cells to 2.2 million cells as shown in table 7-15. The result indicates that the difference between the three in terms of volumetric airflow rates is insignificant as illustrated in table 7-16 and figure 7.14. This result suggests that, the solutions are independent of the grids. Hence, the fine grid was adopted in the present study.

Table 7-15 Mesh Properties

Grid alternatives	Mesh Properties		
	Total No of Cells	*Total No of Nodes*	*No of Iterations*
Coarse Mesh	1,041,535	907,407	5,750
Fine Mesh	1,626,953	1,443,306	5,750
Finer Mesh	2,154,512	1,926,625	5,750

Table 7-16: The Volumetric Flow rates of three different Mesh sizes

Window Number	Volumetric Flow rates (m^3/s)		
	Coarse Mesh	*Fine Mesh*	*Finer Mesh*
W_Screen_1	0.22	0.23	0.23
W_Screen_2	0.26	0.26	0.26
W_Screen_3	0.23	0.24	0.24
W_Screen_4	0.21	0.20	0.20
W_Screen_5	0.33	0.33	0.33
W_Screen_6	0.29	0.30	0.30
W_Screen_7	0.19	0.20	0.20
W_Screen_8	0.11	0.11	0.11

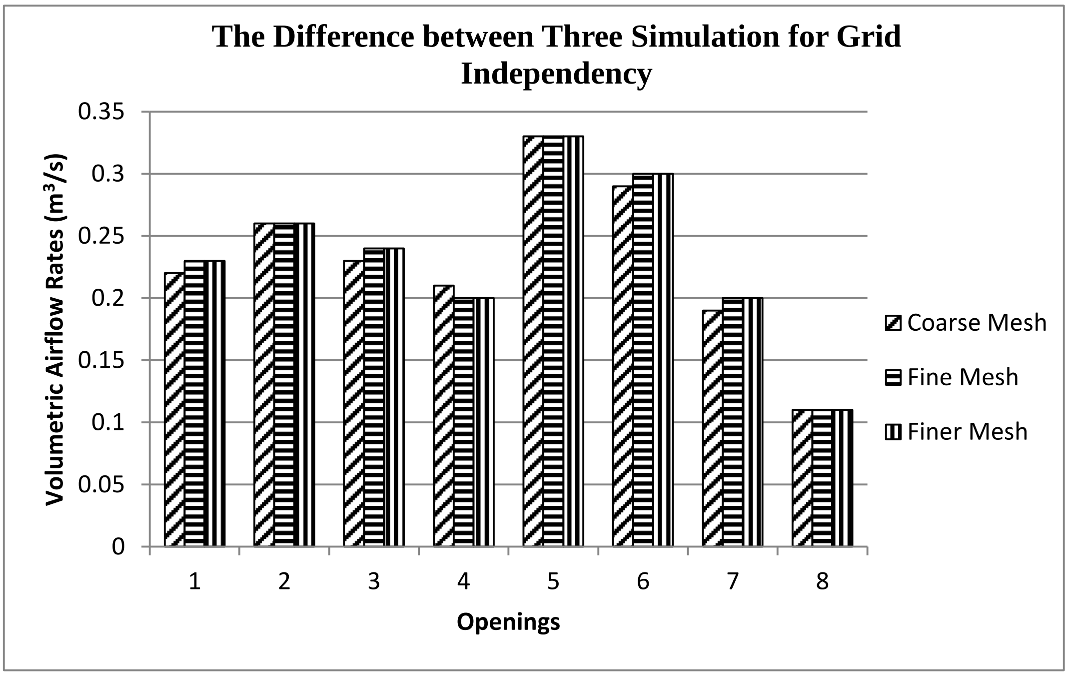


Figure 7.14: The Volumetric Flow rates of three different Mesh alternatives

7.11 Simulation Convergence

Simulation convergence were achieved when the absolute criteria for scaled residuals reached the limits of 10^{-6} for x, y, and z momentums, 10^{-5} for turbulence kinetic energy (k) and turbulence dissipation rates (ε), and 10^{-4} for continuity. These convergence criteria have been successfully used in previous cross-ventilation simulation (Ramponi and Blocken (2012). The scaled residual for the simulation is illustrated in figure 7-15.

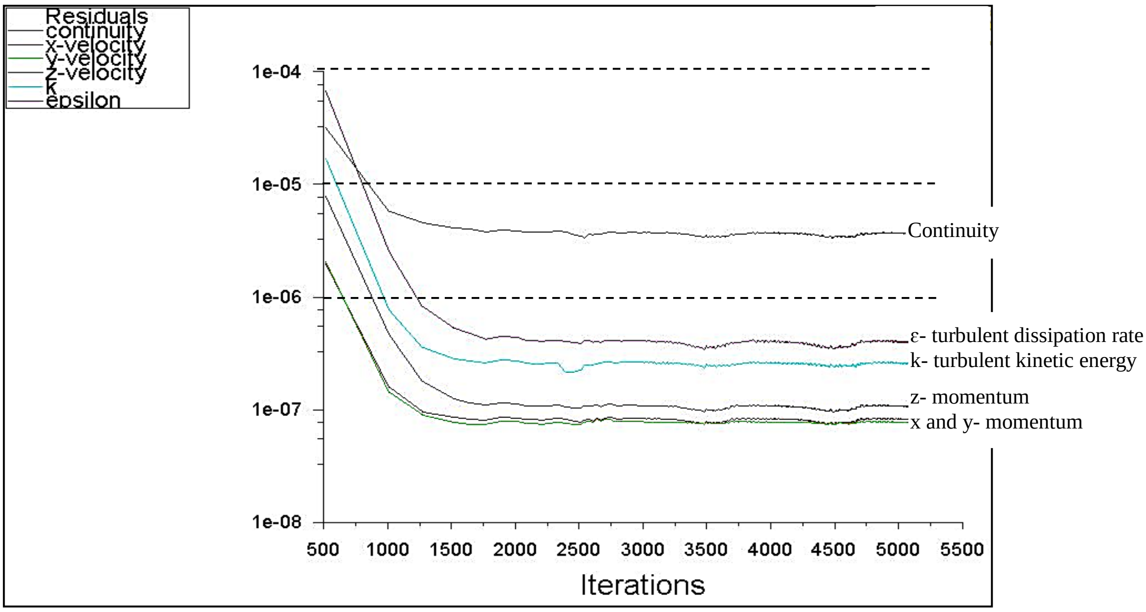


Figure 7.15: Scaled Residuals showing convergence history

7.12 Chapter Conclusion

This CFD simulation was conducted using computational fluid dynamic software Fluent 13.0 and the software was used in validating the hospital CFD ward models with the results of the full-scale measurement presented in chapter six (6). The chapter presents and discussed various boundary condition and parameters used in the CFD simulation process. The model geometry was created using ANSYS design modeller software, while Harpoon meshing tool from SHARC was used for the creation of the computational grids (Mesh).

The surface roughness of the grounds within the computational domain was applied using the Davenport (2001) classification of the effective terrain roughness. The horizontal homogeneity of the Atmospheric Boundary Layer (ABL) of the velocity magnitude, turbulent kinetic energy and the turbulent dissipation rates were achieved through iterative simulation of an empty computational domain and the outlet boundaries were used as the inlet boundary conditions.

Moreover, in this study, the 3D steady RANS equations were solved together with the realizable k-ε turbulent model by Shih et al (1995). To apply the inlet velocity boundary condition, the wind speed data obtained from the nearby meteorological station was adjusted using the vertical profile logarithmic law equations recommended by Blocken et al (2004), and the formula derived by Simiu and Scanlan (1986). Furthermore, the values of the turbulent kinetic energy and turbulent dissipation rates at the inlet boundaries were determined using the relationship between the vertical velocity magnitude and the friction velocity and applied using a User Defined Function (UDF).

In order to mimic the existing hospital wards in the study area, all the openings in the simulated models were treated with insect screens to prevent the penetration of mosquitoes, dust and other insects. The porosity of the insect screen was applied using the porous media boundary condition in the Fluent 13.0 CFD simulation tool. The correlation derived by Miguel et al (1997) relating the screen permeability (K) and the inertial factor (Y) to the screen porosity were used in the application of porous boundary conditions.

The outcome of the validation study indicates that the difference between the CFD simulation and the full-scale measurement is ≤15%, which is within the acceptable error margin as indicated by Willemsen and Wisse (2002). However, the Air Change Rates (ACR) in all the nine (9) cases simulated fall short of the ASHRAE's recommended 6 ach^{-1} for patient room apart from one. The minor difference between the full-scale measurement and the simulation signifies the reliability of the CFD simulation tool in modelling ventilation rates in buildings.

Having developed a reliable CFD model of a typical hospital ward in Northern Nigeria, and validated this model against measurements conducted in Chapter 5, the next phase of the research is to use the CFD model to develop and improve sustainable ventilation design for these hospital wards. Thus, the CFD Fluent 13.0 software is capable of performing the simulation to satisfy the acceptable indoor air quality requirements.

Chapter Eight

Computational Fluid Dynamic Simulation Results

Chapter Structure

8.1 Introduction

8.2 Computational Fluid Dynamic (CFD) Simulation in Buildings

8.3 Natural Ventilation in Multi-bed Hospital Ward

8.4 Average Indoor velocity, turbulent kinetic energy and Temperatures

8.5 Percentage Dissatisfied with Air Quality

8.6 Local Indoor velocity and turbulent Intensity

8.7 Local Draught Risk

8.8 Building Orientation and natural ventilation

8.9 Openings Insect Screen and natural ventilation

8.10 Outdoor Wind Speed and natural ventilation

8.11 Monthly evaluation of natural ventilation in hospital wards of semi-arid climates

8.12 Chapter Conclusion

8 Chapter Eight: CFD Simulation Results

8.1 Introduction

The processes and guidelines followed in conducting the CFD simulation together with the boundary condition used were presented in the previous chapter (chapter 7). In this chapter, the influence of various opening positions on ventilation rates in hospital multi-bed wards has been investigated, considering seventeen (17) different configurations. The existing hospital ward at the Umaru Shehu Ultra-Modern Hospital Maiduguri (USUHM) has been adopted and used as the base-case model in the study. This hospital was selected because it is the representative of all the other hospital wards in terms of design and opening configurations. However, the investigations are all conducted with the assumption that the wards are empty. Moreover, all the openings in the wards studied are treated with insect screen to prevent the penetration of mosquitoes, dust and other insects. The consequences of installing these insect screens on ventilation rates are investigated.

Furthermore, the study also investigated the effects of building orientation, outdoor wind speed and different insect screen porosity on ventilation rates in the hospital wards of the study area. The best opening configuration in terms of ventilation rates and airflow distribution at occupancy (bed) levels has been established and presented. Since the aim of this study is to enhance ventilation rates to provide acceptable and healthy indoor air quality for the hospital wards of the study area, the level of dissatisfaction with indoor air quality in the investigated configurations has been estimated. This chapter (Chapter 8) and the next chapter (Chapter 9) were intended to satisfy objective number 4, which is *"To explore the potentials of using natural ventilation strategies for achieving acceptable indoor air quality with the presence of Harmattan dust and Mosquitoes"*

8.2 Computational Fluid Dynamic (CFD) Simulation in Buildings

Computational Fluid Dynamics (CFD) remains one of the major computational approaches employed in investigating natural ventilation in buildings. This is because, it provides a cost effective, speedy and accurate alternative to the scale model testing, thereby providing more informative results. The recognition of CFD simulation as an effective alternative to other investigation methods is facilitated by the development of turbulence modelling and improvement in computer speeds (Bangalee et al. 2012). With the above mentioned advantages CFD simulation has been widely and successfully employed in investigating the prediction of airflows inside and around buildings

(Ramponi and Blocken 2012; Yang, 2004; Cook, et al. 2005; Asfour and Gadi, 2008; Chiang, et al. 2000; Gao, et al. 2007; Assimakopoulos et al. 2006). The success of CFD in terms of widespread application and acceptance in ventilation studies is largely connected to its simultaneous use with theoretical and experimental models, due to the increasing importance of verification and validation of available CFD codes (Li and Nielson, 2011).

Therefore, in this study, wind induced cross ventilation strategies with different opening characteristics were tested using reference wind speed of 2.6 m/s (Local wind speed, equivalent to 4.1m/s airport value) at 10 m above ground level. The wind speed data was collected from the nearest meteorological station. The percentage of opening in relation to the ward floor area required to provide acceptable ventilation rate to achieve the ASHREA standard of 6 ach^{-1} (Ninomura and Bartley, 2001) has been used as a benchmark to test the simulated cases. The installation of insect screens on the openings of the multi-bed ward to prevent mosquitoes is responsible for reduction in air change rate. The airflow pattern for the wards simulated is also studied. In this study, all wall and ceiling surfaces were assumed adiabatic except the floor surface where a temperature of 2.3^{o}C less than the air temperature was enforced to account for the cooler flow surface due to thermal mass.

8.3 Natural Ventilation in Multi-bed Hospital Ward

Natural ventilation is produced by pressure difference driven by the mechanism of wind or buoyancy in buildings. The variation in wind pressure along building façade, together with the temperature difference between indoor and outdoor air causes a flow circulation and establishes natural ventilation in buildings through provided openings (Bangalee et al. 2012). The major advantage of natural ventilation in hospital buildings is its ability to provide significant ventilation rates, which could be an added advantage especially for wards with high risk of airborne infections (Qian et al. 2010). However, owing to the complexity and unsteadiness of the wind, the prediction of the wind driven component of natural ventilation is challenging (Lo et al. 2013). Likewise, quantifying the performance of ventilation systems and their influence on infection risk is also difficult, specifically for large naturally ventilated buildings with multiple openings (Gilkeson et al. 2013). This is due to the difficulty in explaining the exact behaviour of flows entering buildings in indoor spaces from multiple openings and how they interact and mixed up. However, factors such as the location and the size of the opening, the incoming air velocity, the direction, and the temperature difference play a vital role for the flow through a particular opening to be influenced by the flow through another opening (Bangalee et al. 2012).

The ventilation effectiveness of seventeen (17) different opening configurations/cases considered has been studied. This is to ascertain the case with highest airflow and air change rates while considering other environmental parameters such as indoor air velocity and turbulent intensity. The description of these cases has been illustrated in table 8.18 in page 232. These configurations are generally divided into three classes. The first category is those with openings located on the wall façade only, inlets in the windward and outlets in the leeward, which includes cases 1-7 and case 8 with outlet located by the side. The second category is those with opening situated in the wall facade and on the roof top that is inlets in the windward walls and outlets on top of the roof, which includes cases 9-15. The third category is the combination of the above two divisions in which the inlet is located at the windward wall while the outlet is situated both on the roof and the leeward walls. Perhaps, it has to be noted that, the bulk of the hospital buildings in the study area are single storey, as a result cross ventilation via walls and roof are possible.

8.3.1 Air Change rates (ACR) and Volumetric Airflow Rates

Air change rates and volumetric airflow rates remains among the major factors that determines ventilation efficiency and effectiveness in buildings. In this study both air change rates and airflow rates have been employed to determine the ventilation efficiency of all the opening configurations investigated. However, air change rates or air flow rates only provide the overall ventilation effectiveness of a given environment without describing the airflow distribution and effectiveness at the occupancy levels. Therefore, the idea of airflow pattern and distribution is required to study ventilation effectiveness at different occupancy locations in building indoor environment. Airflow pattern are an important factor that affects ventilation requirements of both patient and other healthcare workers in hospital wards, as the transportation of droplet from patients' respiratory activities is closely associated with the pattern of the airflow in the ward. The proper distribution of airflow in a space can be enhanced by different types of outlet opening arrangements (Yau et al. 2011).

8.3.1.1 Changing window configuration on walls

This category is those with openings located on the wall façade only, inlets in the windward and outlets in the leeward, which includes cases 1-7 and case 8 with outlet located by the side. Case 1 is the base-case which is the replication of the existing hospital ward in the study area. The existing case has eight openings, four inlets and four outlets designed with the intention of providing cross ventilation to the occupants. Cross ventilation is usually provided by creating multiple openings on different facades of a building. The action of any wind striking on these facades will then create pressure differences between those openings and consequently encourage a robust airflow through the indoor environment (Jiang et al. 2003).

The volumetric airflow rate and the air change rate obtained from case 1 is 1.16 m^3/s and 9.14 ach^{-1} respectively, which is higher than the required standard air change rate of 6 ach^{-1} in hospital wards as enshrined by ASHREA (2011). However, the airflow distribution in this case is good near the inlets and the outlets and close to the ceiling, but poor at the occupancy level in the centre of the ward as illustrated in vertical cross section in figure 8.1. The inefficient airflow distribution at the centre of the ward is also confirmed by horizontal sections and 3D streamline shown in table 8-1. Therefore it is essential to improve the airflow circulation and distribution at the centre of the ward.

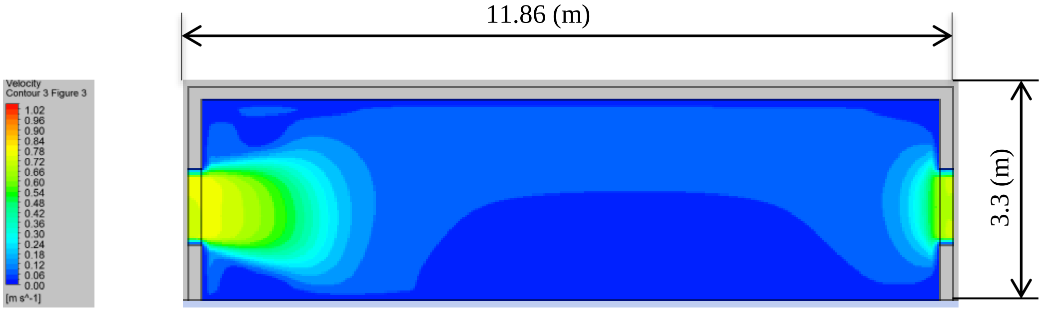
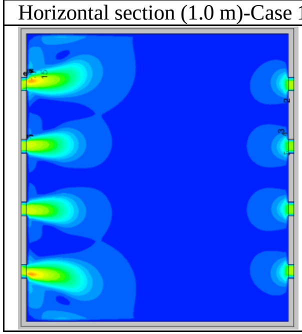
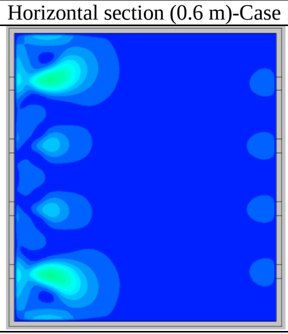
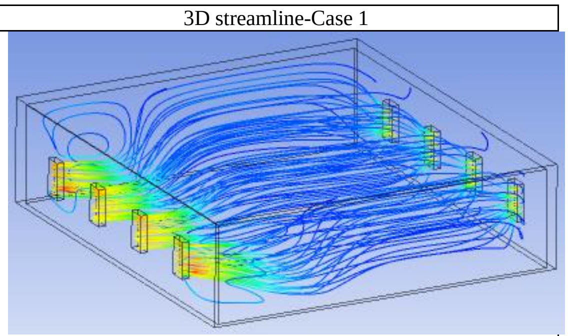


Figure 8.1: Vertical section of case 1 showing airflow circulation and distribution

The horizontal section at 1.0 m above floor level was intended to represent patient relatives and other healthcare workers seated on chair, while the horizontal section at 0.6 m above floor levels was proposed to signify a patient lying on a bed.

Table 8-1: Horizontal sections and 3D streamline of Case 1 showing airflow distribution

Horizontal section (1.0 m)-Case 1	Horizontal section (0.6 m)-Case 1	3D streamline-Case 1
		

Furthermore, Case 2 has inlet at the centre on the windward wall and the outlet is placed at higher position closed to the ceiling on the leeward side of the ward as illustrated in Figure 8.2. The volumetric airflow rate ($1.18m^3/s$) and the air change rate ($9.3\ ach^{-1}$) in this case are slightly higher than in case 1. This is connected with the location of the outlets at higher positions that permits the case to benefit from the effects of both wind and buoyancy ventilation. However, the indoor air distribution at the occupancy level is poor especially at the centre and close to the leeward wall, and near the high level openings as illustrated in figure 8.2. The horizontal cross section at 1.0 m and 0.6 m above floor level and the 3D streamline diagram shown in table 8-2 also substantiate on the inefficiency in airflow distribution at occupancy level in this case.

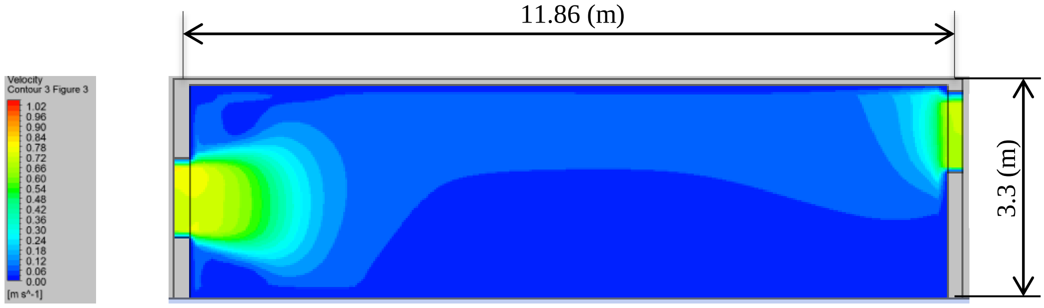
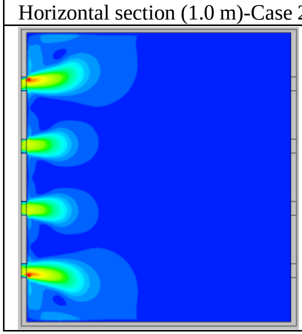
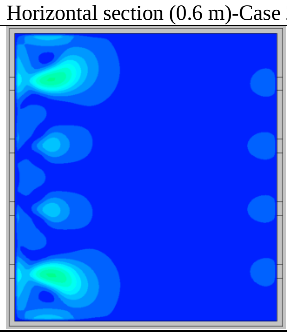
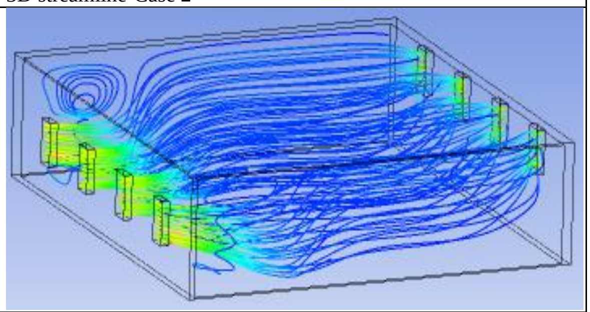


Figure 8.2: Vertical section of case 2 showing airflow circulation and distribution

Table 8-2: Horizontal sections and 3D streamline of Case 2 showing airflow distribution

Horizontal section (1.0 m)-Case 2	Horizontal section (0.6 m)-Case 2	3D streamline-Case 2
		

Likewise, Case 3 has inlets positioned at the centre of the windward wall and outlets situated at lower level near the floor on the leeward wall. The volumetric airflow rate ($1.14m^3/s$) and the air change rate ($8.98\ ach^{-1}$) in this case are lower than both case number 1 and 2, but above the ASHRAE standard of $6\ ach^{-1}$. This is because the case functions using wind effect only without buoyancy as the air outlets are much closer to the floor level. Moreover, the indoor airflow distribution at the centre of the ward at the occupancy level is inadequate as illustrated in figure 8.3. The horizontal cross section at occupancy levels of 1.0m and 0.6m above floor level as shown in table 8-3, confirms the insufficiency of ventilation at the bed levels at the centre of the ward.

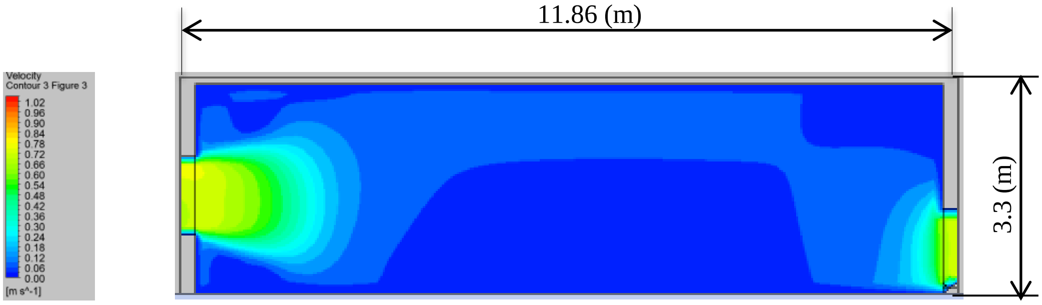
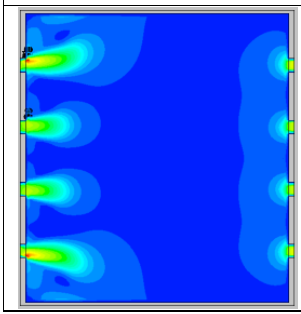
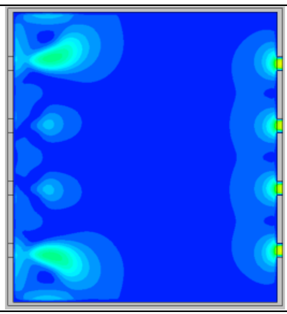
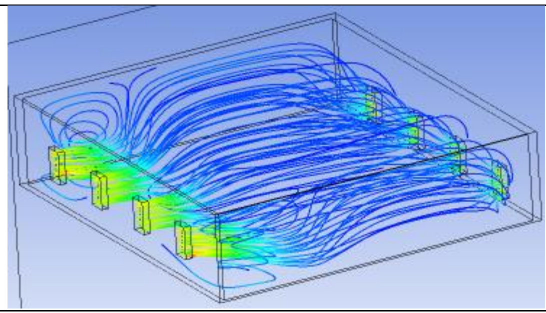


Figure 8.3: Vertical section of case 3 showing airflow circulation and distribution

Table 8-3: Horizontal sections and 3D streamline of Case 3 showing airflow distribution

Horizontal section (1.0 m)-Case 3	Horizontal section (0.6 m)-Case 3	3D streamline-Case 3
		

Furthermore, in case 4, the inlets are located at higher position near the ceiling on the windward wall and the outlets are located at lower position near the floor on the leeward wall. The case has airflow rate of $1.18m^3/s$ and air change rates of 9.3 ach^{-1}, which is above the ASHREA standard of 6 ach^{-1} in patient rooms. This positioning of the inlet in higher position and the outlet in lower position resulted in poor air distribution at the occupancy level near the high level openings i.e. bed level at the windward side and the centre. But the air distribution is good close to the outlets because, the outlet openings are located right above the floor at occupancy height as illustrated in figure 8.4. The horizontal sections of the ward at 1.0m and 0.6m above floor level and the 3D stream line of case 4 is presented in table 8-4. Numerous factors necessitate the placement of openings near the ceiling with their sills high above occupancy level, including architectural, functional or privacy requirements, which usually leads to poor ventilation conditions in the occupied zone of the indoor space (Givoni 1994).

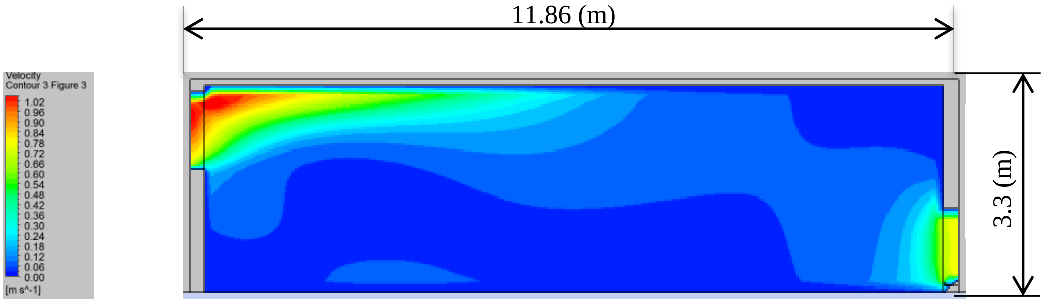
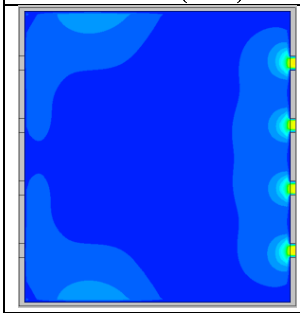
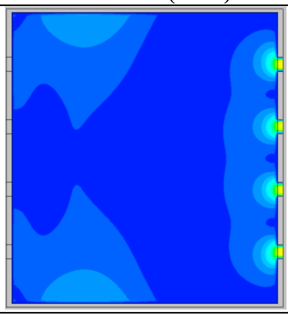
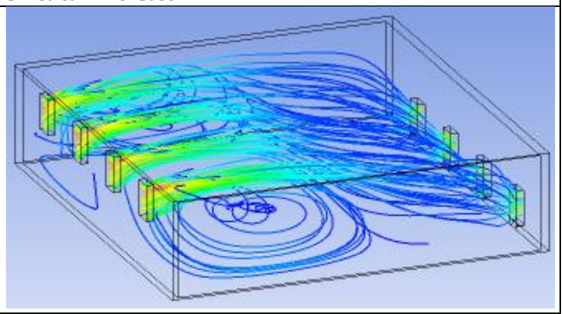


Figure 8.4: Vertical section of case 4 showing airflow circulation and distribution

Table 8-4: Horizontal sections and 3D streamline of Case 4 showing airflow distribution

Horizontal section (1.0 m)-Case 4	Horizontal section (0.6 m)-Case 4	3D streamline-Case 4
		

On the question of Case 5 which is direct opposite of case 4, the inlet openings are located in a lower position close to the floor and the outlet openings are situated at higher position near the ceiling. This study found that the volumetric airflow rate (1.08m^3/s) and air change rate (8.51 ach^{-1}) are lower than in case 4, because of the location of the inlet openings at lower positions. Owing to the effect of the logarithmic wind profile approaching the building, the wind speed increases with height, and hence, the location of the inlet openings at lower positions will have great influence on the volumetric flow rate and consequently air change rate. Moreover, the airflow distribution and circulation at occupancy (bed) levels in this case is poor at the centre of the ward and in the leeward side near the outlet openings. But the airflow distribution is good at the bed level near the inlet openings by the windward side as illustrated in figure 8.5. This is due to the placement of the inlet openings at lower positions within the occupancy level. But this case is not realistic, as it might create draughty conditions for patients on the beds near or directly opposite the inlet openings.

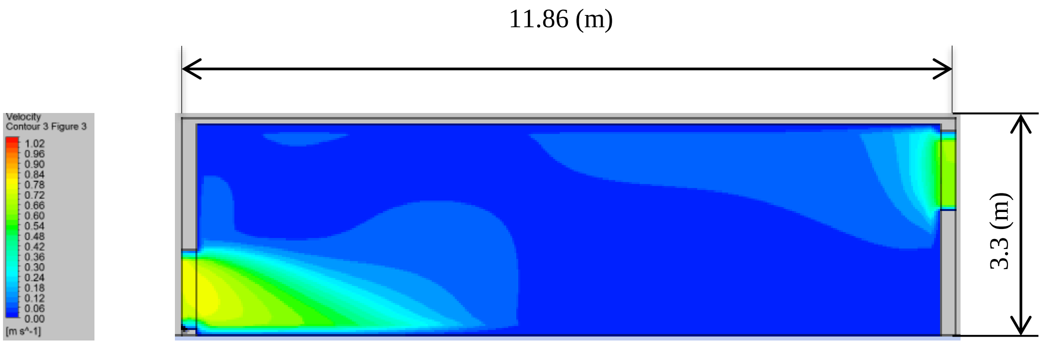
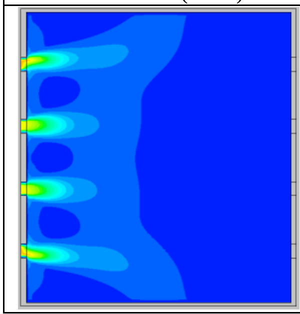
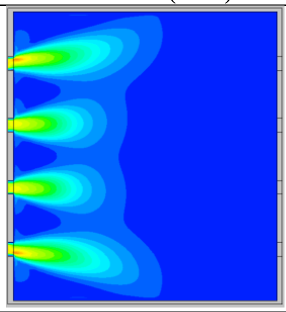
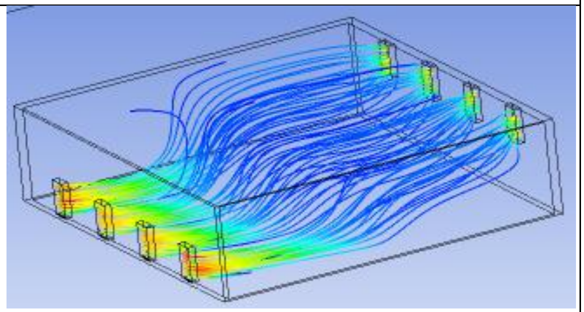


Figure 8.5 : Vertical section of case 5 showing airflow circulation and distribution

The airflow intensity, distribution and circulation are better at lower levels than in higher occupancy levels. This is demonstrated by the difference between horizontal section at 1.0 m and 0.6 m above ground level and 3D streamline shown in table 8-5.

Table 8-5: Horizontal sections and 3D streamline of Case 5 showing airflow distribution

Horizontal section (1.0 m)-Case 5	Horizontal section (0.6 m)-Case 5	3D streamline-Case 5
		

It is interesting to note that in all the eight (8) cases of this category, case number (6) six has the highest airflow rate and air change rate of 1.22m^3/s and 9.61 ach^{-1} respectively. In case 6, the improved ventilation rate is achieved by having the inlet and outlet openings close to the ceiling, which has the effect of creating a high level air channel resulting in improved airflow rates. But this case is not practically realistic due to the location of both the inlet and the outlets openings above the occupancy level resulting in deficient circulation and distribution of air at the occupancy (bed) levels. The vertical section of case 6 showing airflow distribution and circulation is illustrated in figure 8.6, confirming the inadequacy or total absence of airflow at the bed level close to the floor surface.

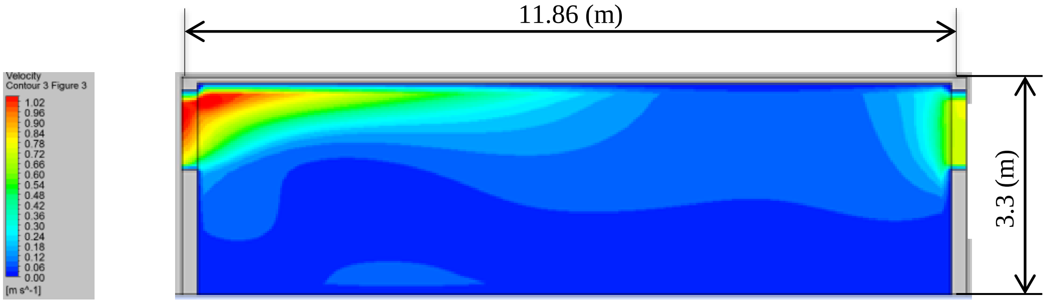
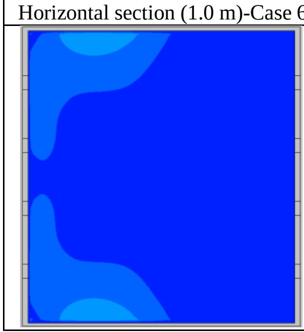
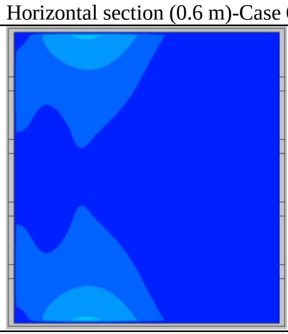
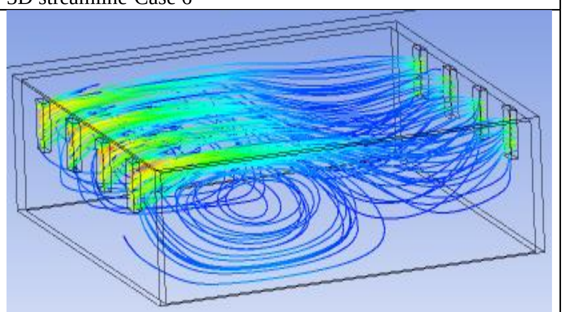


Figure 8.6: Vertical section of case 6 showing airflow circulation and distribution

Moreover, the airflow distribution covers less than 50% of the total floor area at both 1.0 m and 0.6 m above floor level as illustrated in table 8-6. Hence, air change rates only cannot be used to ascertain ventilation efficiency in hospital wards. Other parameters such as airflow distribution, circulation and indoor air speed should also be considered as well.

Table 8-6: Horizontal sections and 3D streamline of Case 6 showing airflow distribution

Horizontal section (1.0 m)-Case 6	Horizontal section (0.6 m)-Case 6	3D streamline-Case 6
		

The positioning of openings in Case 7 is directly opposite of case 6, both the inlet and outlet openings are located at a lower level near the floor at the windward and leeward walls respectively. The volumetric airflow rate and the air change rates in the case are 1.04m^3/s and 8.20 ach^{-1} respectively, which is the lowest in this category but has satisfied the ASHRAE standard of 6 ach^{-1}. A possible explanation for achieving the lowest air change rate might be as a result of the location of both the inlet and the outlet openings at lower levels near the floor. Apart from achieving the lowest air change rate, this case is also poor in providing efficient airflow distribution and circulation at occupancy level at the centre of the ward as illustrated in figure 8.7. The airflow distribution at occupancy level is better near the windward and leeward sides of the ward opposite the inlet and outlet openings. But this case is not realistic because of the positioning of the openings right above the floor, which will create a draughty condition for patients close to the inlet and outlet openings. Moreover, the horizontal sections of the ward at 1.0 m and 0.6 m above floor level and the 3D streamline in table 8-7 provides more detail about the airflow pattern in case 7.

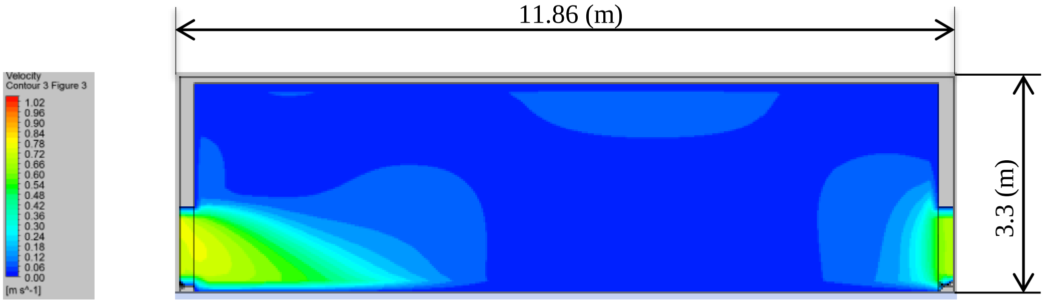
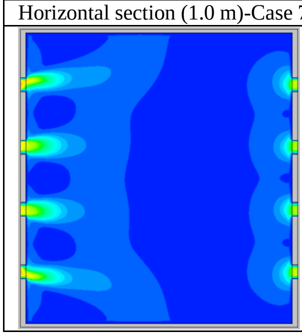
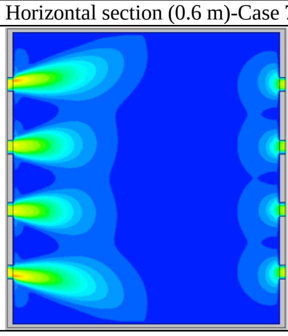
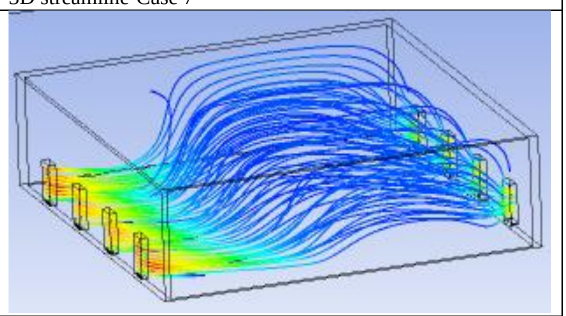


Figure 8.7: Vertical section of case 7 showing airflow circulation and distribution

Table 8-7: Horizontal sections and 3D streamline of Case 7 showing airflow distribution

Horizontal section (1.0 m)-Case 7	Horizontal section (0.6 m)-Case 7	3D streamline-Case 7
		

The last case in the first category is Case 8, which has inlet openings located at the centre of the windward wall and the outlet openings on the centre of the side wall. The volumetric airflow rate and the air change rate in this case are 1.08 m^3/s and 8.51 ach^{-1} respectively. Even though, the performance of this case is good in terms of the air change rate which is above the ASHRAE standard of 6 ach^{-1}, the airflow distribution and circulation at the occupancy level is deficient. The airflow coverage and distribution is only good near the inlet and outlet openings and poor in the remaining parts of the ward as illustrated in figure 8-8 and table 8-8.

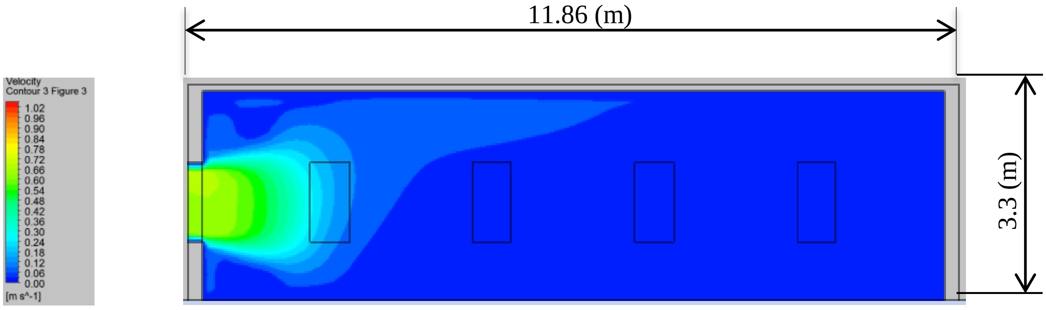
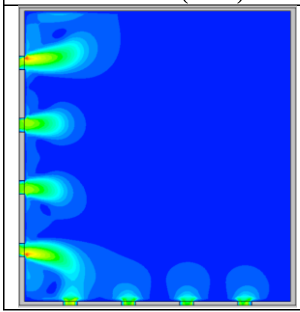
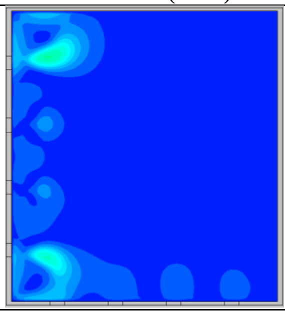
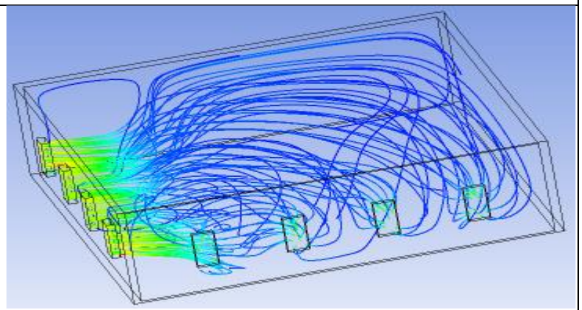


Figure 8.8: Vertical section of case 8 showing airflow circulation and distribution

Table 8-8: Horizontal sections and 3D streamline of Case 8 showing airflow distribution

Horizontal section (1.0 m)-Case 8	Horizontal section (0.6 m)-Case 8	3D streamline-Case 8
		

However, these results were not encouraging especially in terms of airflow distribution and circulation. But the air change rates in all the eight (8) cases of this category have exceeded the ASHRAE minimum patients' room requirement of 6 ach^{-1}. Therefore, it is apparent that case number 1 is the best among the 8 cases of this first category based on practicality and air change rates. The inability of these 8 cases to provide acceptable indoor air distribution at the occupancy (bed) level leads to the consideration of additional alternatives (category two) with outlet opening located on the roof.

8.3.1.2 Changing window configurations on wall and roof

The second category comprises of cases number 9 to 15, as illustrated in table 8-18 (see page 232). These cases have inlet openings on the windward wall and outlet openings on the roof. Case number 9 has inlet openings at the centre of the windward wall and outlet openings on the roof near the leeward wall as illustrated in figure 8.9. The volumetric airflow rate and the air change rate in this case are higher than all cases in the first category. The volumetric airflow rate and the air change rate are 1.32m^3/s and 10.40 ach^{-1} respectively. The case works with both wind and stack ventilation effects due to the location of the outlet openings on the roof. However, the airflow distribution at the occupancy level in this case is inadequate at the centre and near the leeward wall, which is connected with the placement of the outlet openings on the roof while leaving the leeward wall without any opening as illustrated in figure 8-9. It is also apparent from table 8-9 that areas near the leeward wall are experiencing inadequate air circulation.

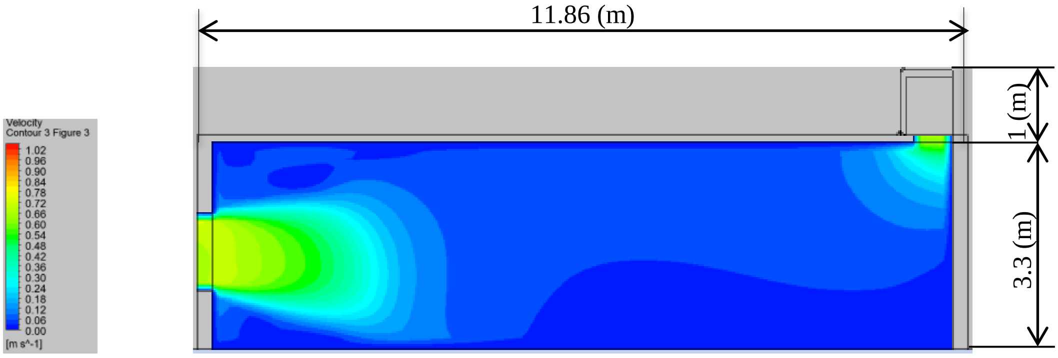
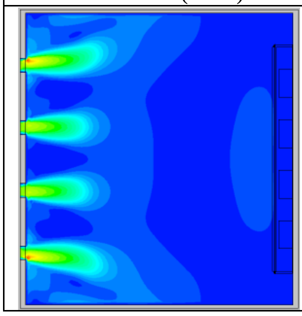
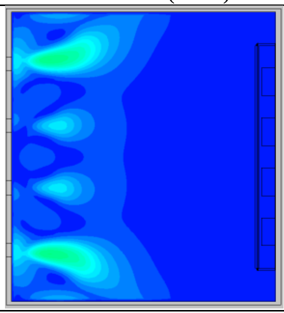
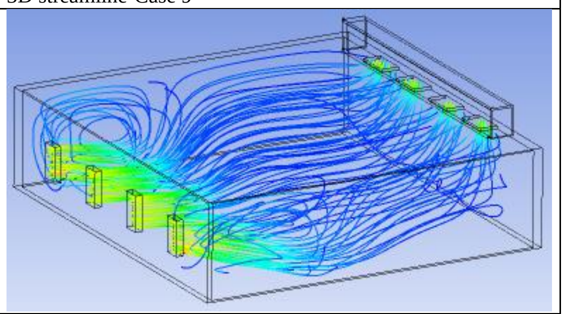


Figure 8.9: Vertical section of case 9 showing airflow circulation and distribution

Table 8-9: Horizontal sections and 3D streamline of Case 9 showing airflow distribution

Horizontal section (1.0 m)-Case 9	Horizontal section (0.6 m)-Case 9	3D streamline-Case 9
		

Likewise, Case number 10 is similar to case 9, but the outlet openings in this case is located at the centre of the roof as shown in figure 8.10. The case generates higher volumetric flow rate and air change rate of 1.58m^3/s and 12.45 ach^{-1} respectively compared to case 9. However, the airflow distribution and circulation is poor and inadequate in almost 50% of the indoor space especially toward the centre and leeward wall. A possible explanation for this result is due to short circuiting between the air supply openings (inlets) and the air exhaust openings (outlets), which according to Jones (1997) reduce ventilation effectiveness and efficiency. Hence, the air does not penetrate deeply into the required space but turned back whenever it reaches outlet openings along the way as shown in figure 8.10. This phenomenon is also well captured in the three diagrams in table 8-10. For an efficient room air distribution, the youngest or the newest air is found near the supply openings and the oldest air is found close to the exhaust openings. And in this case the exhaust openings are placed close to the supply openings leading to the above phenomenon of short circuiting.

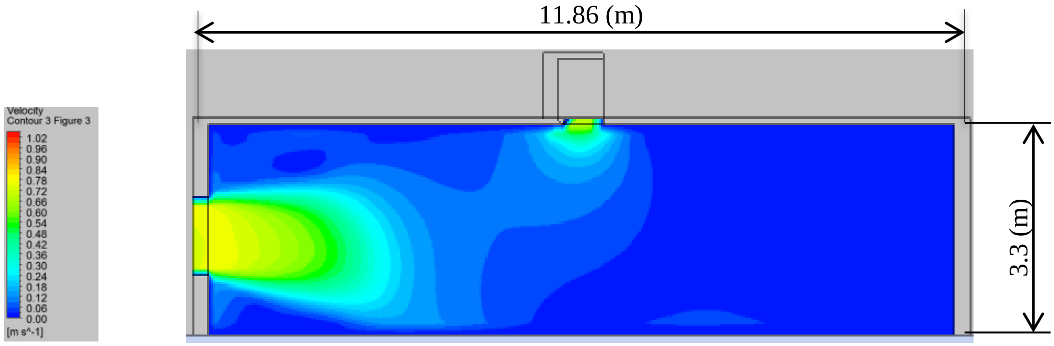
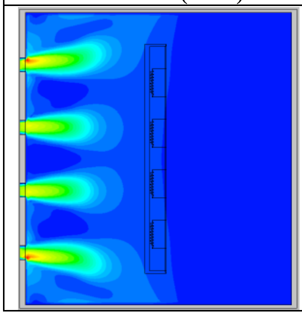
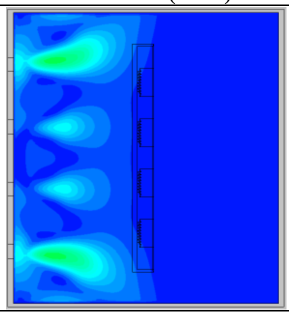
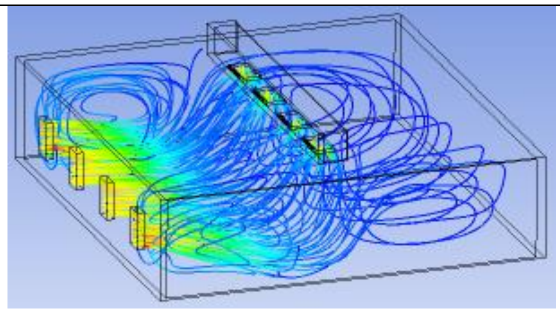


Figure 8.10: Vertical section of case 10 showing airflow circulation and distribution

Table 8-10: Horizontal sections and 3D streamline of Case 10 showing airflow distribution

Horizontal section (1.0 m)-Case 10	Horizontal section (0.6 m)-Case 10	3D streamline-Case 10
		

In Case number 11, the opening configuration is also similar to both cases 9 and 10, but with the outlet openings located on the roof near the windward wall as illustrated in figure 8.11. The case has the highest volumetric airflow rate and air change rate of 1.86m^3/s and 14.68 ach^{-1} respectively among the seven (7) cases of the second category and the entire 17 cases simulated. The short circuiting phenomenon is much worse in case 11 compared to case 10 because of the closeness of the outlet openings to the inlets openings as shown in figure 8.11. This phenomenon resulted in shallow air circulation within the ward covering less space. The figures in table 8-11 have demonstrated the influence of short circuiting on air flow distribution and circulation within the hospital ward in detail.

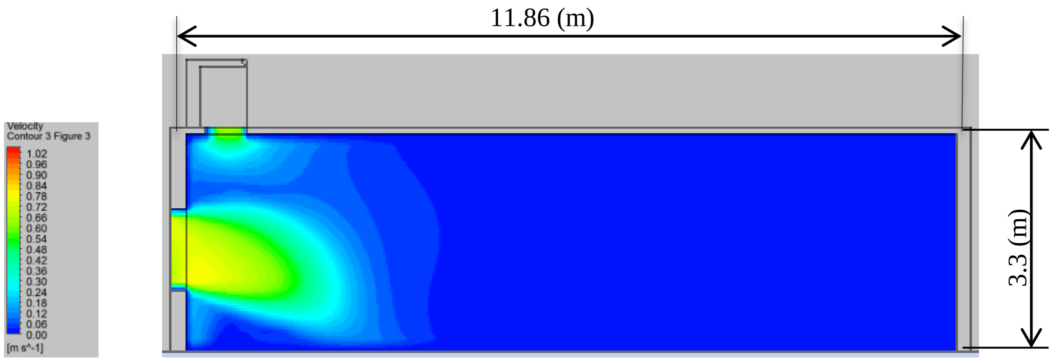
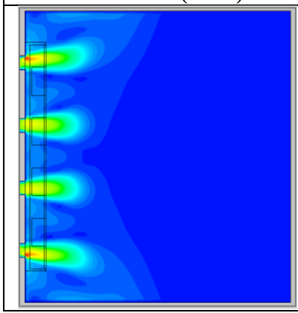
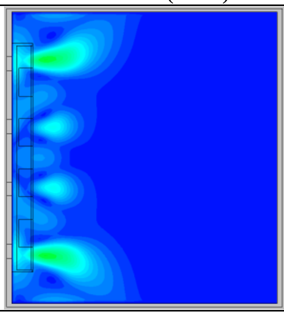
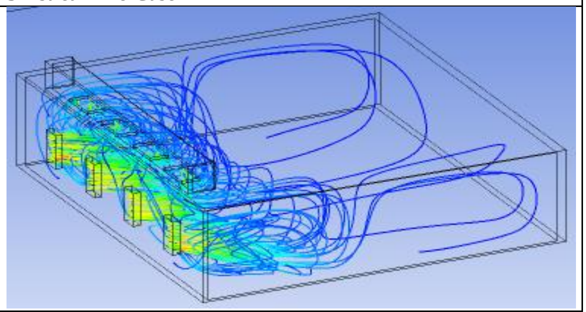


Figure 8.11: Vertical section of case 11 showing airflow circulation and distribution

Table 8-11: Horizontal sections and 3D streamline of Case 11 showing airflow distribution

Horizontal section (1.0 m)-Case 11	Horizontal section (0.6 m)-Case 11	3D streamline-Case 11
		

The opening configuration in case 12 is the combination of case 10 and 11. The inlet openings in this case are located at the centre of the windward wall and the outlet openings are located both at the centre and windward positions of the roof as shown in figure 8.12. The volumetric airflow rate and the air change rate in this case are 1.56m^3/s and 12.29 ach^{-1} respectively. This case is also affected by the short circuiting phenomenon. Owing to the location of openings at the windward side of the roof closed to the inlet openings, the bulk of air turn back without going deep into the room. This consequence also reduces the exhaust capacity of the opening situated at the centre of the roof. The air change rate is lower than in case 11 because, the intensity of the effect of short circuiting has been reduced in this case by locating exhaust openings at the centre of the roof. The horizontal section at 1.0m and 0.6 m height above floor level and the 3D streamline exhibited in table 8-12 have clearly illustrated the effect of short circuiting on airflow circulation and distribution in the ward.

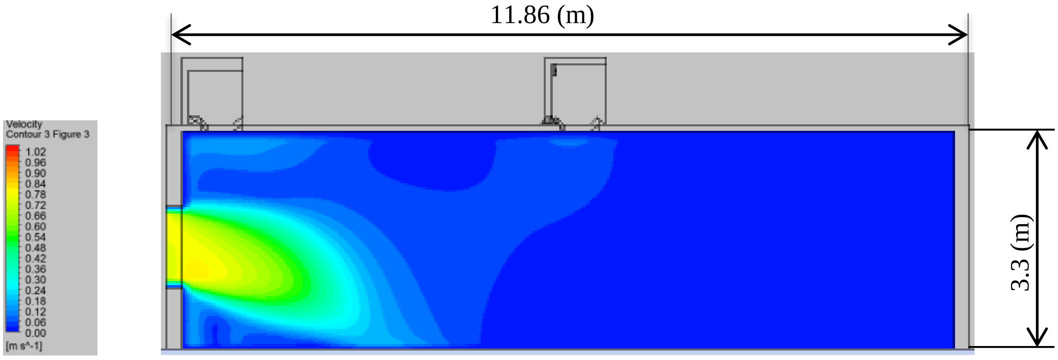
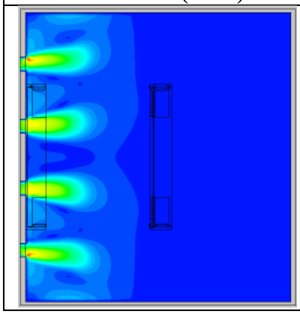
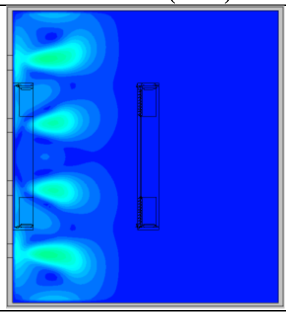
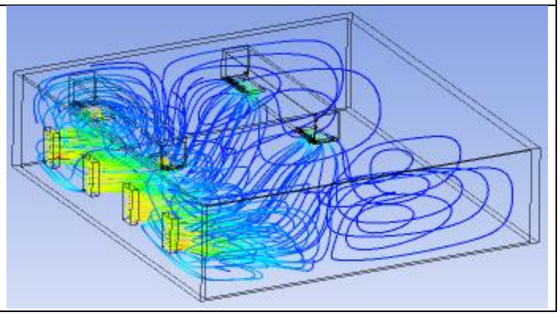


Figure 8.12: Vertical section of case 12 showing airflow circulation and distribution

Table 8-12: Horizontal sections and 3D streamline of Case 12 showing airflow distribution

Horizontal section (1.0 m)-Case 12	Horizontal section (0.6 m)-Case 12	3D streamline-Case 12
		

The opening arrangement in case 13 is similar to that of case 12, but in this case the outlet openings are situated at the centre and leeward portion of the roof as illustrated in figure 8.13. The volumetric airflow rate and the air change rate in this case are 1.20m^3/s and 10.24 ach^{-1} respectively. The air change rate is lower than in case 12 in this case because the effect of short circuiting is also less due to the positioning of some exhaust openings on the roof close to the leeward wall and absence of any exhaust opening towards the windward side of the roof as shown in figure 8.13. Additionally, the positioning of some exhaust opening at the centre of the roof has influence the air flow distribution and circulation especially by diverting part of the air to exhaust before reaching the outlet openings towards the leeward side of the wall. The three diagrams in table 8-13 have exhibited the near absence of airflow circulation in about 50% of the ward floor area.

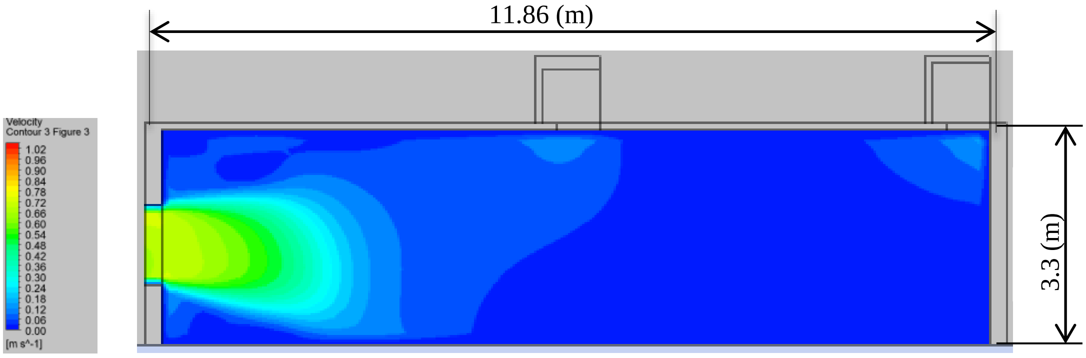
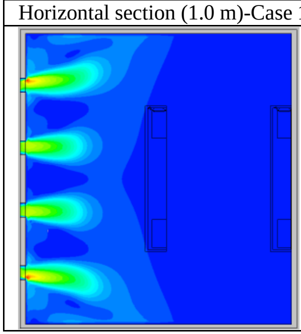
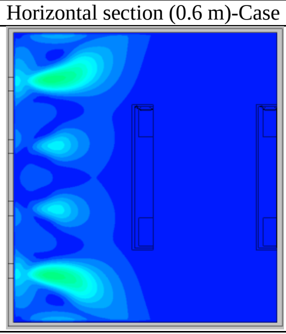
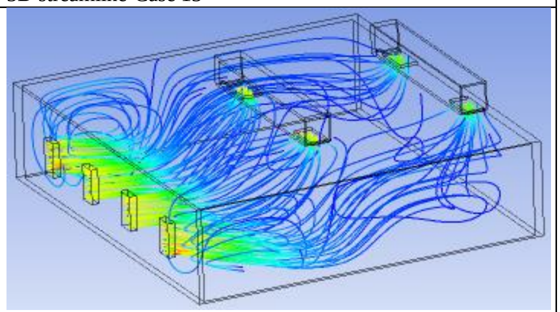


Figure 8.13: Vertical section of case 13 showing airflow circulation and distribution

Table 8-13: Horizontal sections and 3D streamline of Case 13 showing airflow distribution

Horizontal section (1.0 m)-Case 13	Horizontal section (0.6 m)-Case 13	3D streamline-Case 13
		

The opening configuration in case 14 is the combination of cases 9, 10 and 11. In this case, the inlet openings are located on the windward wall and outlet openings are placed towards the windward side, centre and towards the leeward side of the roof as illustrated in figure 8.14. The volumetric airflow rate and the air change rate in this case are 1.42m^3/s and 11.19 ach^{-1} respectively. The air change rate is higher in this case than in case 13 because of locating exhaust opening towards the windward side of the roof (close to the inlet openings) and at the centre of the roof. These two positions have resulted in short circuiting of the air before they reach the final exhaust openings in the leeward side of the roof as illustrated in figure 8.14. Although, the air change rate is high, the airflow distribution and circulation is poor and inadequate in areas far away from the inlet openings as shown in table 8-14. Therefore, the phenomenon of short circuiting airflow has influenced the airflow distribution, circulation and subsequently ventilation efficiency in cases 10, 11, 12, 13, and 14. Whenever the exhaust openings are situated closer to the inlet openings, the room produces high volumetric airflow rates and air change rates, with poor and inadequate air circulation and distribution in the space. Hence, those cases that are affected by the consequences of short circuiting airflow may not effectively remove indoor air contaminants in the indoor spaces, as ventilation air do not reach deep into certain part of the room or space in question.

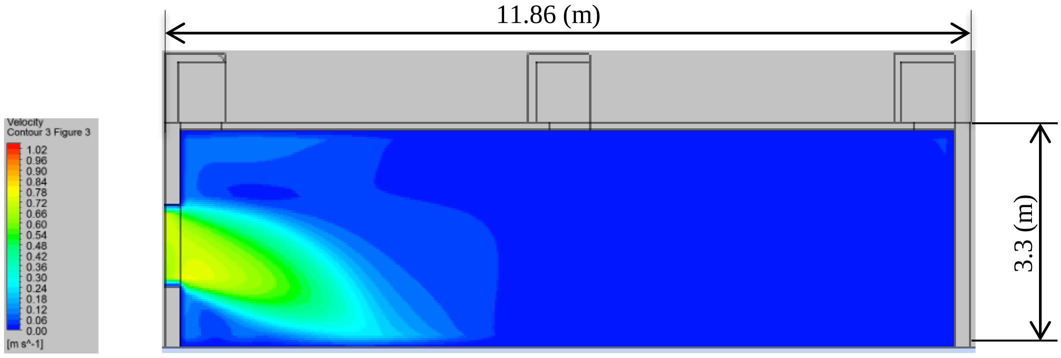
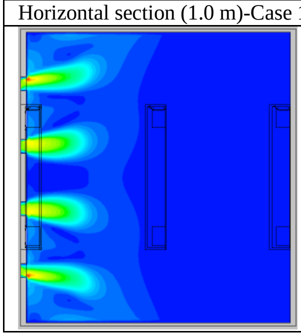
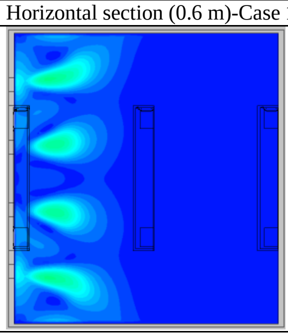
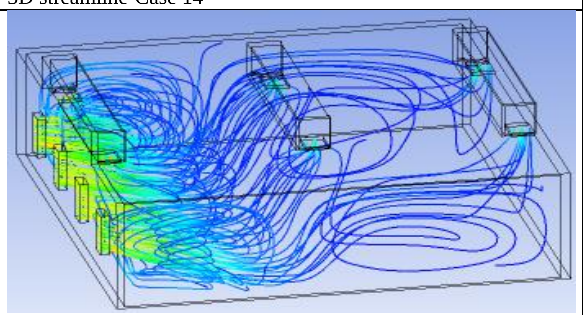


Figure 8.14: Vertical section of case 14 showing airflow circulation and distribution

Table 8-14: Horizontal sections and 3D streamline of Case 14 showing airflow distribution

Horizontal section (1.0 m)-Case 14	Horizontal section (0.6 m)-Case 14	3D streamline-Case 14
		

However, the opening configuration in case 15 is similar to that of case 9, but in this case the outlet openings are located on the leeward wall of the tower instead of the roof. The tower is 2.4 metres height. The volumetric airflow rate and the air change rate in this case are 1.40m^3/s and 10.0 ach^{-1} respectively. This case is not influence by short circuiting and its airflow distribution and circulation is better than all the remaining 6 cases in this category, however, it is not sufficient in some occupancy locations as illustrated in figure 8.15. The airflow distribution in this case has covered more than 80% of the floor area at occupancy (bed) level as displayed in the horizontal sections above 1.0m and 0.6m above floor level and the 3D streamline shown in table 8-15.

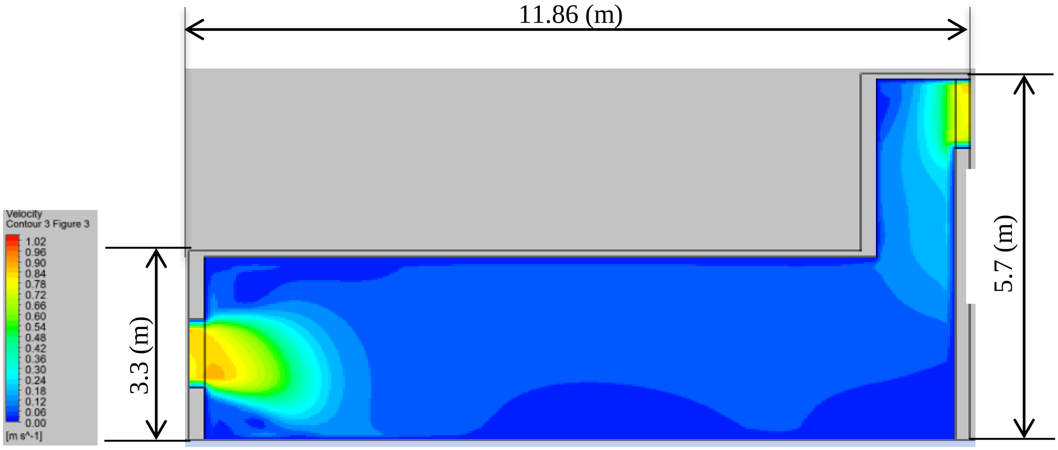
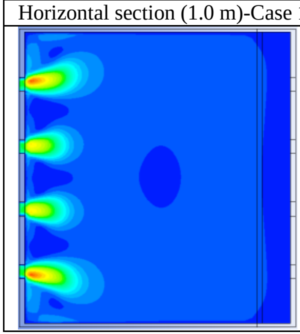
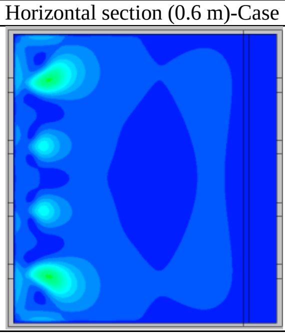
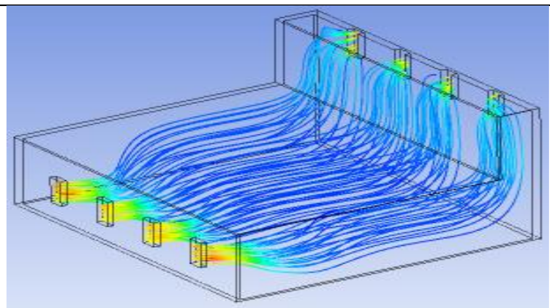


Figure 8.15: Vertical section of case 15 showing airflow circulation and distribution

Table 8-15: Horizontal sections and 3D streamline of Case 15 showing airflow distribution

Horizontal section (1.0 m)-Case 15	Horizontal section (0.6 m)-Case 15	3D streamline-Case 15
		

Therefore, based on the analysis of the 7 cases in the second category, cases number 9 and 15 are the best in terms of volumetric airflow rates and air change rates. These cases are not influence by the phenomenon of short circuiting and the airflow circulation and distribution at occupancy (bed) level in case 15 is better than case 9. However, even the airflow distribution in case 15 is not adequate because there are areas at the occupancy level with poor circulations and distributions (see table 8-15). Hence, to improve the airflow distributions in these two cases, the third category is introduced and will be discussed in the next paragraphs.

8.3.1.3 Changing window configurations on walls and roof with additional openings on the leeward walls

The third Category comprising cases 16 and 17, which are improvement on cases 9 and 15 respectively by introducing another set of outlet openings on the leeward walls apart from the roof as illustrated in figures 8.16 and 8.17. Case 16 is similar to case 9 except the introduction of more outlet openings on the leeward wall of case 16. The volumetric airflow rates in cases 9 and 16 are 1.32m^3/s and 1.72 m^3/s and the air change rates of the two cases are 10.40 ach^{-1} and 13.55 ach^{-1} respectively. The result indicates that the volumetric airflow rates and air change rates in case 16 are higher than case 9, and the airflow distribution at the occupancy (bed) level is better in case 16 compared to case 9. The airflow distribution at the occupancy level is shown in figure 8.16. Additionally, the airflow distribution and circulation at occupancy levels of 1.0 m and 0.6 m height and 3D streamline of the ward interior has been illustrated Table 8-16. The contour in these figures indicates a better distribution of the airflow within the entire ward floor area.

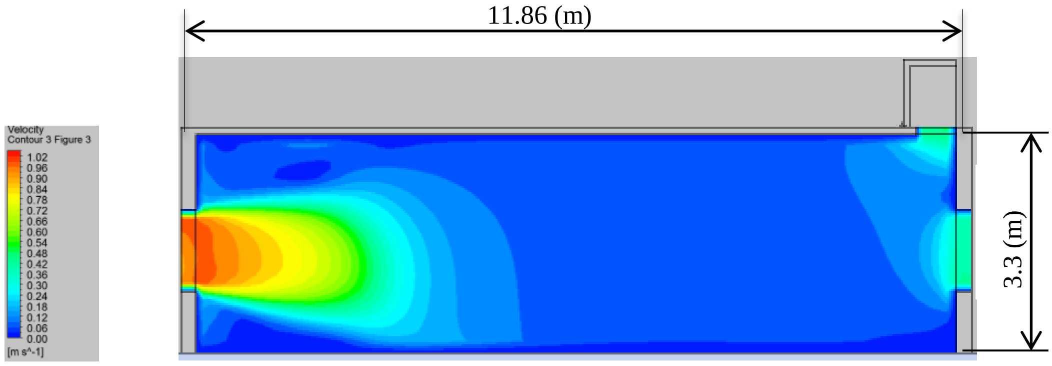
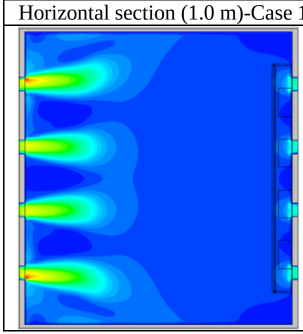
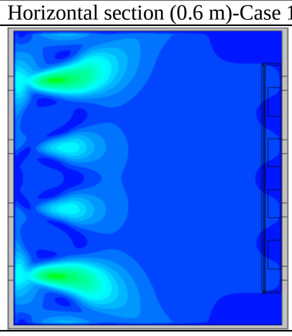
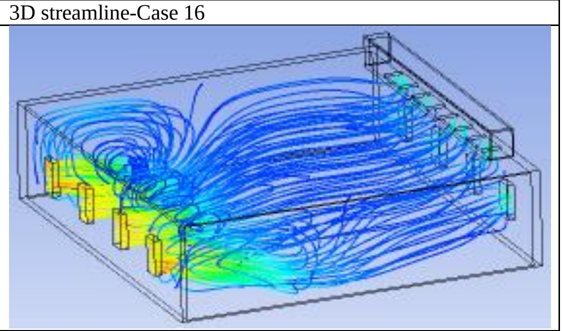


Figure 8.16: Vertical section of case 16 showing airflow circulation and distribution

Table 8-16: Horizontal sections and 3D streamline of Case 16 showing airflow distribution

Horizontal section (1.0 m)-Case 16	Horizontal section (0.6 m)-Case 16	3D streamline-Case 16
		

Case 17 develops the improvements determined in case 16. The Case is similar to case 15 except the introduction of more outlet openings on the leeward wall of case 17. The volumetric airflow rates in cases 15 and 17 are 1.40m^3/s and 1.56 m^3/s and the air change rates of the two cases are 10.0 ach^{-1} and 11.14 ach^{-1} respectively. The result indicates that the volumetric airflow rates and air change rates in case 17 are higher than case 15, and the airflow distribution at the occupancy (bed) level is better in case 17 compared to case 15. The airflow distribution at the occupancy level is shown in figure 8.17. Additionally, the airflow distribution and circulation at occupancy levels of 1.0 m and 0.6 m height and 3D streamline of the ward interior has been illustrated table 8-17. The contour in these figures indicates a good distribution of the airflow within the entire ward floor area.

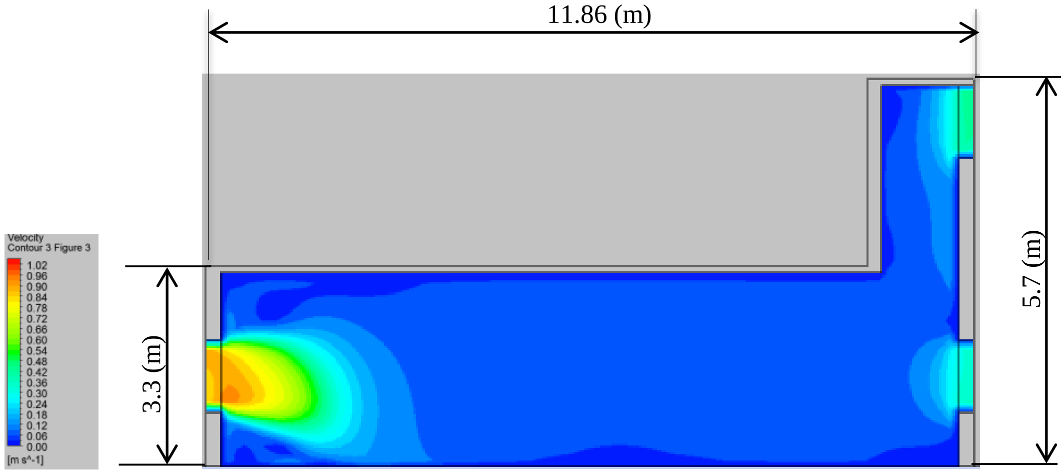
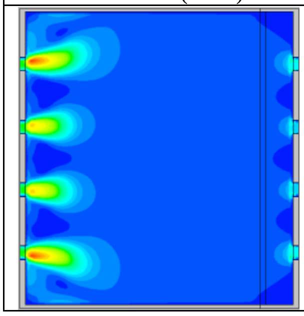
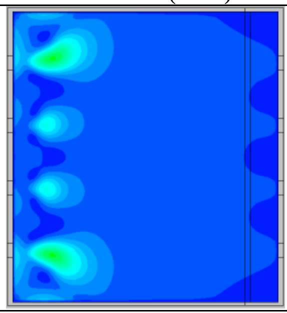
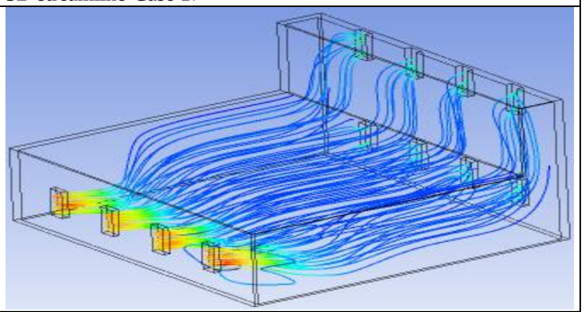


Figure 8.17: Vertical section of case 17 showing airflow circulation and distribution

Table 8-17: Horizontal sections and 3D streamline of Case 17 showing airflow distribution

Horizontal section (1.0 m)-Case 17	Horizontal section (0.6 m)-Case 17	3D streamline-Case 17
		

Interestingly, all the above results indicate that volumetric airflow rates and air change rates alone will not measure ventilation efficiency and effectiveness, rather indoor air circulation and distribution at occupancy level are also essential. This is owing to the influence of short circuiting phenomenon that produces ineffective but high volumetric flow rates and air change rates. Therefore case 16 is the best case in terms of volumetric airflow rate, air change rate and air flow distribution among all the 17 cases simulated and analysed. The volumetric airflow rates in cases 16 and 17 are 1.72 m^3/s and 1.56 m^3/s and the air change rates in these cases are 13.55 ach^{-1} and 11.14 ach^{-1} respectively. Hence, case number 16 was chosen to conduct further studies on the effects of insect screen porosity and orientation and ventilation performance.

8.3.1.4 Comparative analysis of all the 17 Cases simulated

The comparative analysis of the 17 cases studied has been presented in a tabular form in tables 8-18 to 8-23 and figure 8.18 illustrates the difference in air change rates among these cases. These cases are simulated with prevailing wind speeds normal to the openings. The air change rates of all the 17 cases are presented in figure 8.18, showing case 11 with the highest air change rate. But, the air change rate in case 11 is high as a result of short-circuiting, as explained in the previous sections. Case number 16 is the best case in terms of air change rates and airflow circulation within the room. Table 8-18 presents the detailed description and analysis of the 17 cases simulated including diagrams, airflow rates, air change rates, average indoor air velocity, turbulence intensity and air temperature. The volumetric airflow rates of the individual openings are presented in table 8-19. The Screens 1 to 8 in the table means the number of openings with installed insect screens (openings 1 to 4 are the inlets and openings 5 to 8 are the outlets).

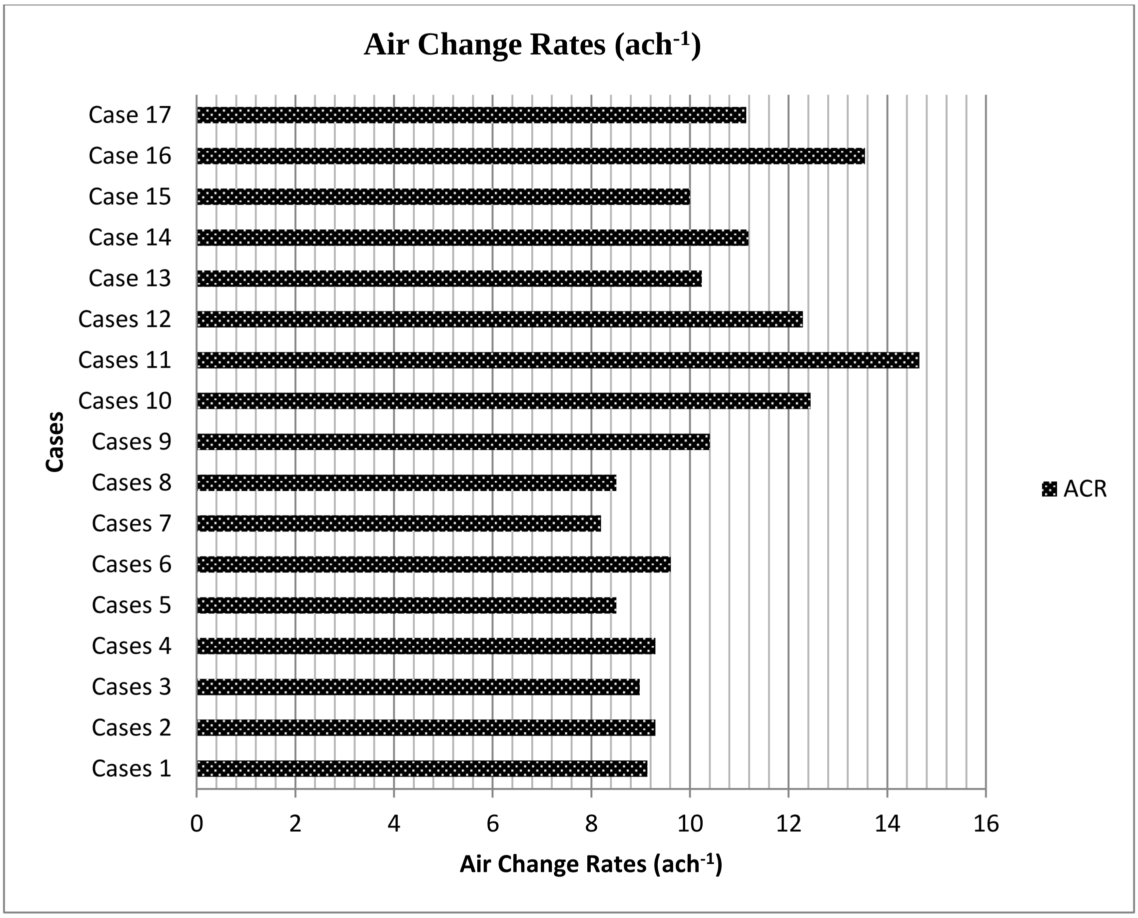
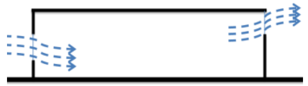
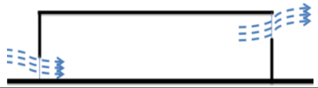
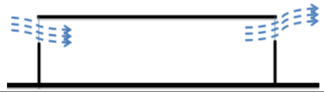
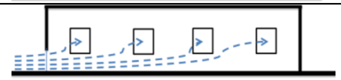
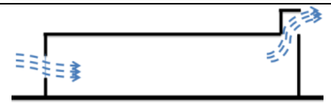
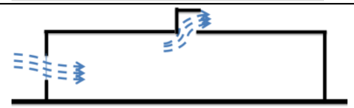
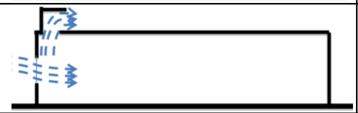


Figure 8.18: Air change rates of different simulated cases compared to the base-case (Case-1)

Table 8-20 and 8-21 presents the qualitative description of horizontal sections of the 17 cases simulated showing airflow circulation pattern in terms of velocity magnitude. Table 8-22 presents the vertical sections of the 17 cases showing air flow circulation pattern.

Moreover, table 8-23 presents the 3D streamlines showing velocity magnitudes of different opening in the 17 cases simulated.

Table 8-18: Indoor Airflow rates characteristics various ventilation strategies in the multi-bed wards

Cases	Description	Diagram	Airflow rate (m^3/s)	Air Change Rates (ach^{-1})	Average Air velocity (m/s)	Turbulence Intensity (%)	Average Temperature (ºC)
Case 1	**Inlets centre & outlets centre**		*1.16*	*9.14*	*0.041*	*3.8*	*27.4*
Case 2	**Inlet centre & outlet up**		*1.18*	*9.30*	*0.040*	*4.3*	*27.4*
Case 3	**Inlet centre & outlet down**		*1.14*	*8.98*	*0.041*	*3.8*	*27.4*
Case 4	**Inlet high & outlet down**		*1.18*	*9.30*	*0.054*	*3.5*	*27.4*
Case 5	**Inlet down and outlet high**		*1.08*	*8.51*	*0.040*	*3.5*	*27.4*
Case 6	**Inlet high and outlet high**		*1.22*	*9.61*	*0.055*	*3.4*	*27.4*
Case 7	**Inlet down and outlet down**		*1.04*	*8.20*	*0.038*	*3.8*	*27.4*
Case 8	**Inlet centre and outlet side**		*1.08*	*8.51*	*0.035*	*3.8*	*27.3*
Case 9	**Inlet centre & outlet roof leeward**		*1.32*	*10.40*	*0.053*	*3.4*	*27.5*
Case 10	**Inlet centre & outlet Roof centre**		*1.58*	*12.45*	*0.053*	*3.8*	*27.4*
Case 11	**Inlet centre & outlet roof windward**		*1.86*	*14.65*	*0.051*	*4.8*	*27.2*

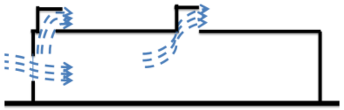
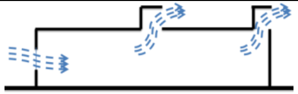
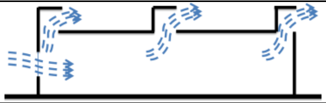
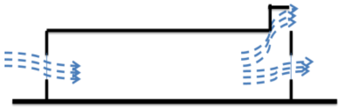
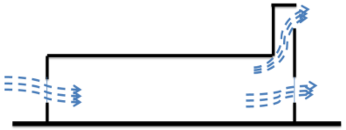
Case 12	**Inlet centre & outlet roof_parallel_2_ windward**		*1.56*	*12.29*	*0.045*	*4.1*	*27.3*
Case 13	**Inlet centre & outlet roof_parallel_2 Leeward**		*1.30*	*10.24*	*0.044*	*3.4*	*27.4*
Case 14	**Inlet centre & outlet roof_parallel_3**		*1.42*	*11.19*	*0.045*	*3.9*	*27.3*
Case 15	**Inlet centre & outlet Tower**		*1.40*	*10.00*	*0.051*	*4.4*	*27.4*
Case 16	**Inlet centre & outlet both roof and leeward wall**		1.72	*13.55*	*0.069*	*4.0*	*27.5*
Case 17	**Inlet centre & outlet both Tower and leeward wall**		1.56	*11.14*	*0.053*	*4.4*	*27.4*

Table 8-19: Volumetric flow rates of the various openings strategies in the multi-bed wards

<table>
<tr><th rowspan="2">Cases</th><th rowspan="2">Description</th><th colspan="4">Inlet openings</th><th colspan="8">Outlet openings</th><th rowspan="2">Total Volumetric flow rates</th></tr>
<tr><th>Screen_1</th><th>Screen_2</th><th>Screen_3</th><th>Screen_4</th><th colspan="2">Screen_5</th><th colspan="2">Screen_6</th><th colspan="2">Screen_7</th><th colspan="2">Screen_8</th></tr>
<tr><td>Case 1</td><td>Inlets centre & outlets centre</td><td>-0.28</td><td>-0.30</td><td>-0.30</td><td>-0.28</td><td colspan="2">0.30</td><td colspan="2">0.28</td><td colspan="2">0.28</td><td colspan="2">0.30</td><td>1.16</td></tr>
<tr><td>Case 2</td><td>Inlet centre & outlet up</td><td>-0.29</td><td>-0.30</td><td>-0.30</td><td>-0.29</td><td colspan="2">0.30</td><td colspan="2">0.29</td><td colspan="2">0.29</td><td colspan="2">0.30</td><td>1.18</td></tr>
<tr><td>Case 3</td><td>Inlet centre & outlet down</td><td>-0.28</td><td>-0.29</td><td>-0.29</td><td>-0.28</td><td colspan="2">0.29</td><td colspan="2">0.28</td><td colspan="2">0.28</td><td colspan="2">0.29</td><td>1.14</td></tr>
<tr><td>Case 4</td><td>Inlet high & outlet down</td><td>-0.30</td><td>-0.29</td><td>-0.29</td><td>-0.30</td><td colspan="2">0.30</td><td colspan="2">0.29</td><td colspan="2">0.29</td><td colspan="2">0.30</td><td>1.18</td></tr>
<tr><td>Case 5</td><td>Inlet down and outlet high</td><td>-0.26</td><td>-0.28</td><td>-0.28</td><td>-0.26</td><td colspan="2">0.28</td><td colspan="2">0.26</td><td colspan="2">0.26</td><td colspan="2">0.28</td><td>1.08</td></tr>
<tr><td>Case 6</td><td>Inlet high and outlet high</td><td>-0.31</td><td>-0.30</td><td>-0.30</td><td>-0.31</td><td colspan="2">0.31</td><td colspan="2">0.30</td><td colspan="2">0.30</td><td colspan="2">0.31</td><td>1.22</td></tr>
<tr><td>Case 7</td><td>Inlet down and outlet down</td><td>-0.25</td><td>-0.27</td><td>-0.27</td><td>-0.25</td><td colspan="2">0.27</td><td colspan="2">0.25</td><td colspan="2">0.25</td><td colspan="2">0.27</td><td>1.04</td></tr>
<tr><td>Case 8</td><td>Inlet centre and outlet side</td><td>-0.26</td><td>-0.28</td><td>-0.28</td><td>-0.26</td><td colspan="2">0.26</td><td colspan="2">0.25</td><td colspan="2">0.27</td><td colspan="2">0.30</td><td>1.08</td></tr>
<tr><td>Case 9</td><td>Inlet centre & outlet roof Leeward</td><td>-0.32</td><td>-0.34</td><td>-0.34</td><td>-0.32</td><td colspan="2">0.34</td><td colspan="2">0.32</td><td colspan="2">0.32</td><td colspan="2">0.34</td><td>1.32</td></tr>
<tr><td>Case 10</td><td>Inlet centre & outlet Roof centre</td><td>-0.38</td><td>-0.41</td><td>-0.41</td><td>-0.38</td><td colspan="2">0.41</td><td colspan="2">0.38</td><td colspan="2">0.38</td><td colspan="2">0.41</td><td>1.58</td></tr>
<tr><td>Case 11</td><td>Inlet centre & outlet roof windward</td><td>-0.44</td><td>-0.49</td><td>-0.49</td><td>-0.44</td><td colspan="2">0.48</td><td colspan="2">0.45</td><td colspan="2">0.45</td><td colspan="2">0.48</td><td>1.86</td></tr>
<tr><td>Case 12</td><td>Inlet centre & outlet roof parallel_2-W</td><td>-0.37</td><td>-0.41</td><td>-0.41</td><td>-0.37</td><td colspan="2">0.47</td><td colspan="2">0.47</td><td colspan="2">0.31</td><td colspan="2">0.31</td><td>1.56</td></tr>
<tr><td>Case 13</td><td>Inlet centre & outlet roof_parallel_2-L</td><td>-0.31</td><td>-0.34</td><td>-0.34</td><td>-0.31</td><td colspan="2">0.29</td><td colspan="2">0.29</td><td colspan="2">0.36</td><td colspan="2">0.36</td><td>1.30</td></tr>
<tr><td>Case 14</td><td>Inlet centre & outlet roof_parallel_3</td><td>-0.33</td><td>-0.38</td><td>-0.38</td><td>-0.33</td><td colspan="2">0.18</td><td colspan="2">0.18</td><td>0.18</td><td>0.18</td><td>0.35</td><td>0.35</td><td>1.42</td></tr>
<tr><td>Case 15</td><td>Inlet centre & outlet Tower</td><td>-0.34</td><td>-0.36</td><td>-0.36</td><td>-0.34</td><td colspan="2">0.36</td><td colspan="2">0.34</td><td colspan="2">0.34</td><td colspan="2">0.36</td><td>1.40</td></tr>
<tr><td>Case 16</td><td>Inlet centre & outlet roof and Wall L</td><td>-0.42</td><td>-0.44</td><td>-0.44</td><td>-0.42</td><td>0.23</td><td>0.19</td><td>0.19</td><td>0.23</td><td>0.22</td><td>0.22</td><td>0.22</td><td>0.22</td><td>1.72</td></tr>
<tr><td>Case 17</td><td>Inlet centre & outlet Tower and Wall L</td><td>-0.38</td><td>-0.40</td><td>-0.40</td><td>-0.38</td><td>0.22</td><td>0.19</td><td>0.19</td><td>0.22</td><td>0.21</td><td>0.16</td><td>0.16</td><td>0.21</td><td>1.56</td></tr>
</table>

Table 8-20: Contours showing velocity magnitudes at 1.0 meters (occupancy level) above floor level

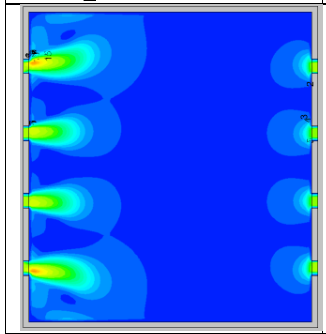
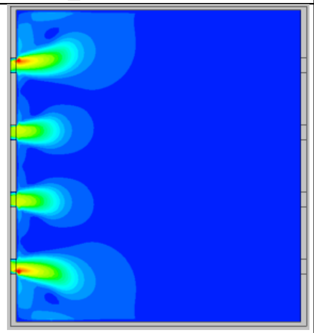
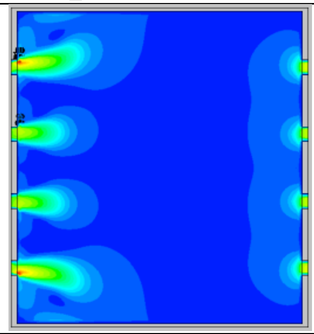
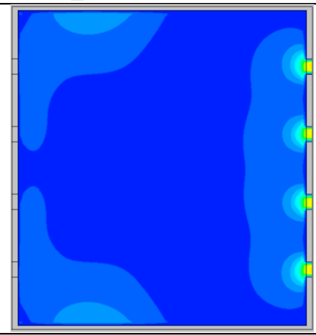
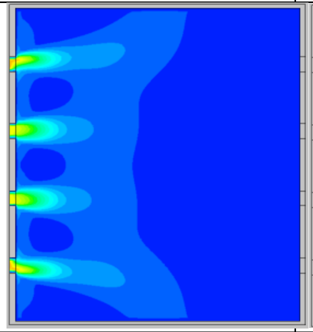
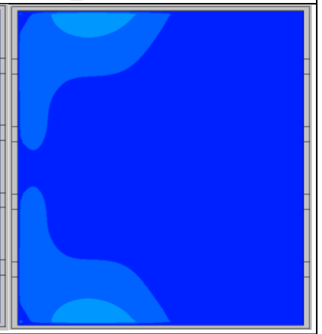
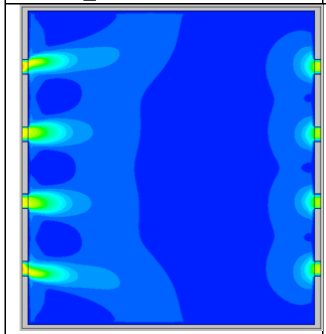
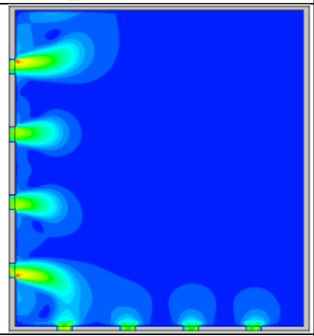
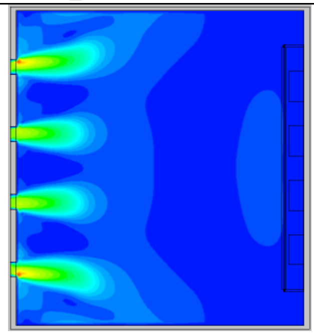
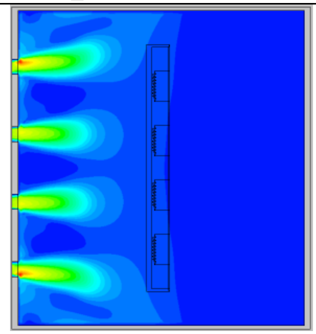
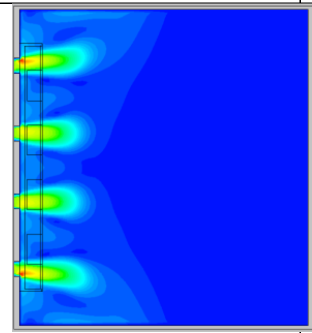
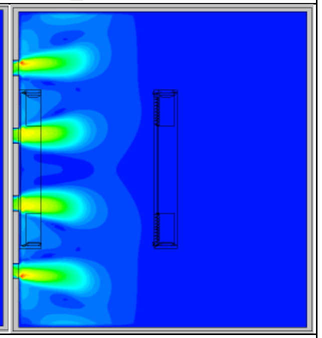
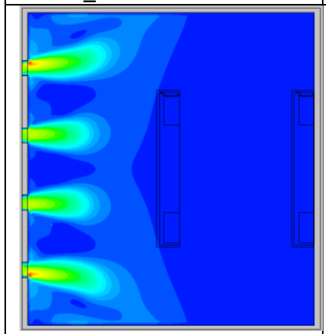
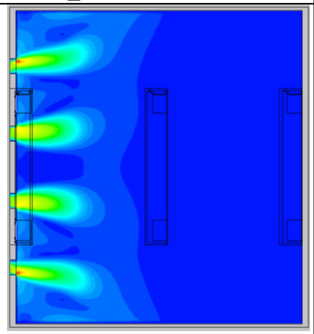
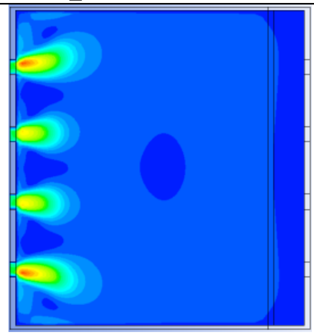
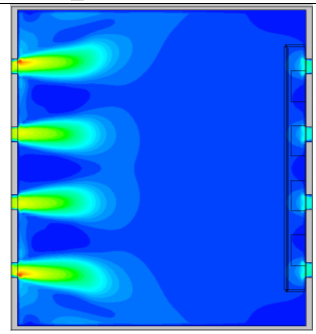
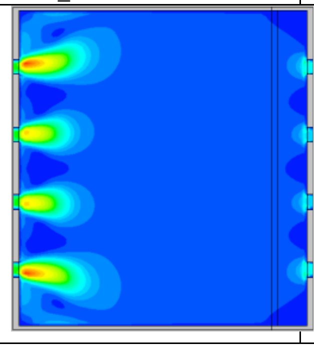
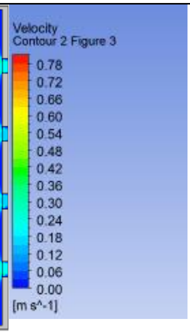
CASE_1	CASE_2	CASE_3	CASE_4	CASE_5	CASE_6
					
CASE_7	CASE_8	CASE_9	CASE_10	CASE_11	CASE_12
					
CASE_13	CASE_14	CASE_15	CASE_16	Case_17	
					

Table 8-21: Contours showing velocity magnitudes at 0.6 meters (occupancy level) above floor level

<table>
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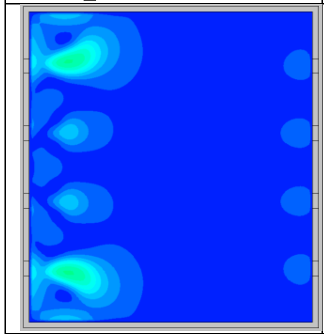
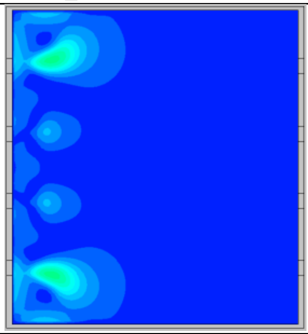
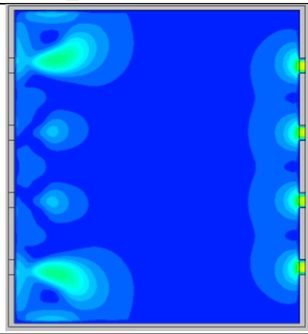
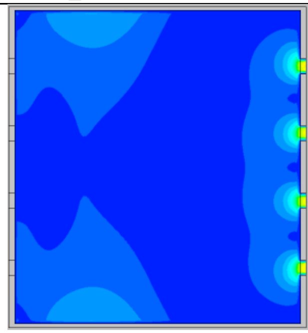
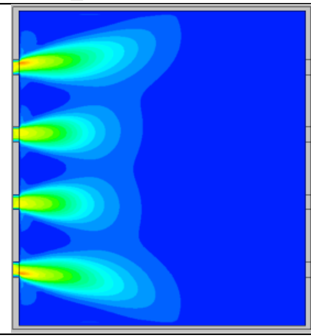
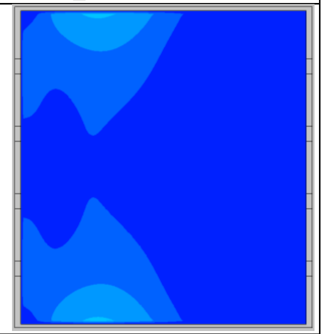
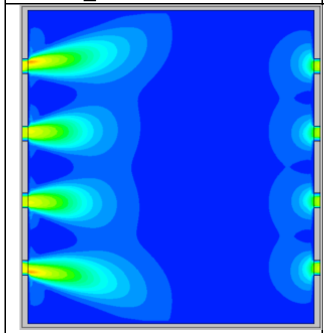
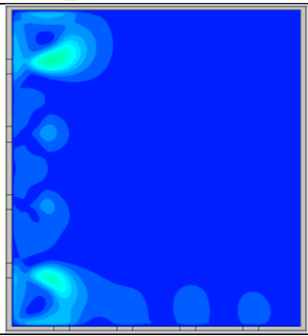
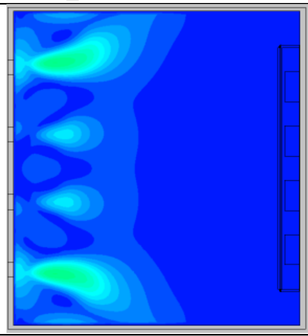
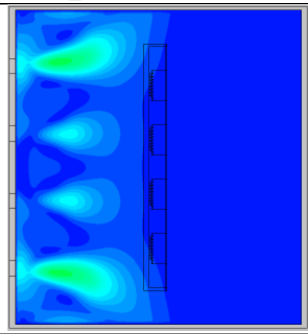
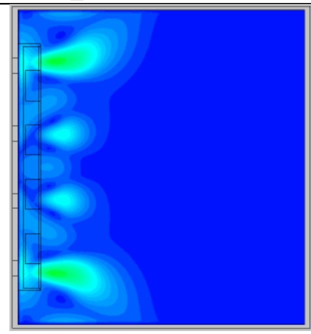
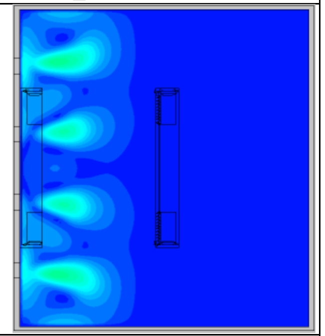
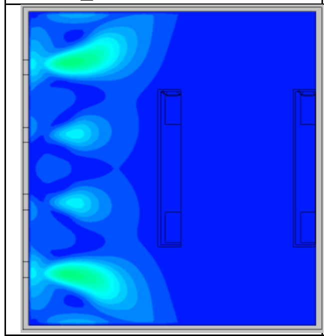
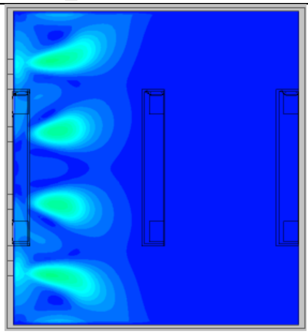
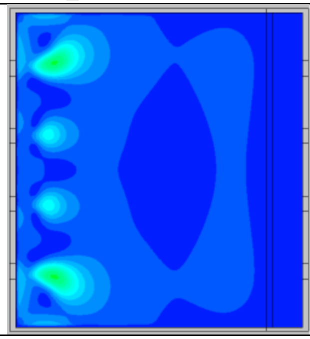
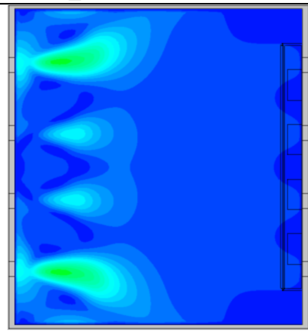
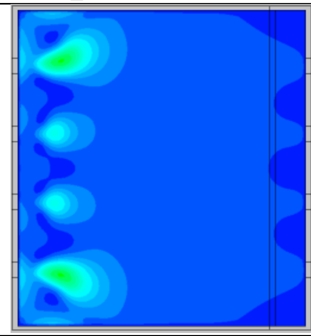
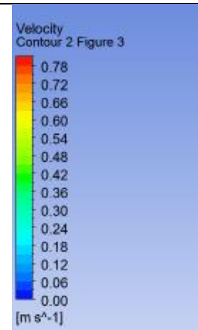
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CASE_7</td><td>CASE_8</td><td>CASE_9</td><td>CASE_10</td><td>CASE_11</td><td>CASE_12</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CASE_13</td><td>CASE_14</td><td>CASE_15</td><td>CASE_16</td><td>CASE_17</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>
</td></tr>
</table>

Table 8-22: Contours showing vertical section of velocity magnitudes at the centre of the ward (through the window)

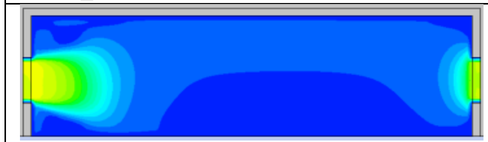
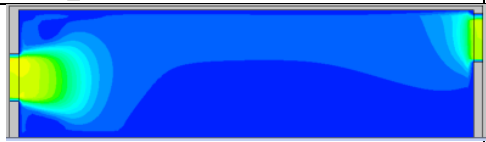
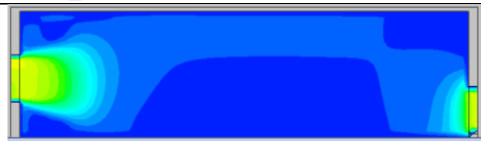
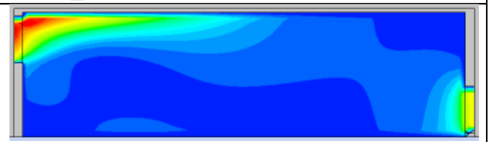
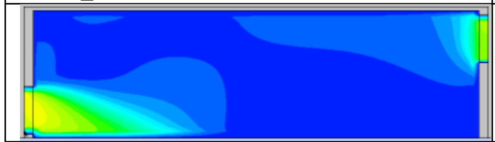
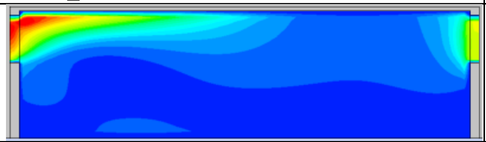
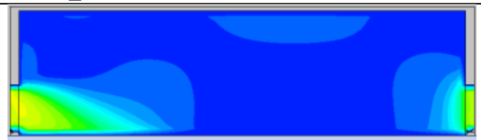
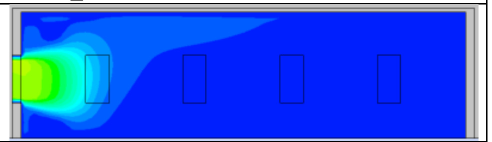
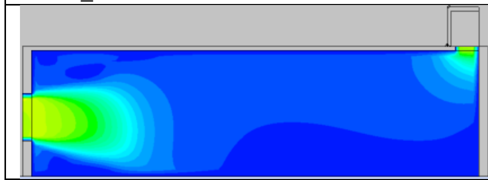
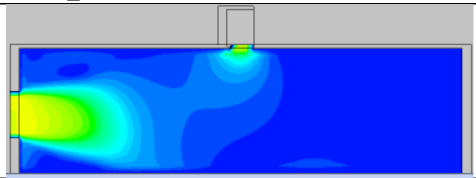
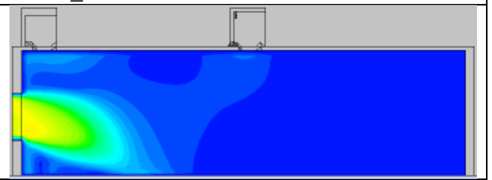
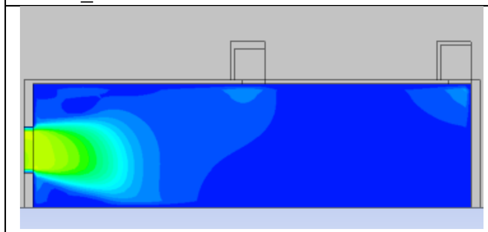
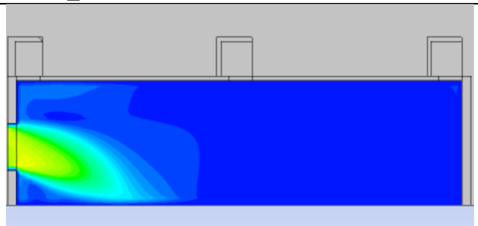
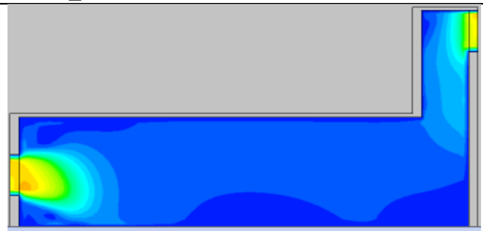
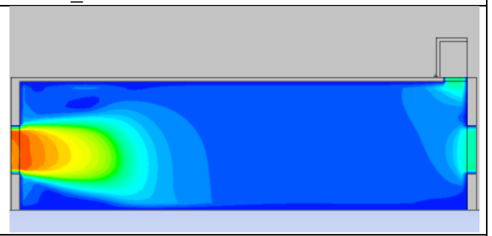
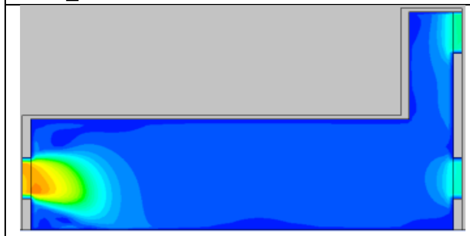
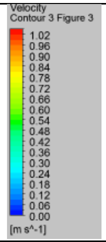
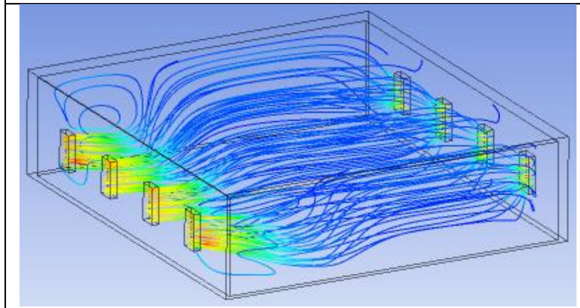
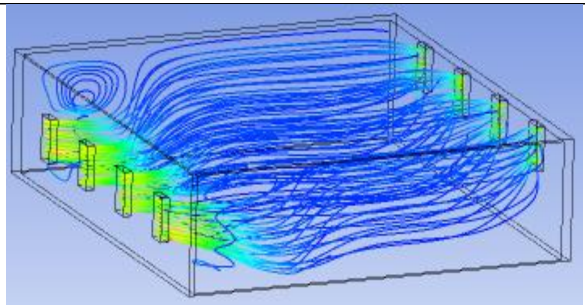
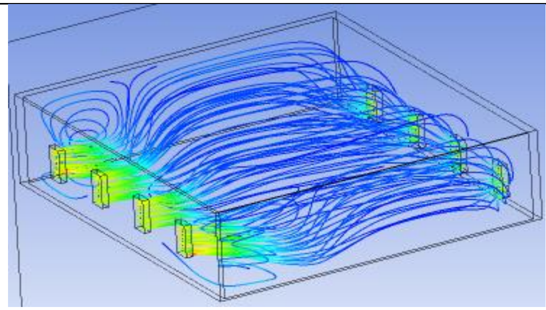
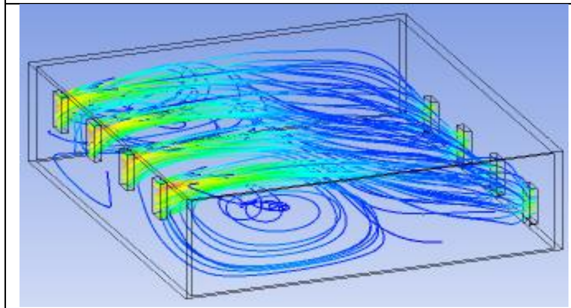
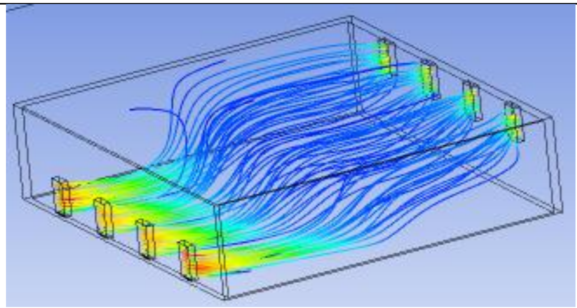
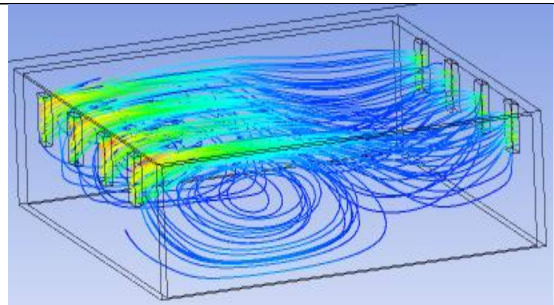
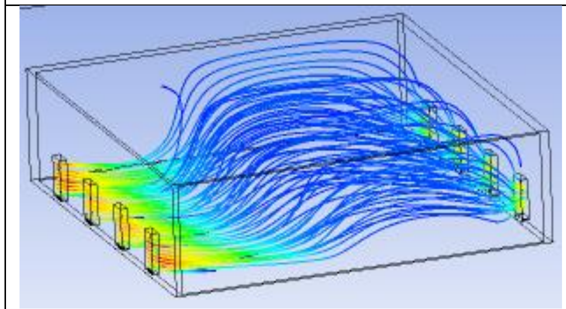
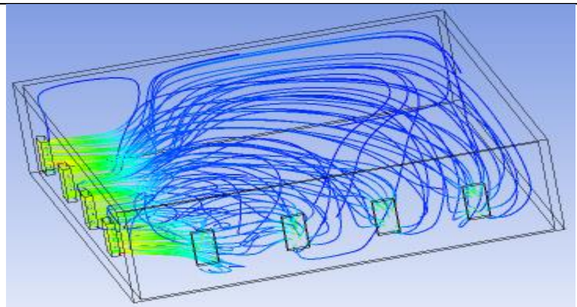
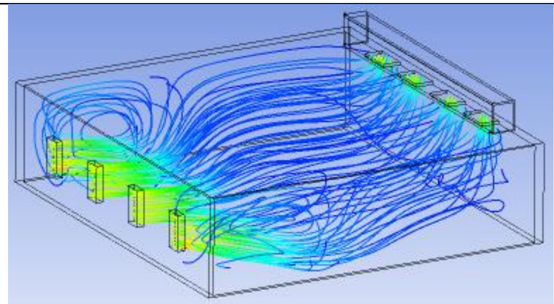
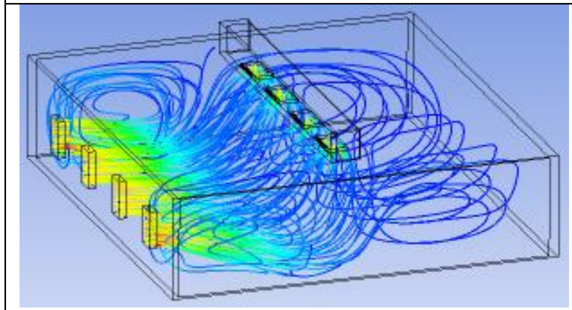
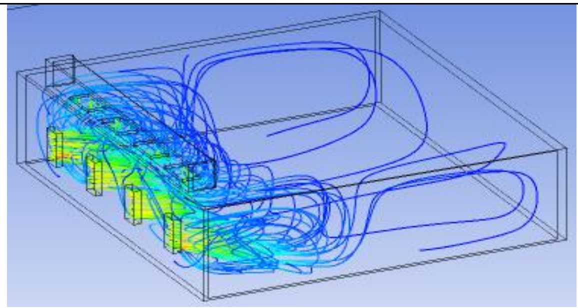
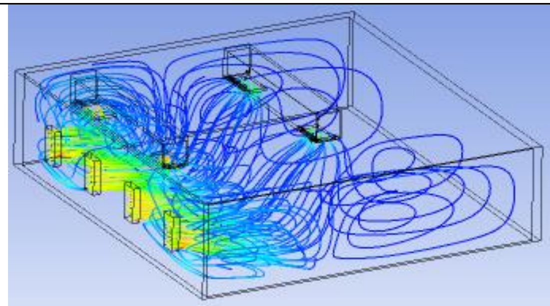
CASE_1	CASE_2	CASE_3	CASE_4
			
CASE_5	CASE_6	CASE_7	CASE_8
			
CASE_9	CASE_10	CASE_11	CASE_12
			
CASE_13	CASE_14	CASE_15	CASE_16
			
Case_17			
			

Table 8-23: 3D streamlines showing velocity magnitudes of different opening cases

CASE_1	CASE_2	CASE_3
		
CASE_4	CASE_5	CASE_6
		
CASE_7	CASE_8	CASE_9
		

CASE_10	CASE_11	CASE_12
		
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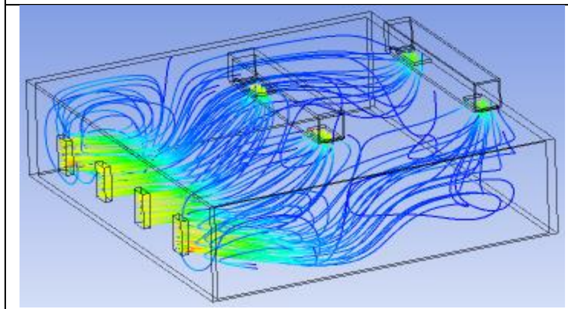
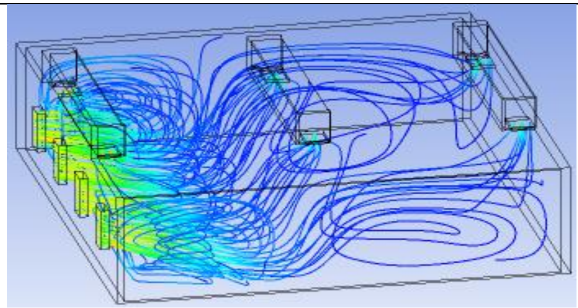
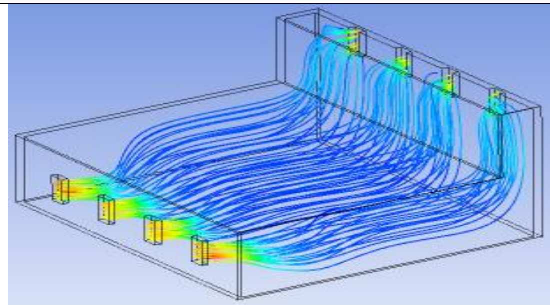
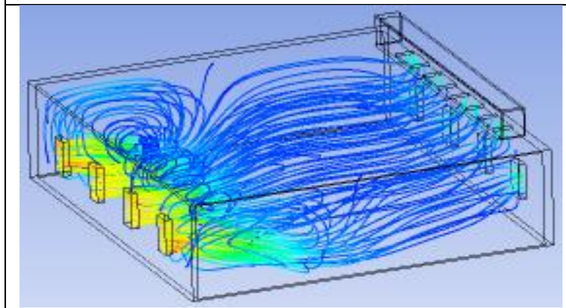
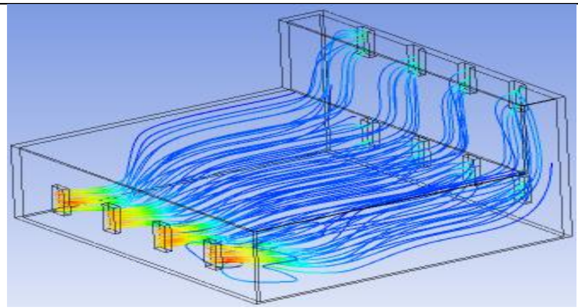
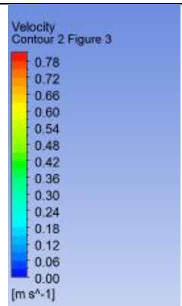
		
CASE_16	Case_17	
		

8.4 Percentage Dissatisfied with Air Quality

According to ASHRAE Position Document (2011) "*The term indoor air quality (IAQ) represents the indoor air concentrations of pollutants that are known or suspected to affect people's comfort, environmental satisfaction, health, or work or school performance".* The indoor air quality of a space can be expressed as the extent to which human requirements are met. This requirement substantially varies from one individual to the other depending on their sensitivity to various environmental parameters (Mumovic and Santamouris 2009). An acceptable indoor air quality is generally prescribed through the required level of ventilation rates (air change per hour) or the outside air supply rates (Olsen, 2011). The PD levels in all the cases are below 15%, which is within the acceptable dissatisfaction level. The prediction of percentage dissatisfied is used to establish ventilation requirements to obtain a specific level of air quality. Air change rates for different ventilation opening scenarios has been obtained through simulation and the corresponding percentages of dissatisfaction caused by a standard person at these ventilation rates were estimated using figure 8-19. The air change rates per standard person for different occupancy levels and their corresponding percentage of dissatisfactions (PD) is shown in table 8-24. The air change rate in L/S per standard person was estimated for hospital multi-bed ward occupancy of 30, 50, 70 and 90 standards person and the results is presented in figure 8.20. The percentage dissatisfied per standards persons is obtained through dividing the ACR in L/S by the number of persons, as presented in table 8-24. The base-case ward was originally designed to accommodate 20 beds. Hence, the 30, 50, 70, and 90 standards person was used to assume 20 patients with; 10 relatives, 20 relatives and 10 HealthCare Workers (HCW)/nurses, 40 relatives and 10 HCW/nurses, and 60 relatives and 10 HCW/nurses respectively. The result in all the 17 cases indicates that the highest percentage dissatisfied (PD) with indoor air quality for 30, 50, 70 and 90 standard persons are 4.5, 7.4, 10 and 13% respectively. Because, ASHREA (2007) defines indoor air quality as *"Air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80 percent or more) of the people exposed do not express dissatisfaction"*.

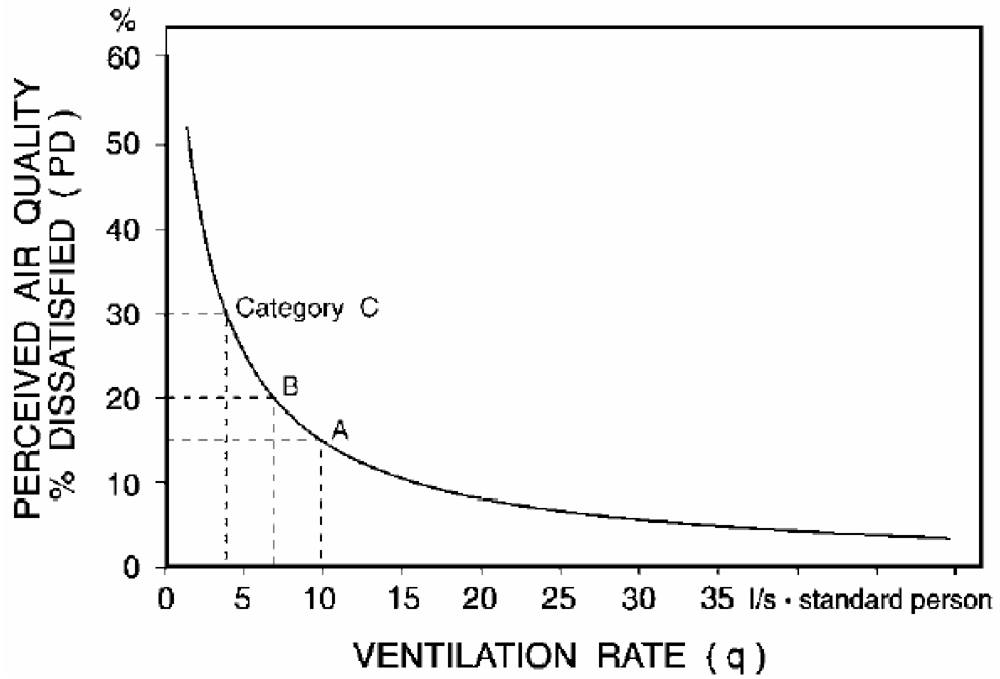


Figure 8.19: Dissatisfaction caused by a standard person at different ventilation rates (Olesen, 2004)

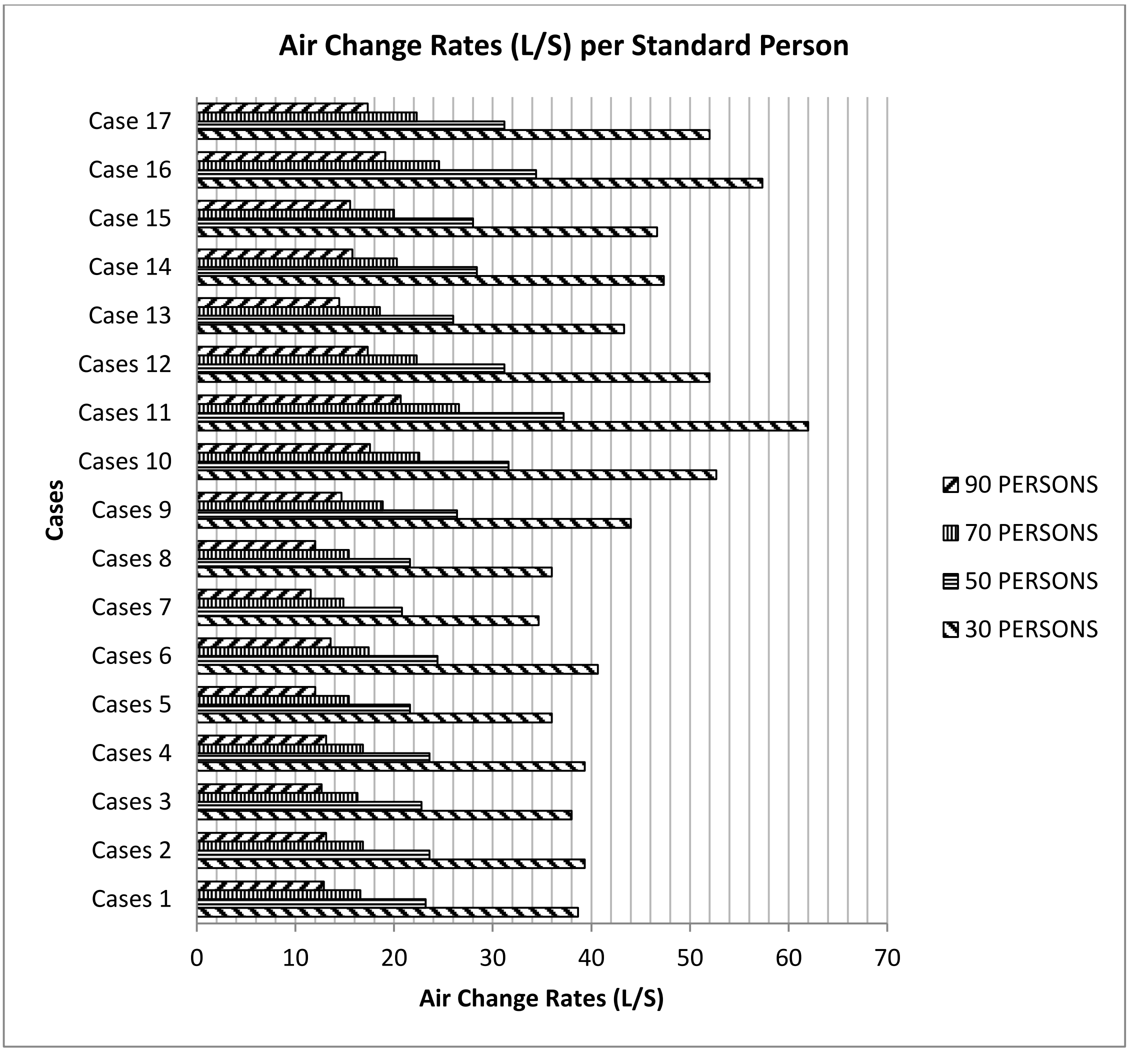


Figure 8.20: Air change rates per standard person for different occupancy levels

Table 8-24: Air change rates per standard person for different occupancy levels and their corresponding percentage of dissatisfactions (PD)

Cases	Airflow rate	Volume	ACR (ach^{-1})	ACR (L/S)	30 Standard Persons	PD (IAQ) %	50 Standard Persons	PD (IAQ) %	70 Standard Persons	PD (IAQ) %	90 Standard Persons	PD (IAQ) %
Cases 1	*1.16*	457	9.14	1160	38.7	4	23.2	7	16.6	9	12. 9	12
Cases 2	*1.18*	457	9.30	1180	39.3	4	23.6	7	16.9	9	13.1	12
Cases 3	*1.14*	457	8.98	1140	38.0	4	22.8	7	16.3	9	12. 7	12
Cases 4	*1.18*	457	9.30	1180	39.3	4	23.6	7	16.9	9	13.1	12
Cases 5	*1.08*	457	8.51	1080	36.0	4.5	21.6	7	15.4	10	12.0	13
Cases 6	*1.22*	457	9.61	1220	40. 7	3.5	24.4	7.4	17.4	9	13. 6	12
Cases 7	*1.04*	457	8.20	1040	34.7	4.5	20.8	7	14.9	10	11.6	13
Cases 8	*1.08*	457	8.51	1080	36.0	4.5	21.6	7	15.4	10	12.0	12
Cases 9	*1.32*	457	10.71	1320	44.0	3	26.4	5.5	18.9	8.5	14.7	10
Cases 10	*1.58*	457	12.60	1580	52.7	2.5	31.6	5	22.6	7	17. 6	9
Cases 11	*1.86*	457	14.65	1860	62.0	2	37.2	4.5	26.6	5.5	20. 7	7
Cases 12	*1.56*	457	12.29	1560	52.0	2.5	31.2	5	22.3	7	17.3	9
Case 13	*1.3*	457	10.24	1300	43.3	3.5	26.0	5.5	18.6	8.5	14.4	10
Case 14	*1.42*	457	11.19	1420	47.3	3.2	28.4	5.5	20.3	7	15. 8	9
Case 15	*1.40*	504	10.29	1400	46.7	3.2	28.0	5.5	20.0	7	15.6	9
Case 16	*1.72*	457	13.55	1720	57.3	2.3	34.4	4.5	24.6	7.4	19.1	8.5
Case 17	*1.56*	504	11.14	1560	52.0	2.5	31.2	5	22.3	7	17.3	9

8.5 Local Indoor Velocity and Turbulent Intensity

The measurement of the local indoor air parameters such as velocity and turbulent intensity are necessary to obtain better understanding of the airflow distribution and efficiency in the hospital wards. In this study, twenty one (21) different points were selected, seven (7) each at the Windward side (W 1-7), Centre of the room (C 1-7) and Leeward side (L 1-7), to study the indoor local velocity and turbulent intensity. Points 1, 3, 5 and 7 in all the three cases (W, C, L) are directly opposite the window openings, while points 2, 4 and 6 positions are directly opposite the walls as illustrated in figure 8-21.

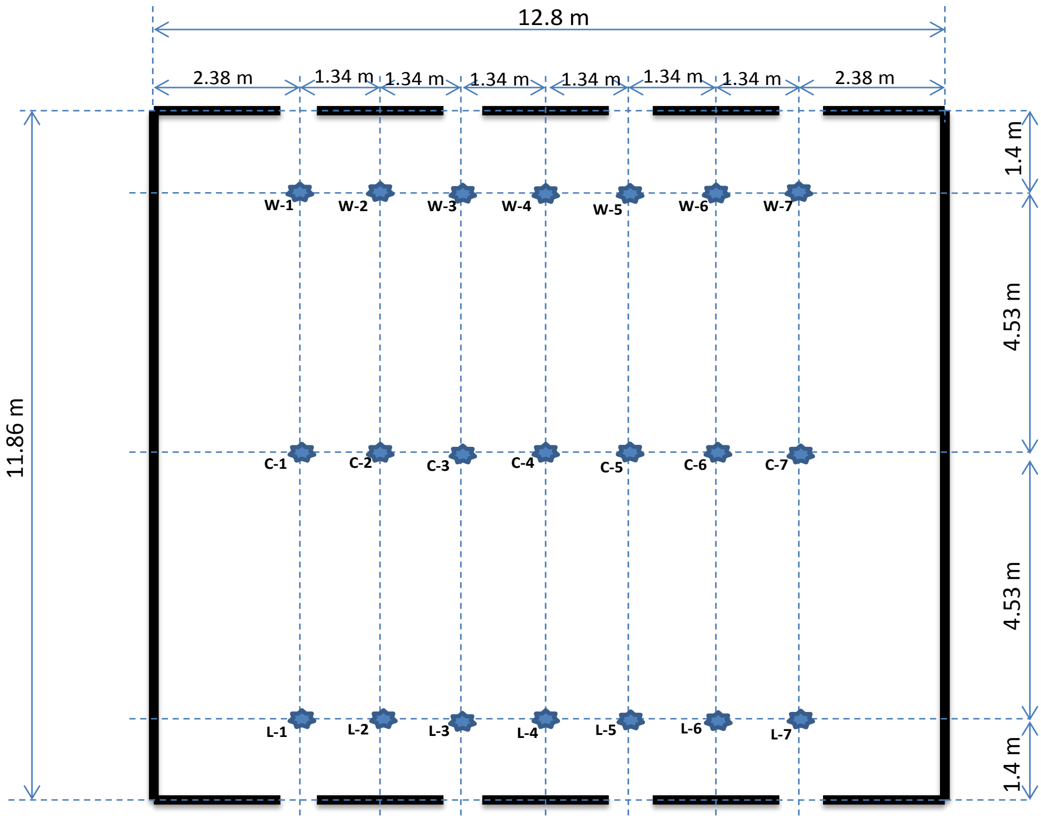


Figure 8.21: The measuring points for local indoor air parameters

8.5.1 Local indoor Air velocity

The local indoor air velocity at various positions of interest provides more detailed information about the idea of airflow distribution within an indoor environment, compared to average indoor air velocity. When considering human comfort in assessing ventilation effectiveness, attention should be given not only to the overall amount of airflow but also to the distribution of air velocities throughout the ventilated room. Moreover, the important consideration, when dealing with ventilation in terms of its effect on comfort, is the air speed over the human body (Givoni 1994).

In this study, the local indoor air velocity at twenty one (21) points has been measured, seven (7) each at the windward, centre and leeward positions of the indoor environments. The measurements were also made at two occupancy heights of 1.0m and 0.6 m above floor level to represent patient relatives seated on chair and patient on beds respectively. These measurements were conducted for both the base-case (Case-1) and the best-case (Case-16). The result shows that, the highest local indoor air speed is obtainable at the points opposite the inlet openings (points 1, 3, 5 and 7) in both 1.0 m and 0.6 m height in the two cases of 1 and 16 as illustrated in figures 8.22 to 8.25.

The results of the local air speed at 1.0 m height above floor level in case 1 indicate that the air speed opposite to the inlets openings (W1) at points 1, 3, 5 and 7 are the highest above 0.29 m/s as illustrated in figure 8.22. According to Gilkeson et al. (2013), indoor air velocities are higher on the air inlet side of a ventilated space before decaying to a considerably lower value further downstream as shown in figure 8.22.

Decaying quite clearly, the air speeds are low at the points opposite the walls (Points 2, 4, and 6). In the windward location, the airflow starts with higher velocity opposite the windows and significantly drops opposite the wall (P2, P4, and P6). In the centre, low air velocities are experienced with little variation in all the positions. Similarly in the leeward side, the velocities are higher adjacent the windows and slightly lower adjacent the wall, but the variation is much lower than the windward side as illustrated in figure 8.22.

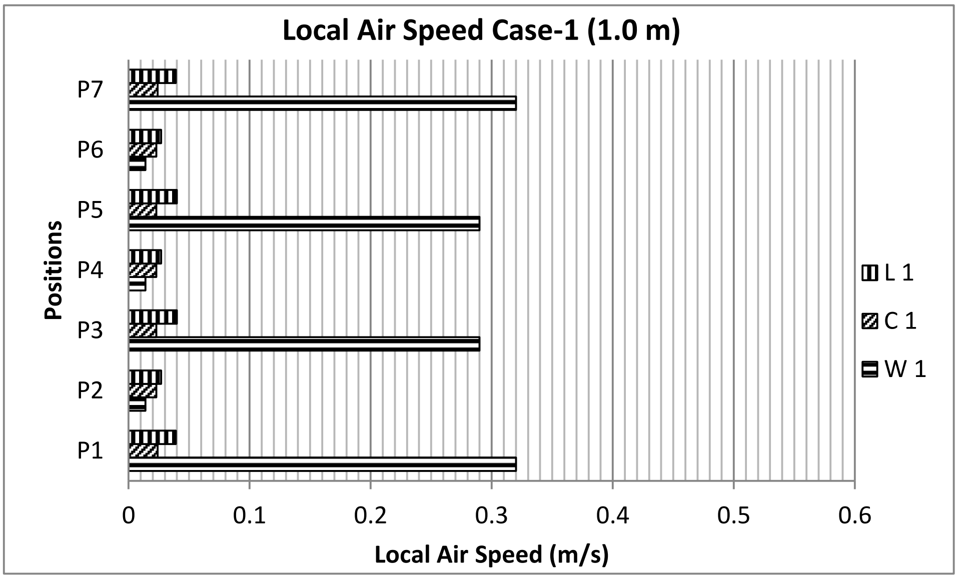


Figure 8.22: Local indoor air speed at 1.0 m above floor level in Case-1

However, the distribution of local air speeds in case 16 are similar to case 1, but the air speeds are higher in case 16. The points opposite the windward openings have the highest speeds and the difference between the points at the centre and the leeward is negligible as illustrated in figure 8.23. However, in points opposite the walls the air speeds at the windward positions are the lowest.

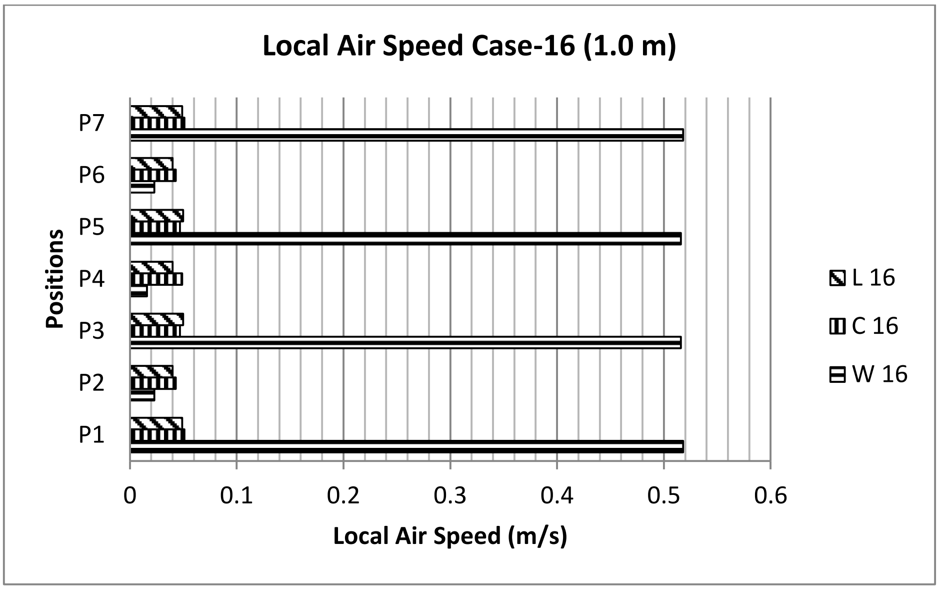


Figure 8.23: Local indoor air speed at 1.0 m above floor level in Case-16

The pattern of indoor air speeds at 0.6 m above floor indicates that, in the windward positions the air speeds are higher at the edges than at the middle of the room in both cases 1 and 16. This may be as a result of the presence of solid walls by the sides of the room, which transforms the airflow by creating higher pressure on the surface. Unlike in case 1, where the air speeds at leeward positions are higher than the centre of the room as illustrated in figure 8.24, but in case 16, the air speeds in the centre positions are higher than that of the leeward positions as illustrated in figure 8.25.

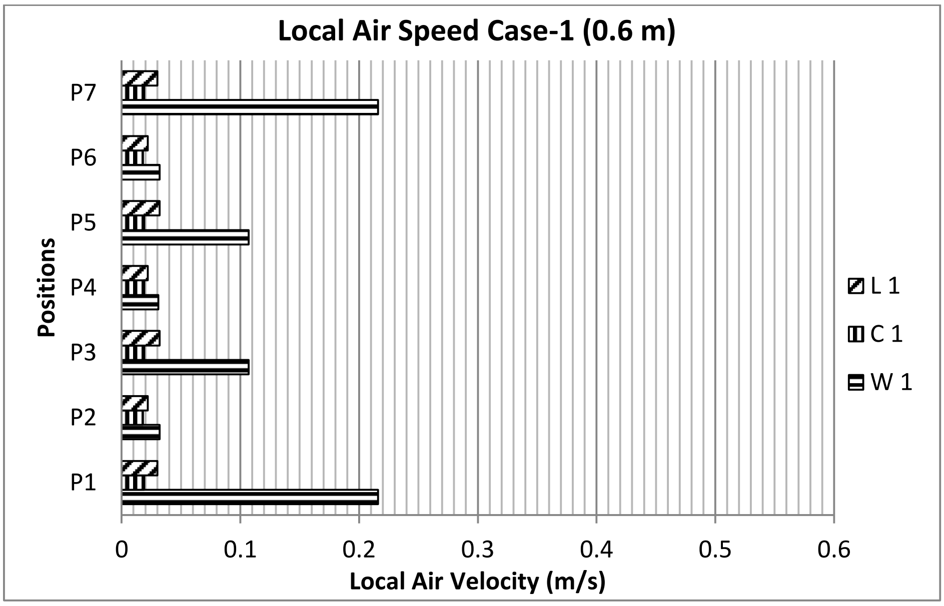


Figure 8.24: Local indoor air speed at 0.6 m above floor level in Case-1

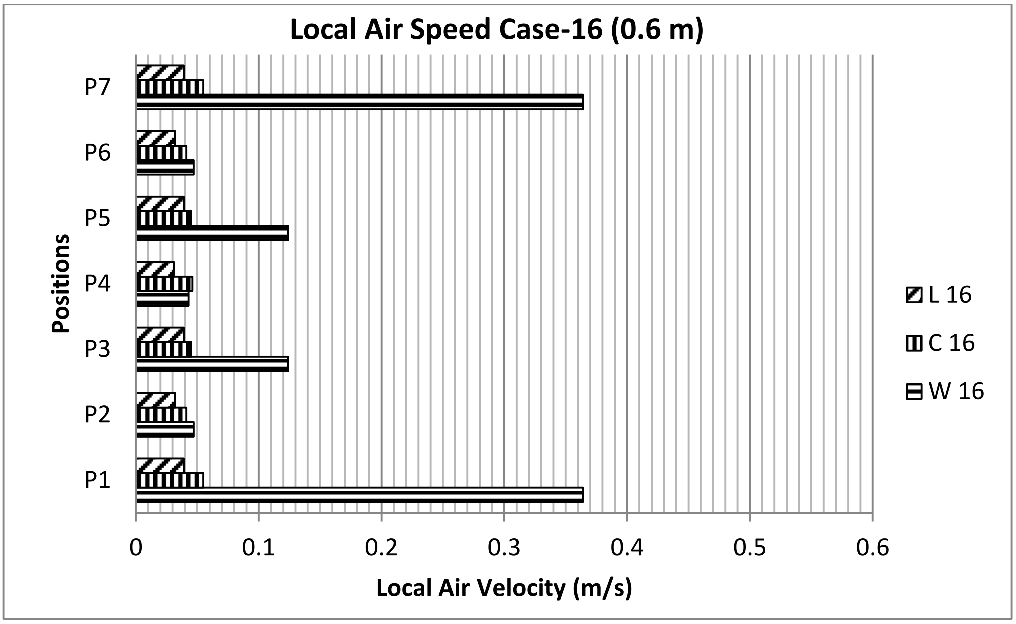


Figure 8.25: Local indoor air speed at 0.6 m above floor level in Case-16

Figures 8.26 to 8.28 compared the two cases directly at the three measurement positions. It is apparent from these figures that, the local air speeds at 1.0 m above floor levels (occupancy height) in Case 16 are higher than Case 1 in all the twenty one (21) positions measured. Another interesting observation from the simulation results is that, the local air speeds for Case 1 are almost the same in all the seven (7) points measured at the centre of the room, while there is variation in case 16 as illustrated in figure 8.27.

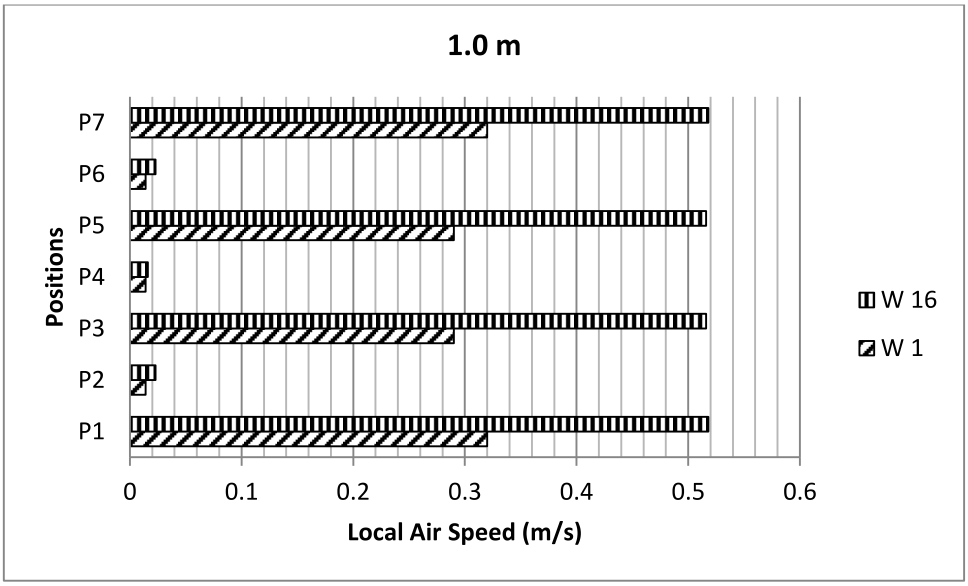


Figure 8.26: The comparative analysis of local indoor air speed at 1.0 m height at the windward sides of Cases 1 and 16

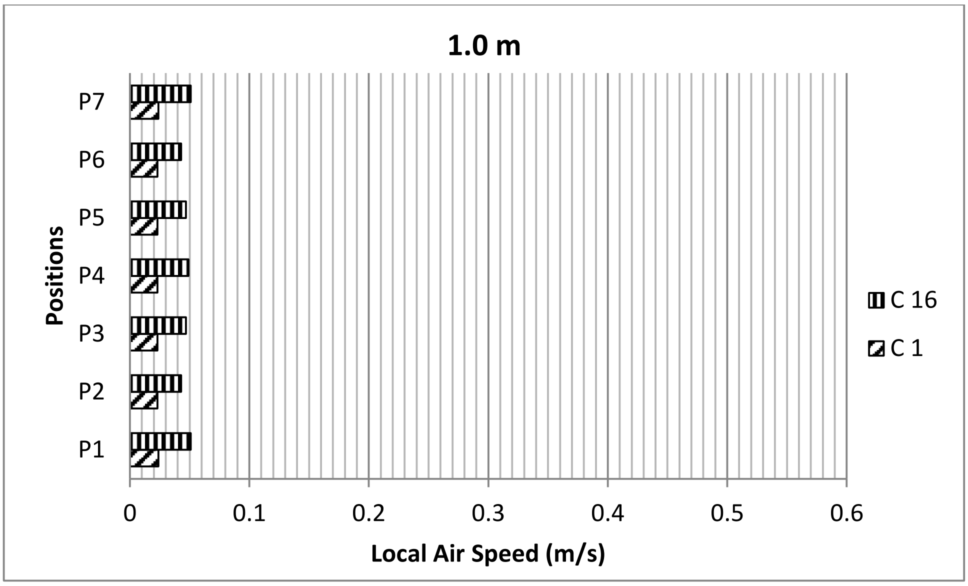


Figure 8.27: The comparative analysis of local indoor air speed at 1.0 m height at the centre of Cases 1 and 16

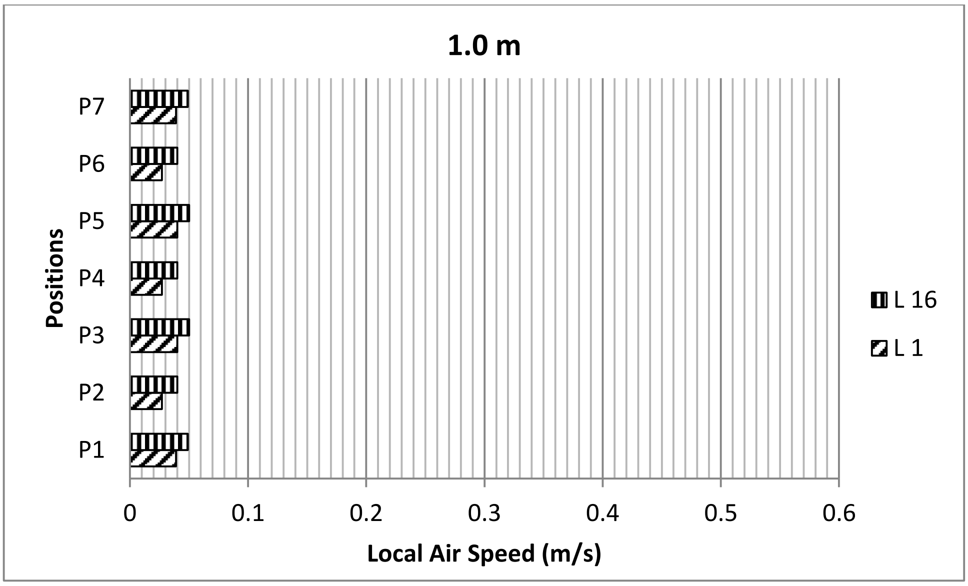


Figure 8.28: The comparative analysis of local indoor air speed at 1.0 m height at the leeward sides of Cases 1 and 16

Similarly, the local indoor air speed at 0.6 m height above floor level (occupancy height) is higher for case 16 compared to case 1 in all the twenty one (21) positions measured, as illustrated in figures 8.29, 8.30 and 8.31 for windward, centre and leeward positions respectively. The results also indicate that the difference in air speed between points opposite to openings and walls is higher at the windward positions compared to the centre and leeward positions as illustrated in figures 8.29, 8.30 and 8.31.

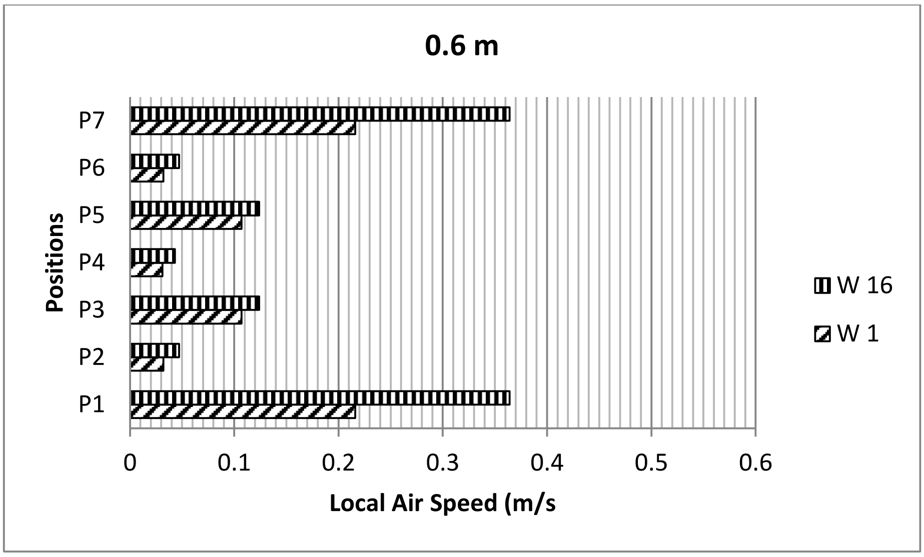


Figure 8.29: The comparative analysis of local indoor air speed at 0.6 m height at the windward sides of Cases 1 and 16

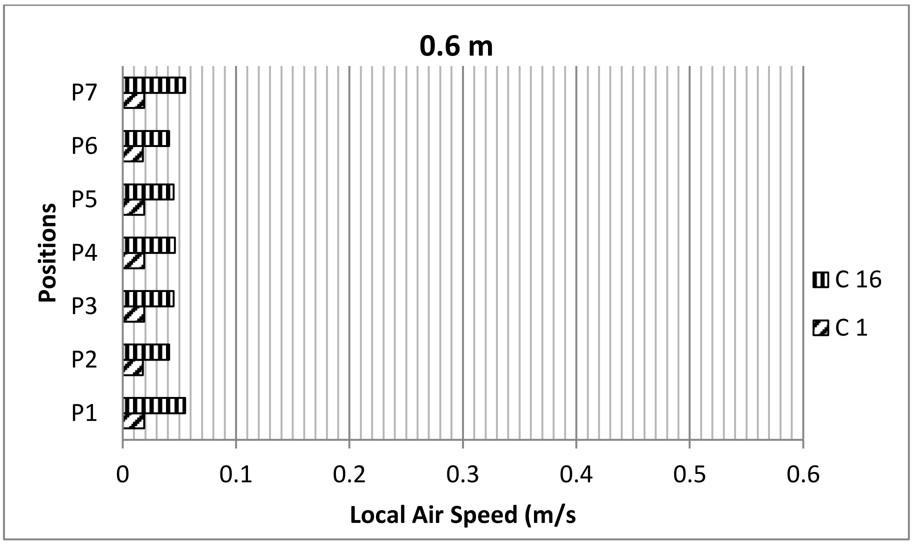


Figure 8.30: The comparative analysis of local indoor air speed at 0.6 m height at the centre of Cases 1 and 16

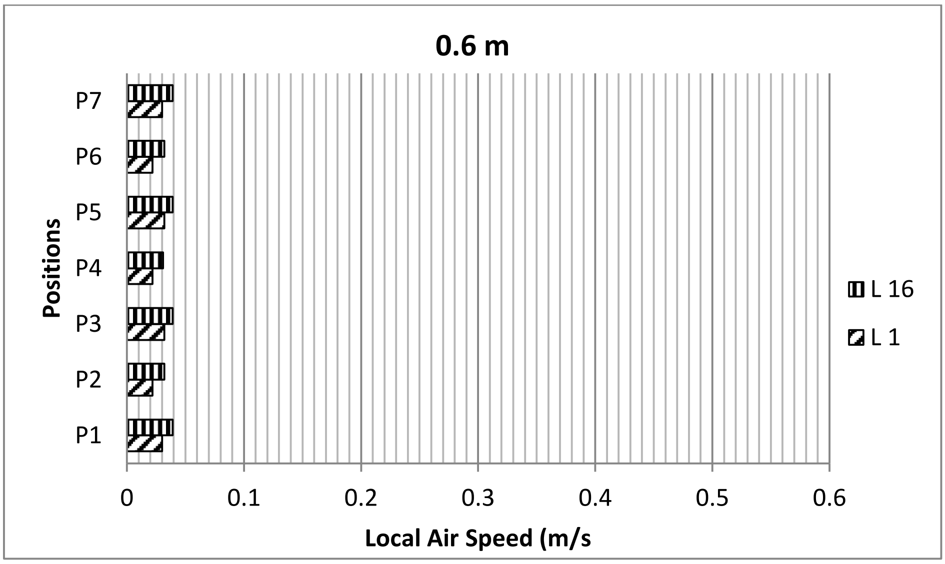


Figure 8.31: The comparative analysis of local indoor air speed at 0.6 m height at the leeward sides of Cases 1 and 16

The influence of the average outdoor wind speed on the local indoor air velocity at different locations in the wards has been investigated for both 1.0 m and 0.6 m occupancy height, using case 16. The average outdoor wind speed used in this study is 2.6 m/s. The highest indoor air velocities at the windward side of the building near and opposite the inlet openings are 20% and 12% of the external wind velocity for 1.0 m and 0.6 m respectively. However, the indoor air velocities in other positions at the centre of the ward and toward the outlet openings are less than or equal to 2% of the outdoor average wind velocity. In general, the indoor air velocities in an open ward are below 10% of the external wind velocity irrespective of the profile height, except the areas near-window region along the upper profile (Gilkeson et al. 2013). It is worth pointing out that, in the present study the installation of insect screens has contributed greatly for the low indoor air velocities obtained in the investigated wards. However, Givoni (1994) has reported that, it is often possible to obtain an indoor air speed of around 1 to 2 m/s in cross ventilated buildings, but the study is referring to indoor air velocities of normal cross ventilated buildings without any insect screen install on their openings. Moreover studies have shown that occupants of naturally ventilated buildings usually tolerate higher range of temperatures and air speed as normal. Hence according to Givoni (1994), the assumption that, inhabitants of developing hot countries living mostly in naturally ventilated buildings are adapted to, and would accept, higher temperature and/or higher humidity is reasonable. Therefore, higher air speed is the most common solution in reducing discomfort for high temperatures and relative humidity (Givoni 1994). However, Yau et al. (2011) in their study indicated that, a local air speed of 0.25 m/s or less is deemed comfortable for inhabitants in the tropics. Furthermore, variations in metabolic rates and clothing among patients and hospital staff would also result in different perceptions and requirements. However, owing to the importance of turbulence intensity in determining human dissatisfaction with draught, the next section discusses the local turbulence intensity at various points in the hospital wards.

8.5.2 Local Indoor Turbulent Intensity

Local turbulent intensity is one of the major factors for determining draught risk in building indoor environment. In this study, local turbulent intensity has been measured at twenty one (21) different locations in the hospital ward, seven (7) locations each at the windward, centre and the leeward sides of the room. Interestingly, the results show that, the higher the air speed, the lower the turbulent intensity in the studied wards. This will be established by comparing figure 8.32, below and figure 8.22 in the previous sections.

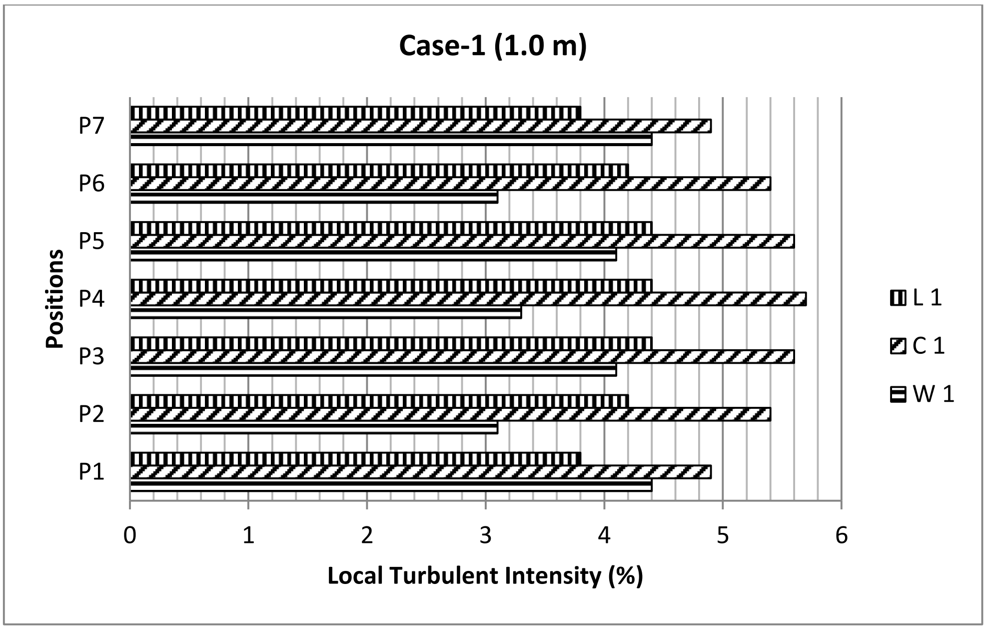


Figure 8.32: Local indoor turbulent intensity at 1.0 m height in Case 1

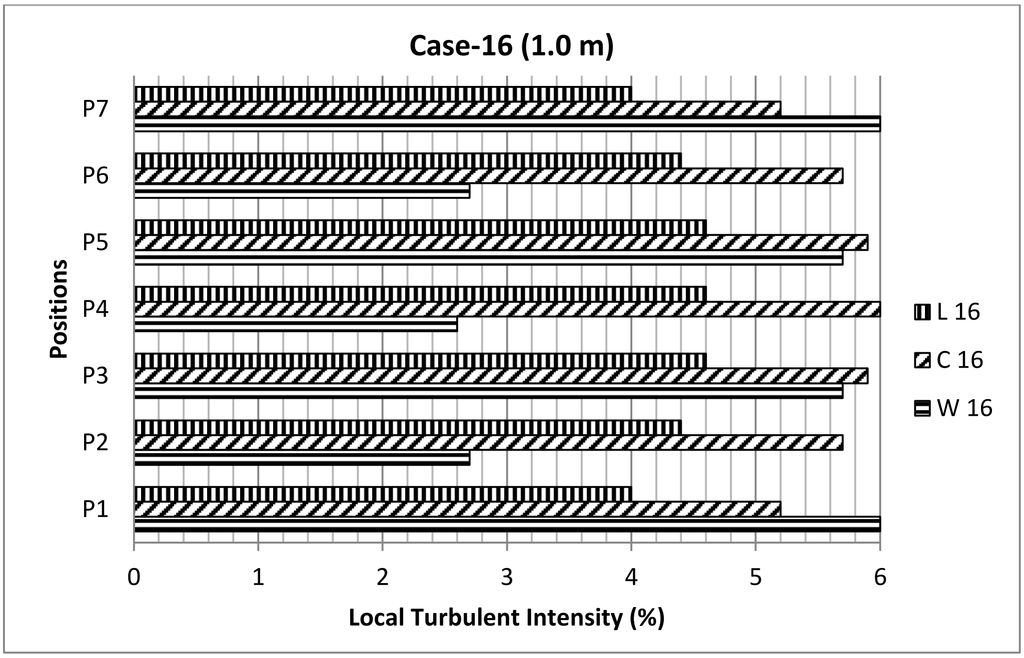


Figure 8.33: Local indoor turbulent intensity at 1.0 m height in Case 16

Moreover, the local turbulent intensity is higher at 1.0 m height compared to lower level of 0.6 m above floor level. This will be established by comparing the data from figures 8.32 to 8.33 with the data in figures 8-34 to 8.35.

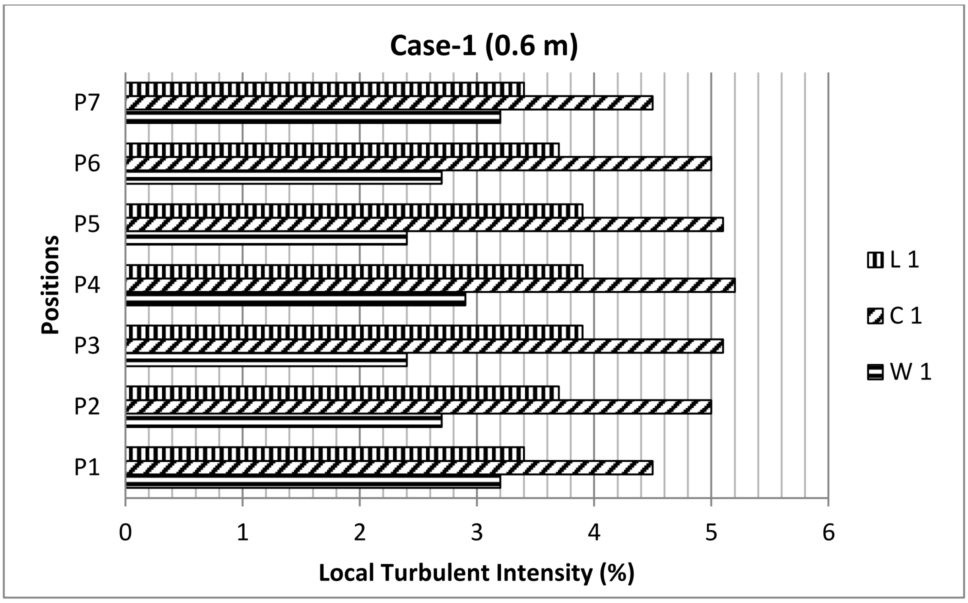


Figure 8.34: Local indoor turbulent intensity at 0.6 m height in Case 1

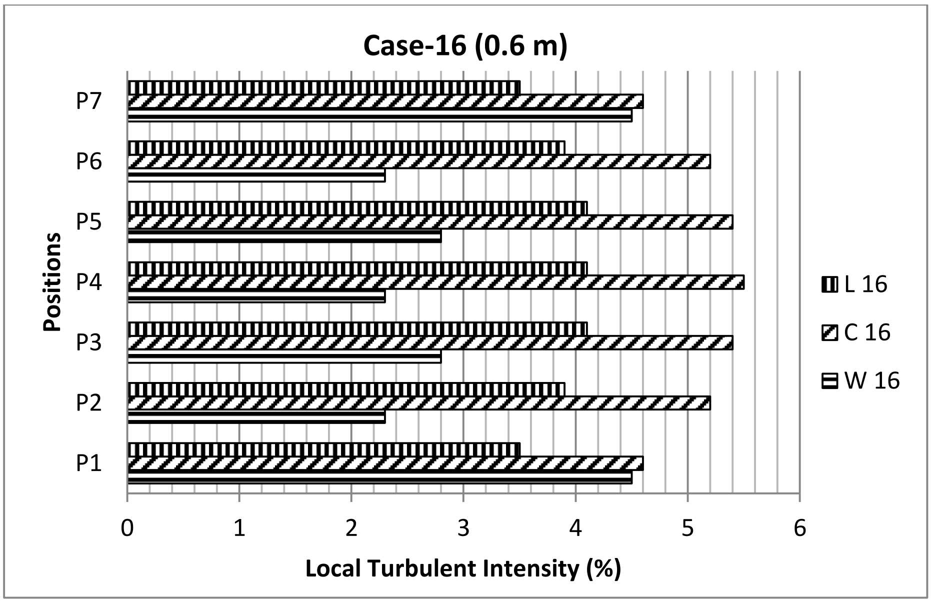


Figure 8.35: Local indoor turbulent intensity at 0.6 m height in Case 16

8.6 Local Draught Risk

The three major factors that determined the percentage of people complaining due to draughts in building includes air temperature, air velocity and turbulence intensity. Air velocity in a given place in a building usually varies with time as a result of turbulence (Roulet, 2005). Hence, the 'percentage of dissatisfied' persons, PD, due to draughts can be estimated from the empirical relationship published by Fanger et al (1988) using equation (22).

$DR = (34 - t)\ (v - 0.05)^{0.62}(0.37vT_u + 3.14)$……………………………………….. (22)

Where

t = Air temperature (^oC)
v = Local indoor mean air velocity (m/s)
T_u = Indoor turbulence intensity

Moreover, turbulence intensity in most rooms usually exceeds 0.3%. Therefore, air velocity should not exceed 0.15 m/s at comfortable temperatures (Roulet, 2005). The air velocity in a room is capable of increasing draught sensation; however under warm conditions, it may also result in improved comfort (Olsen, 2004). The recommended air velocity of 0.15 m/s applies for controlled environment in mild climates. But in uncontrolled buildings with natural ventilations in hot climates, people can experience comfort with higher air speeds. In heated environments air velocities of up to 2 m/s may be comfortable (Szokolay, 2008). Thus, the effect of draught is negligible in naturally ventilation buildings in hot climates like that of the study area.

In this study the percentage of people dissatisfied due to draught in twenty one (21) points has been studied and result shows that all the points at the centre and by the leeward side of the room have no risk of draught. However, the measurement points at the windward, close to the inlet openings which are vulnerable to draught risk has been studied and the results for 1.0 m and 0.6 m occupancy levels has been presented in figures 8.36 and 8.37 respectively. The results indicates that the draught risk is higher in case 16 compared to case 1 at both 1.0 m and 0.6 m occupancy heights. Moreover, the highest draught risk at 1.0 m occupancy height is about 16.8% and 10.2% for case 16 and case 1, respectively as illustrated in figure 8.36. However, the highest draught risk at 0.6 m occupancy level is 10.7% and 6.6% for case 16 and case 1 respectively, as illustrated in figure 8.37.

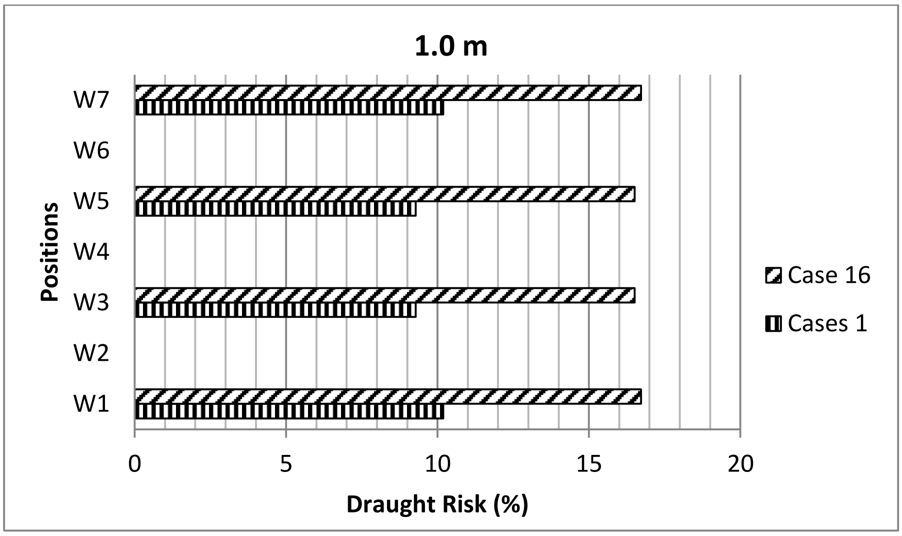


Figure 8.36: The comparative analysis of draught risk at 1.0 m height in the windward positions of case 1 and 16

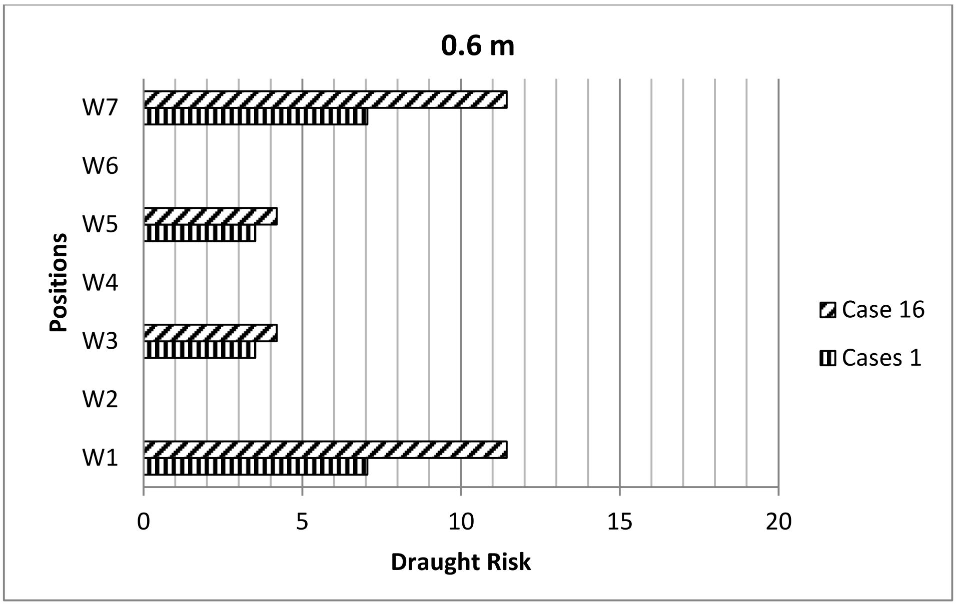


Figure 8.37: The comparative analysis of draught risk at 0.6 m height in the windward positions of case 1 and 16

The effect of draught on occupants comfort is determined largely by the climatic condition of the area. In warm climates such as the one considered in this research, building occupants can withstand higher draught rates and feel comfortable. Therefore, in the context of this study, the higher the draught risk is better.

8.7 Building Orientation and natural ventilation

Building orientation indicates the direction faced by room's external elevation and its choice is determined by many considerations, including the view in all directions, the location of the buildings relative to nearby access road, the topography of the site, the location of source of noise, and the nature of the climate (Givoni, 1976). However, the major concern of this study is the last point which is the nature of the climate, because the study is mainly regarding outdoor wind speed and direction and their effects on indoor airflow rates and direction. The success of any natural ventilation system in buildings is generally determined by the ambient condition in the surrounding environment. Since factors such as wind velocity, wind direction and air temperature may fluctuate frequently from hour to hour (Bangalee et al. 2012). Moreover, the analysis and control of wind-driven natural ventilation is challenging, as airflow around buildings are complex and invariably turbulent (Seifert et al. 2006). Hence, any reliable ventilation system design is expected to be concerned with any kind of atmospheric change in the surrounding environment (Bangalee et al. 2012).

Moreover, the building orientation influences indoor environmental condition in two ways, by its control of the impact of two different climate factors (Givoni, 1976):

i. Solar radiation and its heating consequences on walls and rooms facing different directions.
ii. Ventilation problems related the association between the direction of the prevailing winds and the orientation of the building.

Hence, the consideration of the above two factors together may result in conflicting orientation requirements. Consequently in hot countries one orientation may provide the required low temperatures, while another could produce higher indoor air velocities (Givoni, 1976). This study will concentrate mainly on studying the second factor, as the first one is out of the scope of this research.

The orientation of building openings in relation to wind flow direction is one of the major factors that determines airflow rate in indoor spaces. In this research, four (4) different orientations (figure 8.38) were considered including 0^o, 30^o, 60^o and 90^o in relation to the wind flow directions. In order to reproduce the existing wards in the study area, insect screens of 0.66 porosity has been install to all the openings and the wind velocity imposed on the inlet of the computational domain is 2.6 m/s. These orientations were simulated to ascertain the difference in air change rates and the characteristics of indoor air distribution. Because, the orientation of building openings in relation to the prevailing wind flow direction have significant impact on the indoor ventilation rates.

Studies have established that, building indoor air velocity is higher in cross ventilated cases compared to other kind of ventilations (Bangalee et al. 2012). Additionally, it has been confirmed that, airflow rates in hospital wards need to be deployed with planned patterns as well as directions for effective ventilation in the wards (Li et al. 2008). Generally, optimum ventilation condition is achieved when the inlet windows/openings are directly facing the wind flow direction, and any deviation from this direction will result in the reduction of indoor air speed. Givoni, (1976) shows that in some cases better conditions can be achieved when the wind is oblique to the inlet openings/windows, especially when suitable ventilation condition is required in the entire area of the room/space. The four orientations considered are illustrated in figure 8.38.

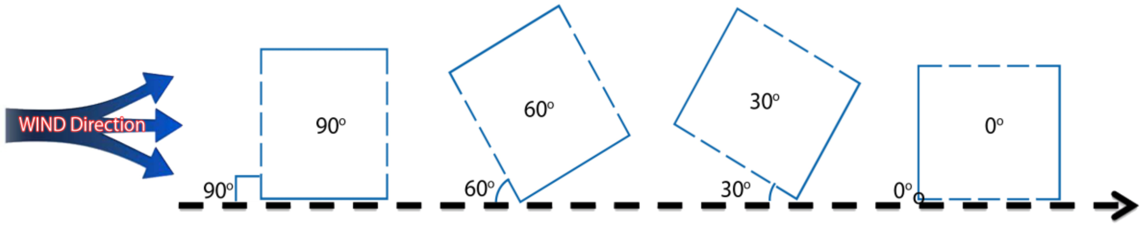


Figure 8.38: Different ward Orientations Studied

8.7.1 Volumetric flow rates and orientations

The simulation was conducted to ascertain the influence of building orientation on volumetric airflow rates using a base-case model (Case 1) and enhanced cases 9 and 16, considering the four (4) selected wind directions. The result showing the volumetric/air flow rates of individual openings (W-Screens 1 to 12) and total volumetric flow rates of the multi-bed ward volume is presented in table 8-25. The contours of velocity magnitudes in the four (4) orientations considered are presented in table 8-26 and table 8-27 at 1.0 m and 0.6 m heights above floor levels respectively. The vertical section of the simulated hospital ward showing indoor air distribution is illustrated in figure 8-28. Moreover the 3D streamline showing the detailed airflow pattern in the hospital wards is shown in table 8-29.

Table 8-25: Volumetric flow rates of different ward orientations for Cases 1, 9 and 16

Openings	Volumetric flow rates (m^3/s)											
	90º Orientation			60º Orientation			30º Orientation			0º Orientation		
	Case 1	Case 9	Case 16	Case 1	Case 9	Case 16	Case 1	Case 9	Case 16	Case 1	Case 9	Case 16
W_Screen_1	-0.28	-0.32	-0.42	-0.30	-0.34	-0.46	-0.20	-0.22	-0.27	0.062	0.059	0.058
W_Screen_2	-0.30	-0.34	-0.44	-0.25	-0.29	-0.43	-0.17	-0.20	-0.24	-0.003	-0.0005	-0.001
W_Screen_3	-0.30	-0.34	-0.44	-0.23	-0.25	-0.37	-0.15	-0.17	-0.22	-0.028	-0.024	-0.025
W_Screen_4	-0.28	-0.32	-0.42	-0.17	-0.19	-0.29	-0.12	-0.14	-0.19	-0.031	-0.029	-0.031
W_Screen_5	-0.30	-0.34	0.23	0.21	0.26	0.22	0.22	0.16	0.15	-0.031	-0.102	0.064
W_Screen_6	-0.28	-0.32	0.19	0.23	0.26	0.20	0.18	0.17	0.13	-0.028	-0.051	0.001
W_Screen_7	-0.28	-0.32	0.19	0.25	0.27	0.17	0.14	0.19	0.10	-0.003	0.000097	-0.026
W_Screen_8	-0.30	-0.34	0.23	0.26	0.28	0.17	0.10	0.21	0.05	0.062	0.147	-0.029
W_Screen_9	-	-	0.22	-	-	0.20	-	-	0.10	-	-	-0.109
W_Screen_10	-	-	0.22	-	-	0.19	-	-	0.12	-	-	-0.055
W_Screen_11	-	-	0.22	-	-	0.20	-	-	0.13	-	-	0.005
W_Screen_12	-	-	0.22	-	-	0.20	-	-	0.14	-	-	0.148
Total volumetric flow rates (m^3/s)	**1.16**	**1.32**	**1.72**	**0.95**	**1.07**	**1.55**	**0.64**	**0.73**	**0.92**	**0.124**	**0.21**	**0.28**

Table 8-26: Indoor air distribution of different ward orientations at 1.0 metres above floor level

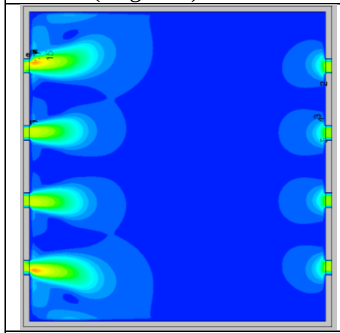
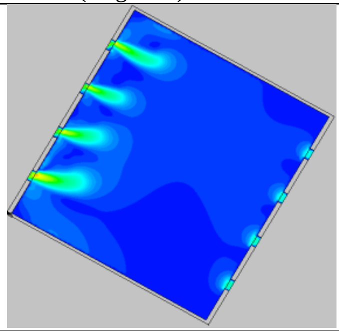
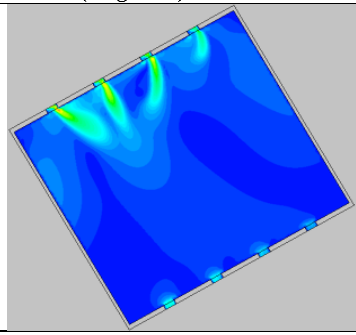
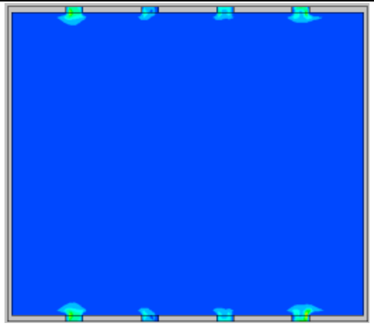
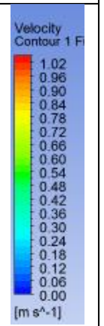
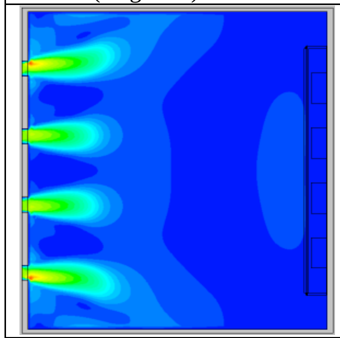
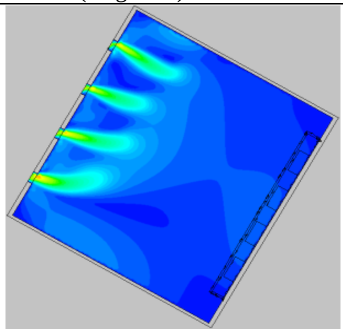
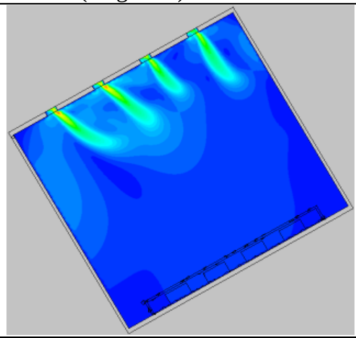
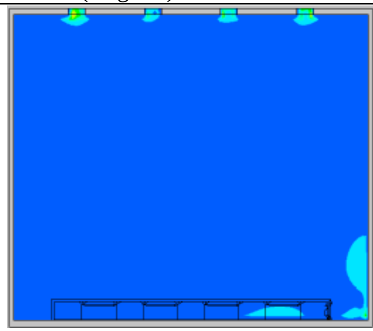
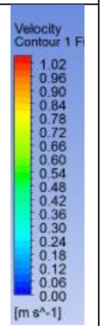
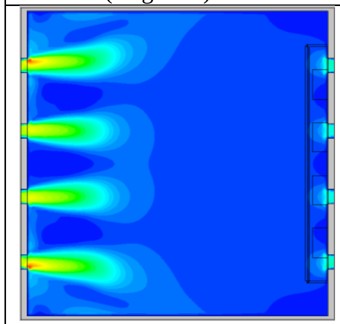
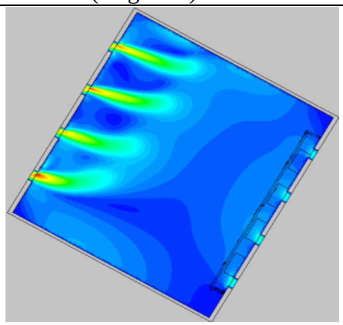
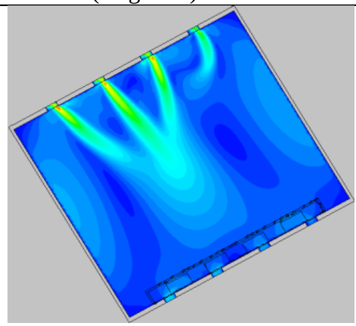
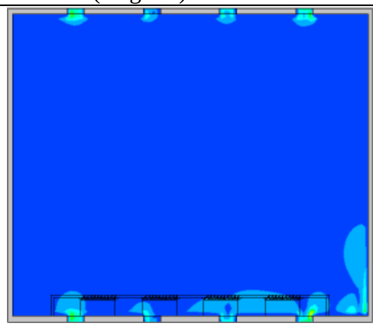
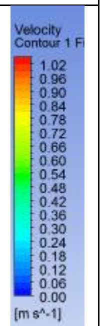
Case-1 (Angle-90)	Case-1 (Angle-60)	Case-1 (Angle-30)	Case-1 (Angle-0)	
				
Case-9 (Angle-90)	Case-9 (Angle-60)	Case-9 (Angle-30)	Case-9 (Angle-0)	
				
Case-16 (Angle-90)	Case-16 (Angle-60)	Case-16 (Angle-30)	Case-16 (Angle-0)	
				

Table 8-27: Indoor air distribution of different ward orientations at 0.6 metres above floor level

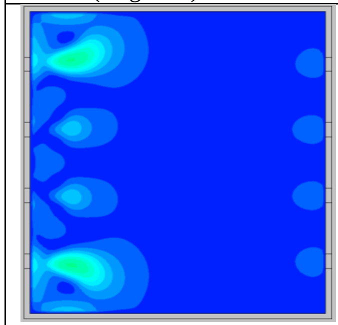
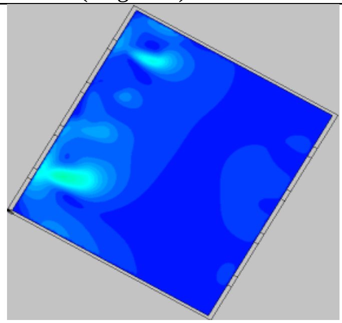
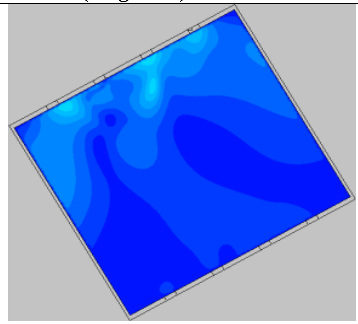
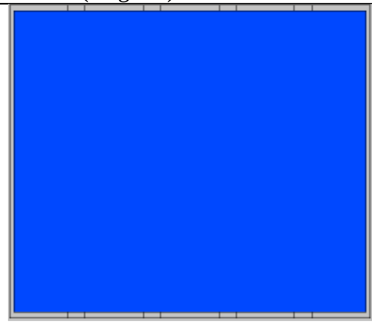
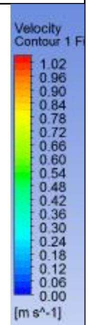
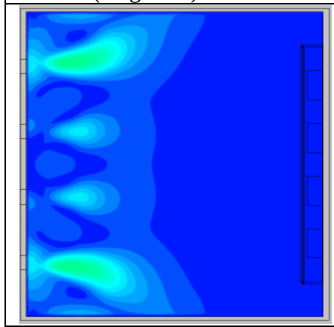
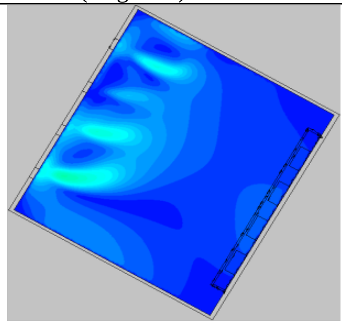
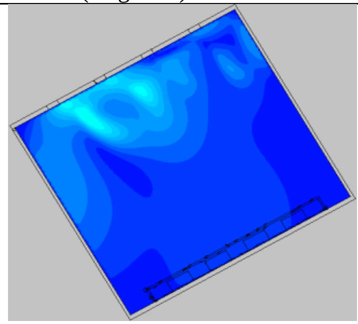
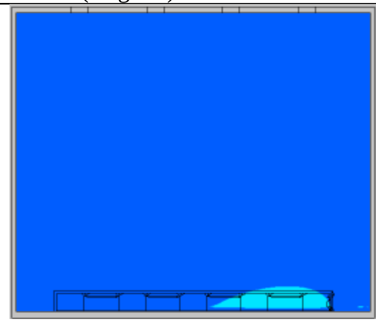
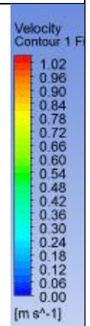
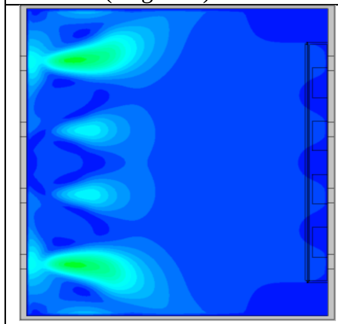
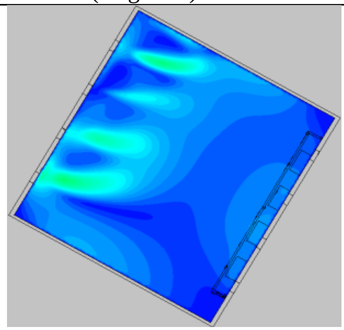
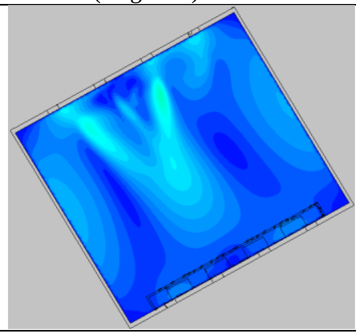
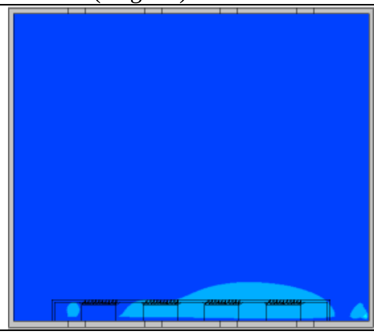
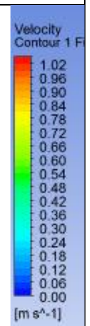
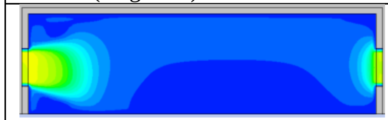
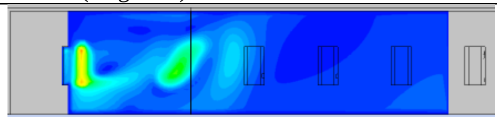
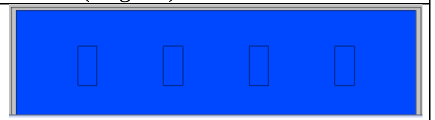
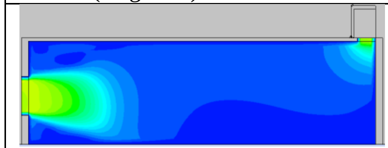
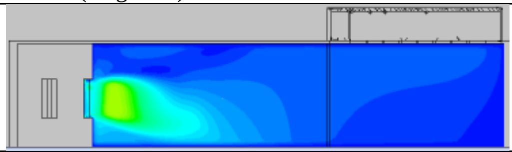
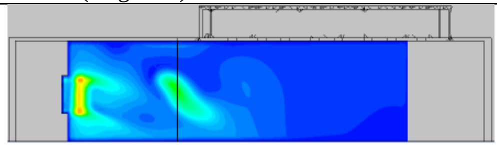
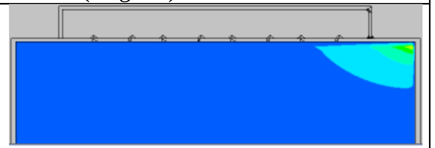
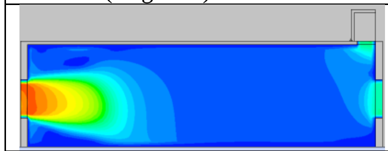
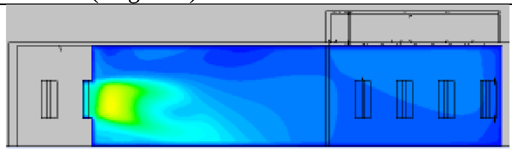
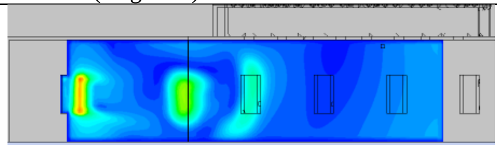
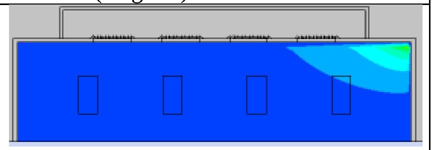
Case-1 (Angle-90)	Case-1 (Angle-60)	Case-1 (Angle-30)	Case-1 (Angle-0)	
				
Case-9 (Angle-90)	Case-9 (Angle-60)	Case-9 (Angle-30)	Case-9 (Angle-0)	
				
Case-16 (Angle-90)	Case-16 (Angle-60)	Case-16 (Angle-30)	Case-16 (Angle-0)	
				

Table 8-28: Vertical indoor air distribution of different ward orientations at the centre of the ward

Case-1 (Angle-90)	Case-1 (Angle-60)	Case-1 (Angle-30)	Case-1 (Angle-0)
			
Case-9 (Angle-90)	Case-9 (Angle-60)	Case-9 (Angle-30)	Case-9 (Angle-0)
			
Case-16 (Angle-90)	Case-16 (Angle-60)	Case-16 (Angle-30)	Case-16 (Angle-0)
			

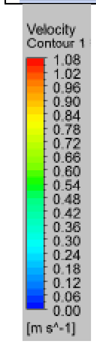
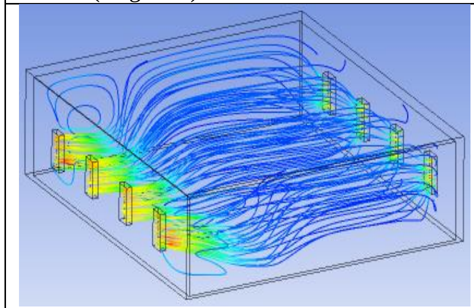
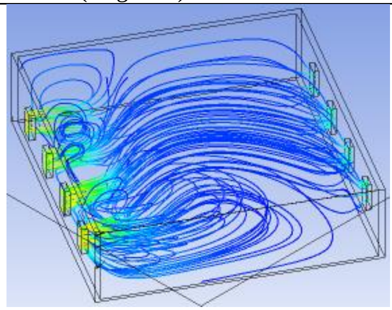
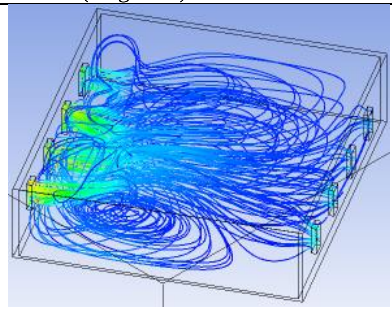
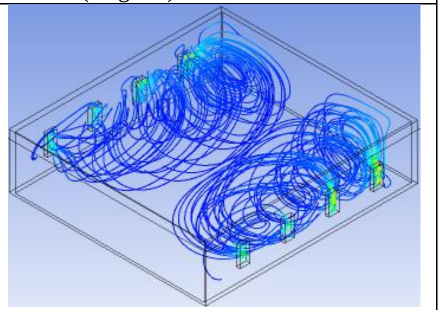
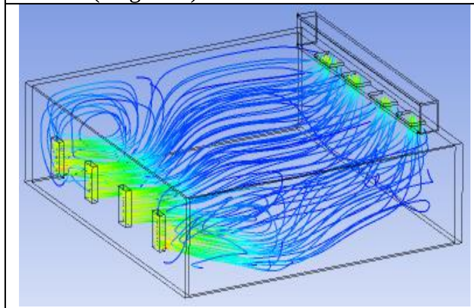
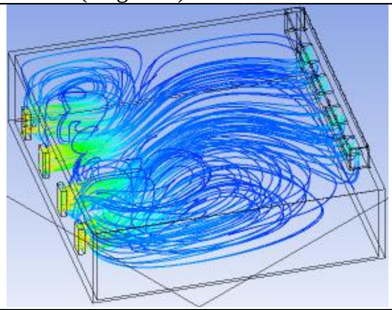
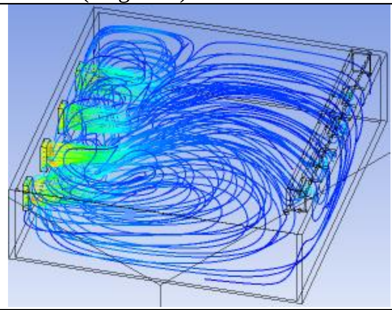
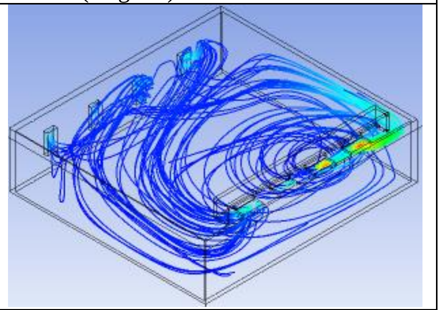
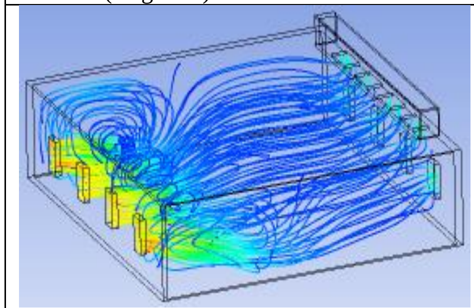
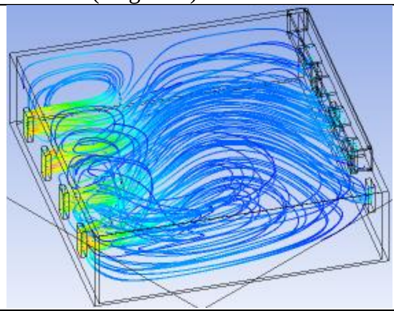
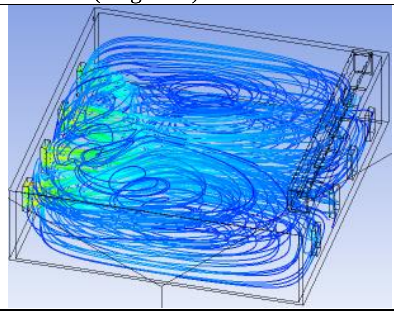
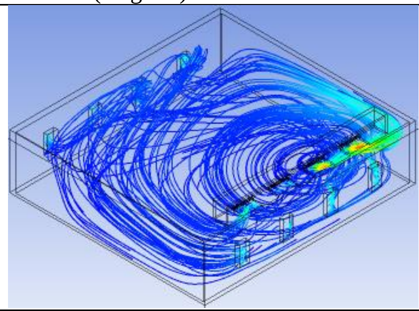


Table 8-29: 3D streamline showing Indoor air distribution of different ward orientations

Case-1 (Angle-90)	Case-1 (Angle-60)	Case-1 (Angle-30)	Case-1 (Angle-0)
			
Case-9 (Angle-90)	Case-9 (Angle-60)	Case-9 (Angle-30)	Case-9 (Angle-0)
			
Case-16 (Angle-90)	Case-16 (Angle-60)	Case-16 (Angle-30)	Case-16 (Angle-0)
			

The volumetric airflow rates for cases with 90° orientation are the highest followed by 60°, 30° and 0° respectively. Table 8-30 and figure 8.39 illustrate the influence of orientation on volumetric airflow rates in the three cases simulated. The higher the angle of attack between the ward openings and the airflow direction, the higher the volumetric airflow rates in the wards. However, airflow distribution and circulation in all the three cases 1, 9 and 16 is better in cases with oblique orientations (30° and 60°), compared to the case with 90° orientation and poor in 0° orientation as illustrated in tables 8-26 to 8-29. This is because, the air distribution in cases with oblique orientation covers longer distance, due to the irregular locations of openings, compared to the cases with 90° orientation, in which the air follow an established patterns to exhaust.

Table 8-30: Volumetric flow rates of different ward orientations for cases 1, 9 and 16

Orientation	Volumetric flow rates (m^3/s)		
	Case-1	Case-9	Case-16
90 Degrees	1.16	1.32	1.72
60 Degrees	0.95	1.07	1.55
30 Degrees	0.64	0.73	0.92
0 Degrees	0.12	0.21	0.28

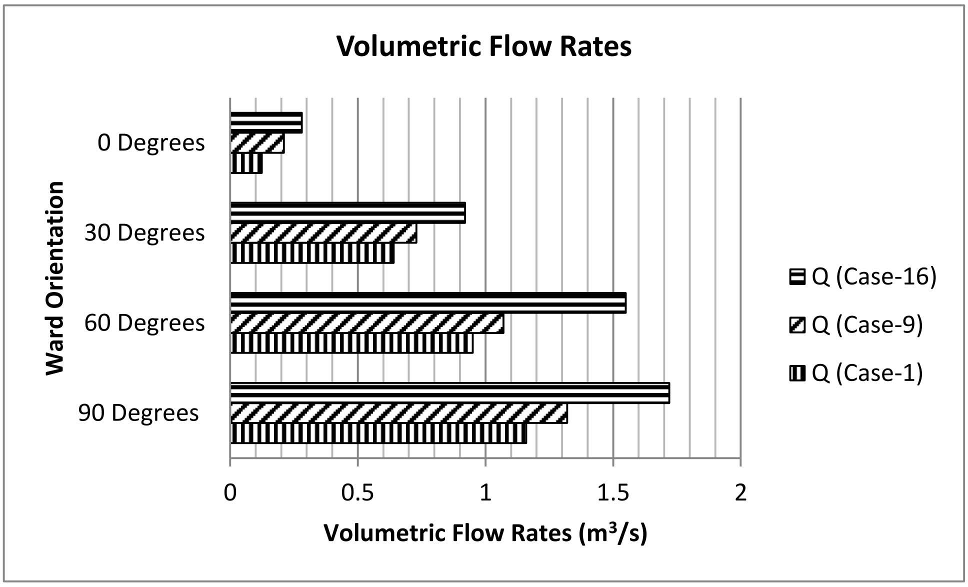


Figure 8.39: Volumetric flow rates of different ward orientations for cases 1, 9 and 16

8.7.2 Air Change Rates and Orientation

The simulation was conducted to ascertain the influence of building orientation on air change rates using the base-case model (Case 1) considering the four selected wind directions. The base-case model has four inlet openings in the windward wall and four outlet openings in the leeward side. The result shows that highest air change rate is achieved when the ward orientation in relation to the wind flow direction is 90°, then 60°, 30°, and 0° respectively. In buildings with oblique outdoor wind incident angle, the ventilation flow rates increases in the range of $40^o \leq \theta \leq 60^o$ for the incident angle, due to the increased in dynamic pressure at the outlets, which is caused by the change of the separated flow pattern around the building (Ohba et al. 2001). Moreover, the air change rates in 90^o and 60^o orientations have satisfied the ASHREA standard of 6 ach^{-1} in the hospital wards, while the remaining two orientations (30^o and 0^o) have not made this requirement as illustrated in figure 8.40.

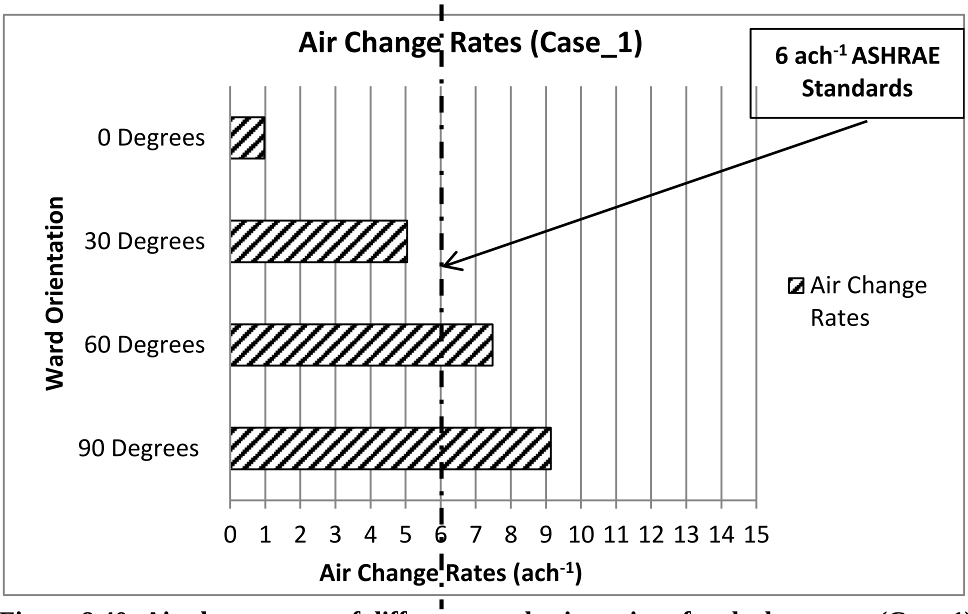


Figure 8.40: Air change rates of different ward orientations for the base-case (Case-1)

Since the objective of this study is to provide effective ventilation at the occupancy (bed) levels in the studied hospital multi-bed wards, another case (Case-9) which is both wind and buoyancy based ventilation has been studied. This is as a result of the inability of case-1 which is wind effect ventilation only to provide required indoor air distribution in the ward. Case 9 has inlets on the windward wall and the outlet on the roof close to the leeward side. The air change rates of different orientations have been studied and the results obtained are quite similar to case-1 (base-case), but the air change rate is higher in case -9. This is because of its benefits from the combination of both wind and buoyancy effects. Moreover, the air change rate in relation to ASHRAE standard of 6 ach^{-1} in this case is similar to case 1. The result shows that ACR of 90^o and 60^o orientations have satisfied the ASHREA standard of 6 ach^{-1}, while the remaining two orientations (30^o and 0^o) have not made this requirement, but the 30^o orientation is very close to realising the standard requirement of 6 ach^{-1} as can be seen in figure 8-41.

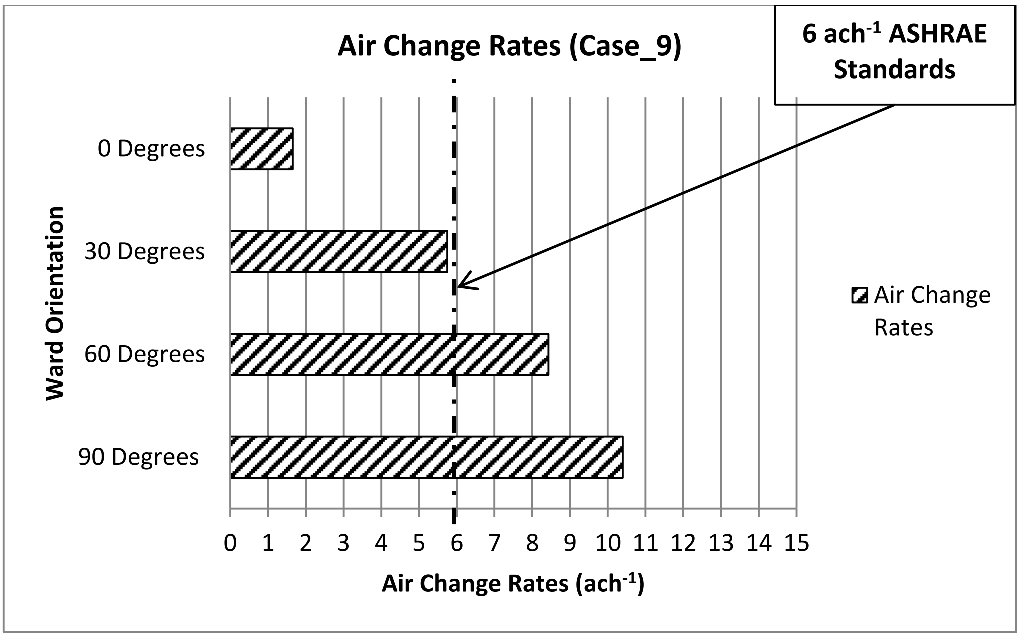


Figure 8.41: Air change rates of different ward orientations for (Case-9)

Due to the inability of both cases 1 and 9 to provide the required air distribution and proper air circulation at the occupancy level in the hospital ward, case 16, which is the combination and enhancement of case 1 and case 9 was introduced and simulated. Case 16 is the same with case 9 but with additional four (4) openings on the leeward walls. The air change rates in this case are higher than in both case 1 and case 9. Moreover, unlike case 1 and 9, where only two orientations have fulfilled the ASHRAE standard, in this case the air change rates in 90^{o} 60^{o} and 30^{o} orientations have reached the ASHREA standard of 6 ach^{-1} in the hospital wards, and one orientation (0^{o}) have not made this requirement as illustrated in figure 8.42.

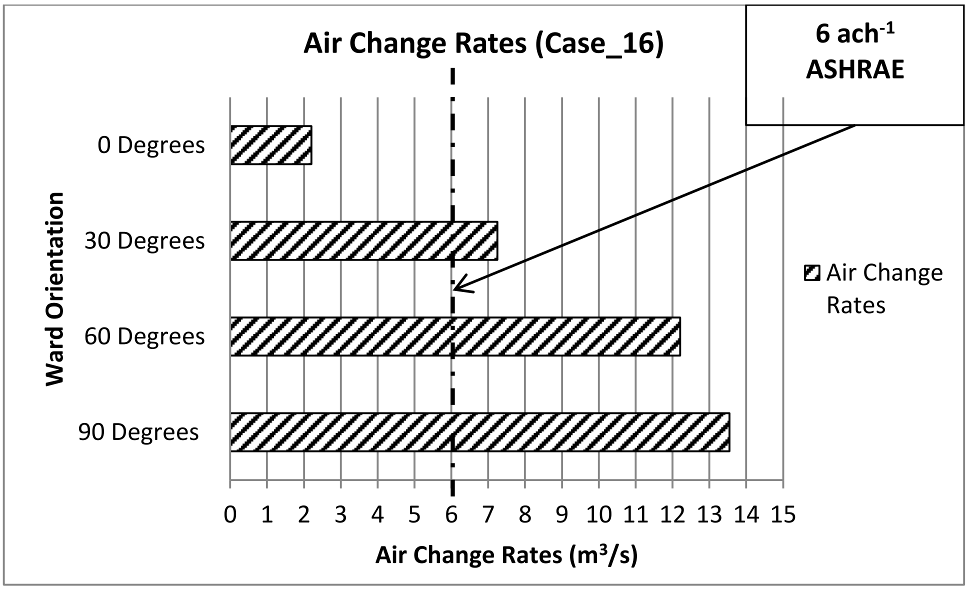


Figure 8.42: Air change rates of different ward orientations for the (Case-16)

The comparative analysis of the three cases (1, 9 and 16) indicates that the air change rates in case 16 are the highest in all the four orientations, which is a pointer to its ability to remove pollutants in the hospital multi-bed wards. Because the higher the air change rates, the greater the ability of a ventilation system to remove indoor air contaminants by replacing the contaminated air with a fresh one. The comparative results of the three cases showing the four (4) different orientation scenarios is illustrated in table 8-31 and figure 8.43.

Table 8-31: Air change rates of different ward orientations for cases 1, 9 and 16

Orientation	Air Change Rates (ach^{-1})		
	Case-1	Case-9	Case-16
90 Degrees	9.1	10.4	13.5
60 Degrees	7.5	8.4	12.2
30 Degrees	5.0	5.8	7.2
0 Degrees	1.0	1.7	2.2

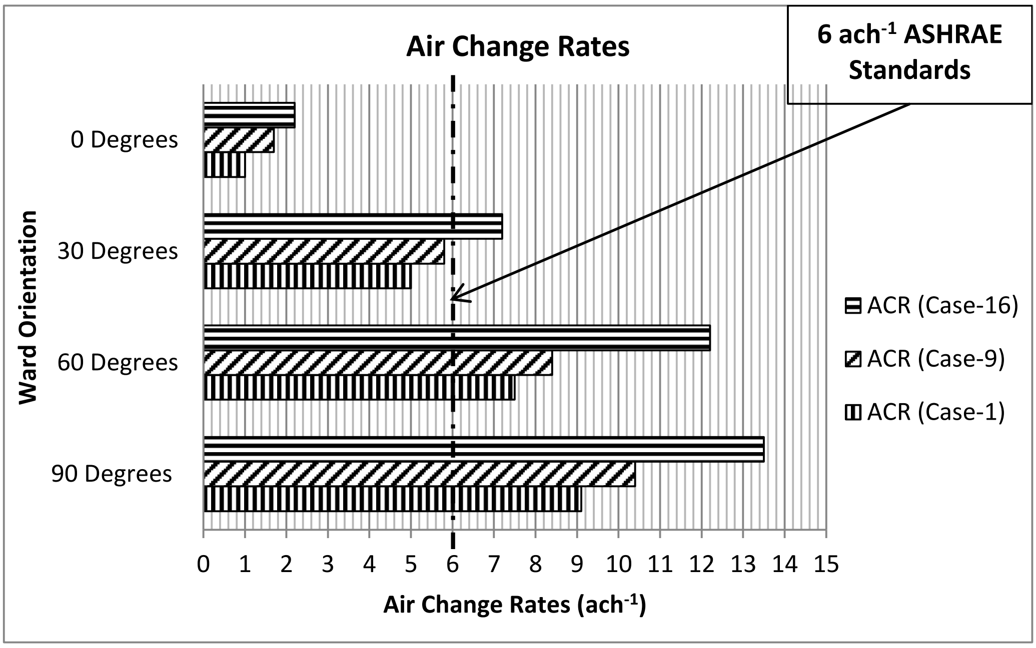


Figure 8.43: Air change rates of different ward orientations for cases 1, 9 and 16

8.7.3 Average Indoor Air Velocity and Orientation

The pattern and speed of the indoor air remain one of the major determinants of indoor air quality and comfort in any building indoor space. Average indoor air velocity for the four (4) different orientations considered for cases 1 (base-case model), 9 and 16 has been studied. The result indicates that the average indoor air speed for wind flows with oblique orientations (30^{o} and 60^{o}) to the inlet openings are higher than the average indoor velocity of wind flow normal (90^{o}) to the inlet openings as illustrated in figure 8.44. Previous researchers have also obtained similar results. In cross ventilated room, with outdoor wind flow direction normal to the openings, the air flows straight through the room, thereby ventilating only a narrow section, in which the air velocity is locally high. Similarly, if the wind has to change direction within the room, a larger volume is influenced by the airflow and hence the average velocities are higher (Givoni, 1976). This change of direction will generate a turbulent flow throughout the entire space. While the overall airflow is reduced leading to subsequent reduction in air change rates, the distribution of air velocities in the space is enhanced resulting in higher average velocity (Givoni 1994). Therefore, oblique orientation provides better air distribution of the indoor space compared to the normal orientation. Buildings that are subjected to oblique winds, with angles ranging between 30 and 60^o away from the normal, can supply enhanced ventilation conditions both in individual rooms and in entire dwellings (Givoni, 1994). Moreover, the average indoor air velocity for the case with opening orientation parallel (0^o) to the wind flow direction is the lowest among the four (4) cases considered as shown in figure 8.44 and table 8-32.

Table 8-32: Indoor Average Air Velocity of different ward orientations for cases 1, 9 and 16

Orientation	**Average Indoor Air Velocity (m/s)**		
	Case-1	Case-9	Case-16
90 Degrees	0.04	0.05	0.069
60 Degrees	0.05	0.08	0.11
30 Degrees	0.06	0.07	0.11
0 Degrees	0.01	0.02	0.028

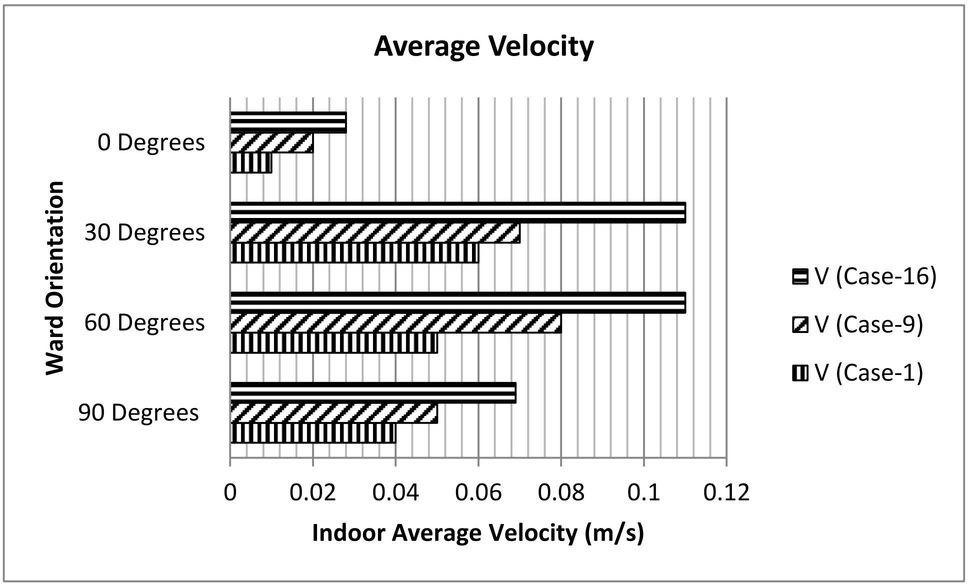


Figure 8.44: Indoor Average Air Velocity of different ward orientations for cases 1, 9 and 16

8.7.4 *Average Turbulence Intensity and Orientation*

However, the variation of average indoor turbulence intensity in relation to building opening orientation is less obvious as illustrated in table 8-33 and figure 8.45, comparing the indoor average turbulence intensities of the four (4) orientation cases simulated. But the turbulent intensity is higher in case 1 compared to the other two cases considered. This might be connected with the absence of opening in the roof for stack ventilation in Case 1. Because, both Cases 9 and 16 have openings in the roof for stack ventilation. Since turbulent intensity increases with decreasing air speeds, thus Case 1 has the lowest air speed as can be seen in figure 8.44, which consequently raise the turbulent intensity.

Table 8-33: Indoor Average Turbulence Intensity of different ward orientations for cases 1, 9 and 16

Orientation	Average Indoor Turbulence Intensity (%)		
	Case-1	Case-9	Case-16
90 Degrees	3.8	3.4	4
60 Degrees	4	3.2	3.7
30 Degrees	3.2	3.1	2.6
0 Degrees	4.5	4.4	4.1

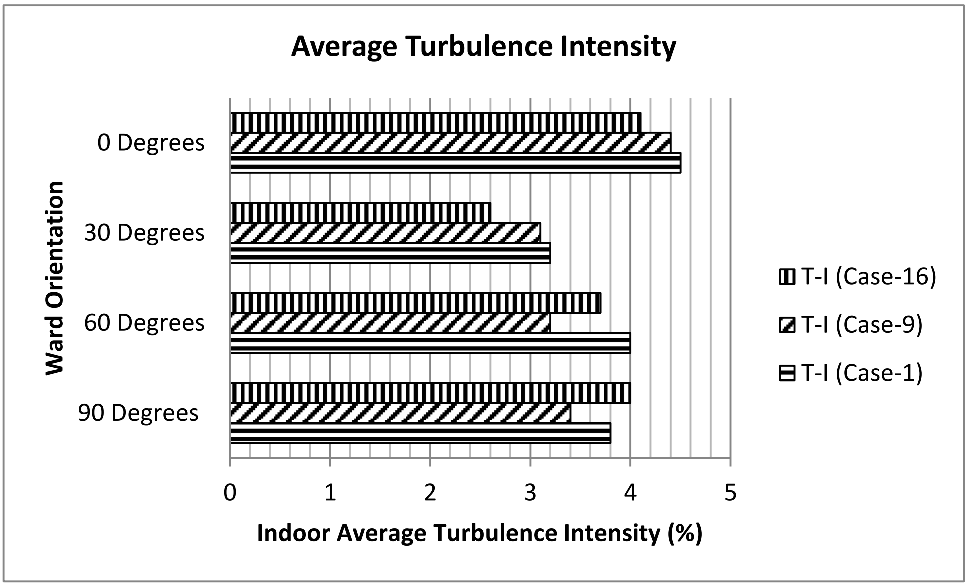


Figure 8.45: Indoor Average Turbulence Intensity of different ward orientations for cases 1, 9 and 16

8.8 Openings Insect Screen and natural ventilation

Insect screens are crucial parts of opening system design in many parts of the world, especially in the tropics to prevent insects such mosquitoes and tsetse fly from entering the building. However, as a consequence, these screens may cause significant reduction in airflow through openings. A study from wind tunnel assessment confirms that the consequence of insect screens is largely determined by the combination of wind direction and number and position of inlet openings. The decrease in indoor air speed in buildings owing to the installation of insect screens over a single central window is found to be greater with an oblique than with a perpendicular wind direction. This is probably due to the possibility of the oblique wind slipping over the screen, thereby creating an ineffective pressure in front of the opening (Givoni, 1976). However, in this study, insect screens with different porosities ranging from 0.9 to 0.1 and an opening without insect screen have been simulated to ascertain their effect on the airflow rates in hospital wards. Various ventilation parameters such as volumetric airflow rates, air change rates, air velocity and turbulent intensity have been studied. The outdoor air velocity of 2.6 m/s has been used for the simulation.

8.8.1 Volumetric flow rates and screen porosity

The influence of different screen porosities on volumetric flow rates of cases 1 (base-case) and 16 have been studied. The volumetric airflow rates of individual openings: inlet openings (W-Screen 1 to 4) and the outlet openings (W-Screen 5 to 8 and 5 to 12 in case 16) is presented in table 8-34. The volumetric flow rates decreases as the insect screen porosity decreases. But the disparity is higher in the transition between an opening without insect screen (P-1: the unobstructed opening), and the highest porosity (0.9) as illustrated in table 8-35 and figure 8.46. The volumetric airflow rate in the improved case 16 is higher than in case 1 (base-case) with about 27-38 % variation as shown in table 8-35. The difference between the two cases (1 and 16) is illustrated in figure 8.47. As the porosity decreases there is a gradual convergence of the base case (Case 1) and Case 16 as could be observed in table 8-35 and figure 8.47.

Table 8-34: Volumetric flow rates for different Porosities (Cases 1 and 16)

Openings	Volumetric flow rates for different Porosities																			
	No-Screen(P-1.0)		P-0.9		P-0.8		P-0.7		P-0.6		P-0.5		P-0.4		P-0.3		P-0.2		P-0.1	
	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16
W_Screen_1	-0.77	-1.10	-0.38	-0.56	-0.34	-0.51	-0.29	-0.45	-0.25	-0.38	-0.20	-0.30	-0.14	-0.23	-0.097	-0.15	-0.052	0.084	0.016	-0.027
W_Screen_2	-0.80	-1.11	-0.40	-0.59	-0.36	-0.53	-0.31	-0.47	-0.26	-0.39	-0.21	-0.32	-0.15	-0.24	-0.10	-0.16	-0.054	0.086	0.018	-0.029
W_Screen_3	-0.80	-1.11	-0.40	-0.59	-0.36	-0.53	-0.31	-0.47	-0.26	-0.39	-0.21	-0.32	-0.15	-0.24	-0.10	-0.16	-0.054	0.086	0.018	-0.029
W_Screen_4	-0.77	-1.10	-0.38	-0.56	-0.34	-0.51	-0.29	-0.45	-0.25	-0.38	-0.20	-0.30	-0.14	-0.23	-0.097	-0.15	-0.052	0.084	0.016	-0.027
W_Screen_5	0.80	0.54	0.40	0.31	0.36	0.28	0.31	0.25	0.26	0.21	0.21	0.17	0.15	0.12	0.10	0.08	0.054	0.044	0.017	0.013
W_Screen_6	0.77	0.54	0.38	0.25	0.34	0.23	0.29	0.20	0.25	0.17	0.20	0.14	0.14	0.11	0.097	0.07	0.052	0.040	0.017	0.015
W_Screen_7	0.77	0.61	0.38	0.25	0.34	0.23	0.29	0.20	0.25	0.17	0.20	0.14	0.14	0.11	0.097	0.07	0.052	0.040	0.017	0.015
W_Screen_8	0.80	0.61	0.40	0.31	0.36	0.28	0.31	0.25	0.26	0.21	0.21	0.17	0.15	0.12	0.10	0.08	0.054	0.044	0.017	0.013
W_Screen_9	-	0.56	-	0.30	-	0.27	-	0.24	-	0.20	-	0.16	-	0.12	-	0.08	-	0.042	-	0.013
W_Screen_10	-	0.56	-	0.29	-	0.26	-	0.23	-	0.19	-	0.15	-	0.12	-	0.08	-	0.043	-	0.015
W_Screen_11	-	0.50	-	0.29	-	0.26	-	0.23	-	0.19	-	0.15	-	0.12	-	0.08	-	0.043	-	0.015
W_Screen_12	-	0.50	-	0.30	-	0.27	-	0.24	-	0.20	-	0.16	-	0.12	-	0.08	-	0.042	-	0.013
Total volumetric flow rates	**3.14**	**4.42**	**1.56**	**2.30**	**1.40**	**2.08**	**1.20**	**1.84**	**1.02**	**1.54**	**0.82**	**1.24**	**0.58**	**0.94**	**0.40**	**0.62**	**0.21**	**0.34**	**0.07**	**0.112**
Vol. flow rates difference between cases 1 and 16	**1.28**		**0.74**		**0.68**		**0.64**		**0.52**		**0.42**		**0.36**		**0.22**		**0.13**		**0.042**	
% difference between cases 1 and 16	**29%**		**27%**		**33%**		**35%**		**34%**		**34%**		**38%**		**35%**		**38%**		**38%**	

Table 8-35: Total volumetric airflow rates for different porosities (m^3/s) (Cases 1 and 16)

Cases	Total volumetric airflow rates for different porosities (m^3/s)									
	P-1.0	P-0.9	P-0.8	P-0.7	P-0.6	P-0.5	P-0.4	P-0.3	P-0.2	P-0.1
Case-1	3.14	1.56	1.40	1.20	1.02	0.82	0.58	0.40	0.21	0.07
Case-16	4.42	2.3	2.08	1.84	1.54	1.24	0.94	0.62	0.34	0.112

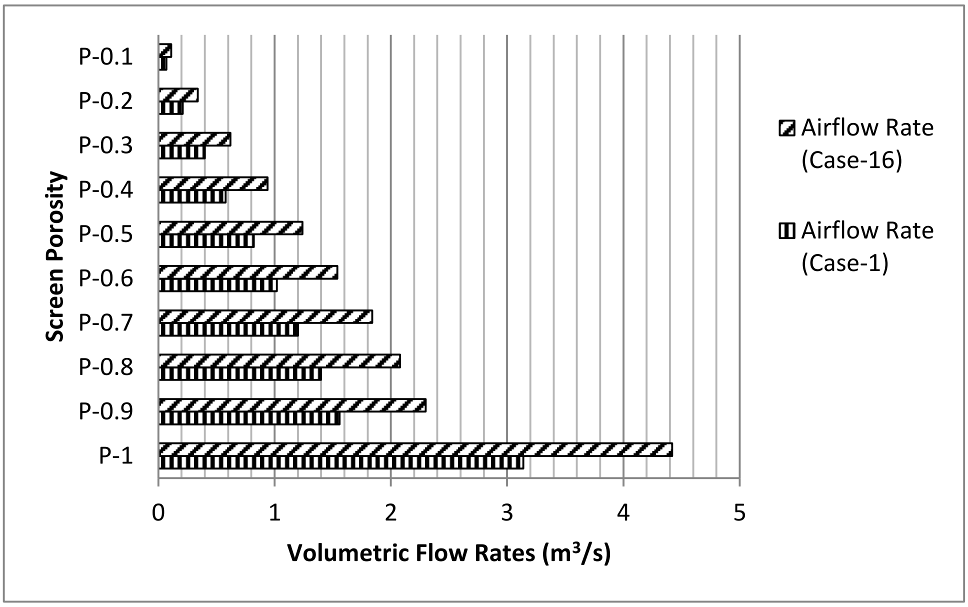


Figure 8.46: Volumetric airflow rates for different Porosities

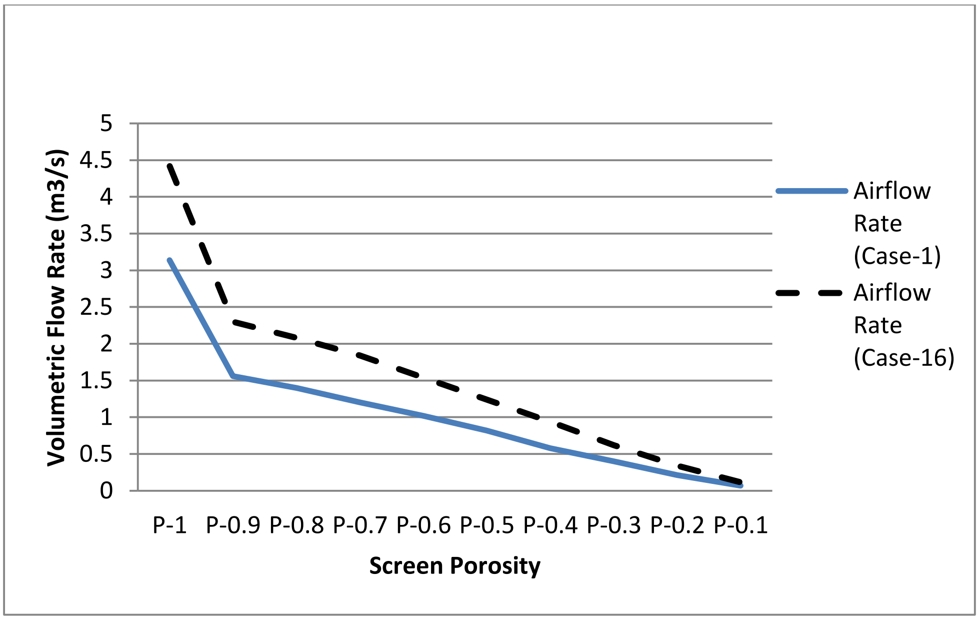


Figure 8.47: Volumetric flow rates gradient for different Porosities

8.8.2 Air Change Rates (ACR) and screen porosity

The effect of air change rates on insect screen porosity is similar with that of volumetric flow rate and screen porosity. As the screen porosity increases, the air change rates also increase and vice versa. In case-1 the air change rates of openings screens with porosities from 0.5 to 1.0 have satisfied the ASHRAE standard of 6 ach^{-1} in hospital wards, while the remaining with porosities from 0.1 to 0.4 did not fulfilled the ASHRAE condition.

Likewise, in case-16 the air change rates of openings with screen porosities ranging from 0.4 to 1.0 have satisfied the ASHREA standard while the remaining openings with porosities from 0.1 to 0.3 did not fulfilled the condition as illustrated in table 8-36 and figure 8-48. Therefore, the improved cases 16 resulted in achieving the ASHRAE standard with lower porosities compared to case 1.

Table 8-36: Air Change Rates (ACR) of different Porosities (ach^{-1}) (Cases 1 and 16)

Cases	Air Change Rates (ACR) of different Porosities (ach^{-1})									
	No-Screen (P-1.0)	P-0.9	P-0.8	P-0.7	P-0.6	P-0.5	P-0.4	P-0.3	P-0.2	P-0.1
Case-1	24.7	12.3	11.0	9.5	8.0	6.5	4.6	3.2	1.7	0.6
Case-16	34.8	18.1	16.4	14.5	12.1	9.8	7.4	4.9	2.7	0.9

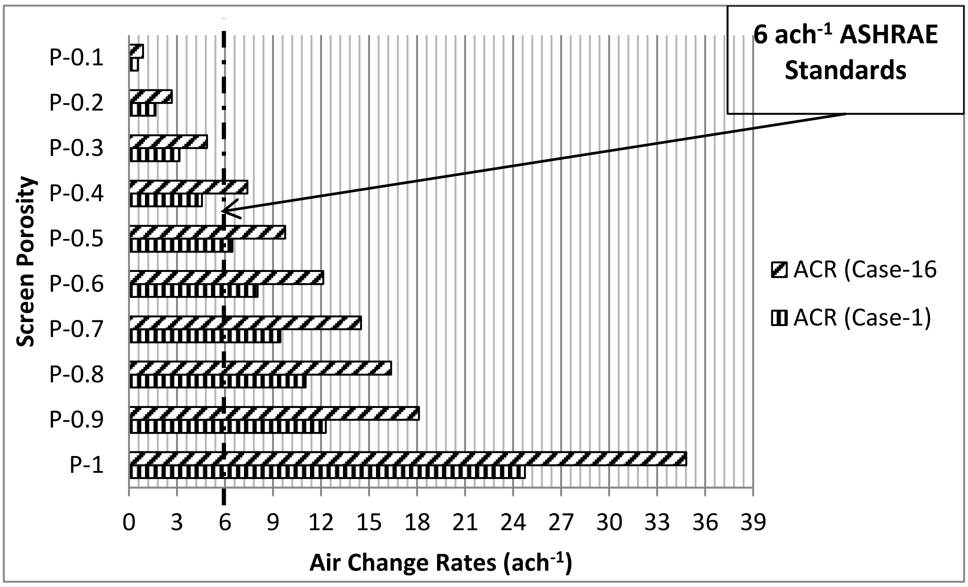


Figure 8.48: Air change rates for different Porosities

8.8.3 Average Indoor Air Velocity and screen porosity

The effect of indoor air velocity on indoor air quality, contaminant removal and comfort is critical. The average indoor air velocities for different porosities ranging from 0.1 to 0.9 and opening without screen for both cases 1 and 16 has been simulated and analysed. The result indicated that the indoor air velocity increases as the porosity increases and vice versa, as illustrated in table 8-37 and figures 8.49 and 8.50. However, the average indoor air velocities of screen porosities 0.1 to 0.9 in both case 1 and 16 are less than 0.15 m/s maximum requirements.

Table 8-37: Average indoor air velocities for different screen porosities (m/s) (Cases 1 and 16)

Cases	Average indoor air velocities for different screen porosities (m/s)									
	No-Screen (P-1.0)	P-0.9	P-0.8	P-0.7	P-0.6	P-0.5	P-0.4	P-0.3	P-0.2	P-0.1
Case-1	0.157	0. 058	0.05	0.042	0.034	0.026	0.020	0.016	0.012	0.008
Case-16	0.302	0.105	0.09	0.075	0.06	0.045	0.032	0.022	0.016	0.010

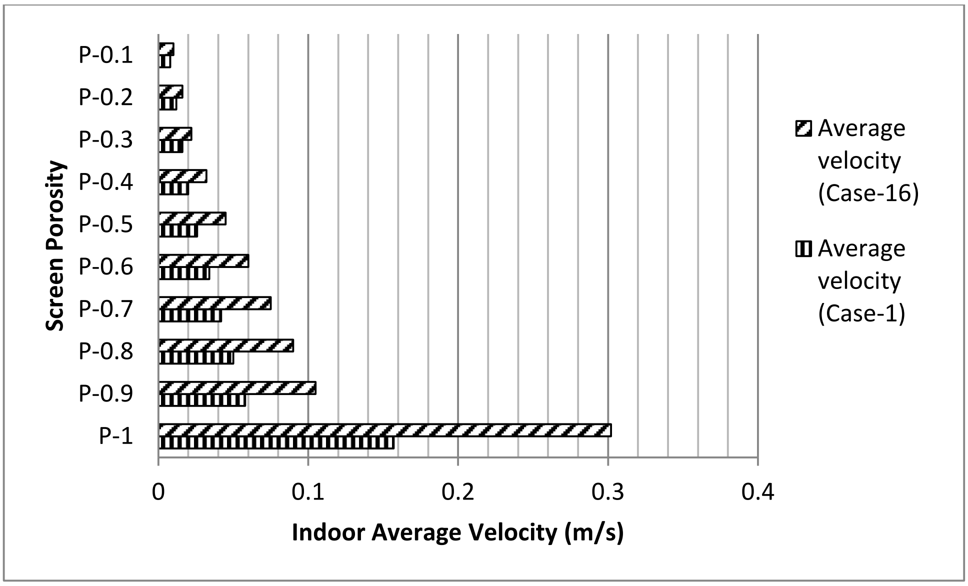


Figure 8.49: Average indoor air velocity for different Porosities

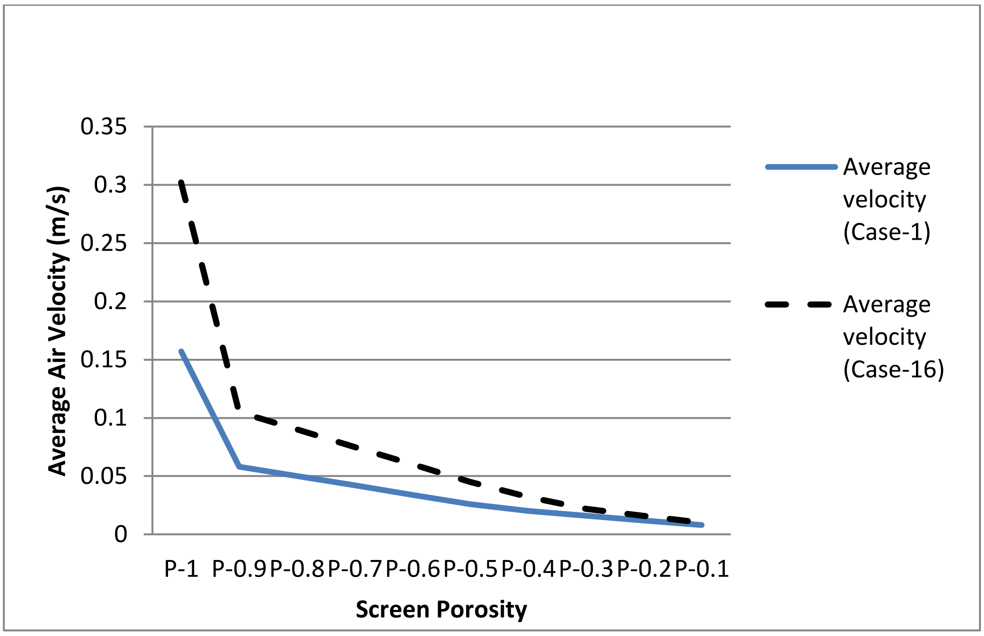


Figure 8.50: Average indoor air velocity gradient for different Porosities

8.8.4 Average Indoor Air Turbulent Intensity and screen porosity

The influence of indoor turbulent intensity on the screen porosity is negligible. There is no significant difference in the turbulent intensity when the screen porosity is changing as illustrated in table 8-38 and figure 8.51. However, the average indoor turbulent intensity in case 1 is higher than case 16 for all the opening porosities simulated as illustrated in figure 8.51. This result indicates that the average turbulent intensity increases when the indoor air velocity decreases. Case 16 with higher indoor air velocities has lower turbulent intensity, as case 1 with lower indoor air velocity has higher turbulent intensity (compare figures 8-49 and 8-51 for air velocity and turbulent intensity respectively).

Table 8-38: Average indoor turbulent intensity for different porosities (%) (Cases 1 and16)

Cases	Average indoor turbulent intensity for different porosities (%)									
	No-Screen (P-1.0)	P-0.9	P-0.8	P-0.7	P-0.6	P-0.5	P-0.4	P-0.3	P-0.2	P-0.1
Case-1	4.68	4.35	4.34	4.33	4.32	4.31	4.30	4.30	4.30	4.30
Case-16	4.06	4.02	3.99	3.96	3.95	3.94	3.93	3.92	3.92	3.92

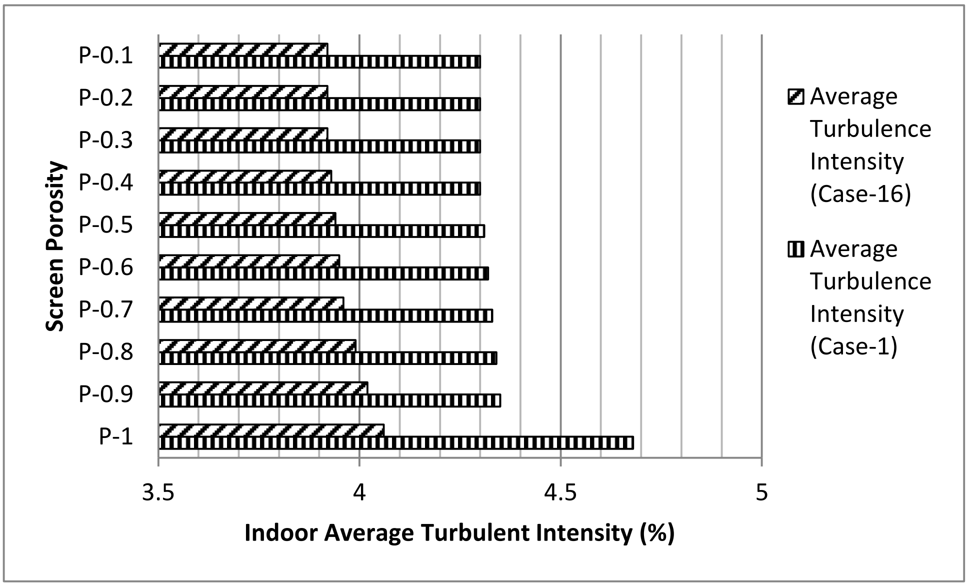


Figure 8.51: Average indoor turbulence intensity for different Porosities

8.9 Outdoor Wind Speed and natural ventilation

The magnitude and pattern of natural air movement through a building is determined by the strength and direction of the natural driving forces and the resistance of the flow path. Natural ventilations in building are regulated by two driving forces of wind and density difference (CIBSE (1997). The strength and direction of outdoor air is one of the major factors that determine air flow rates in indoor environment. In this study, apart from using velocity of 2.6m/s (corrected wind speed) to investigate the effect of different opening positions, different outdoor air speeds ranging from 1m/s to 7 m/s (Airport values) as obtainable in the study area has also been employed to ascertain their effects on volumetric flow rate, air change rate, indoor air velocity and turbulent intensity. The corrected values for these wind speed (1m/s to 7 m/s) in accordance with city terrain has been presented in chapter 7, section 7.4 (table 7.4). In order to mimic the reality of the study area, insect screens of 0.66 porosities have been install on all the openings.

8.9.1 Volumetric airflow rates and outdoor wind speed

The influence of outdoor air speed on the volumetric airflow rates of hospital multi-bed ward for the base-case (case-1) and the best-case (case-16) has been studied. The result shows that the volumetric airflow rates increases with the outdoor air speed in both cases. The higher the outdoor air speed, the higher the volumetric airflow rates and vice versa.

According to a findings from study conducted by Bangalee (2012), the mass flow rates through building openings increases linearly with rising incoming outdoor wind velocity. The study also remarkably observed that the flow at the centre of the indoor space also changes with the same pattern as it changes at the opening. In other word, the airflow rate through the openings and the indoor air velocity changes linearly, if the outdoor wind velocity varies linearly.

The volumetric airflow rates of the individual inlet and outlet openings are presented in table 8-39. Window Screens (W-Screen) 1 -4 are the inlet openings for all cases and W-Screen 5-8 and 5-12 are the outlet openings in case 1 and 16 respectively (see table 8-39). The relationship between outdoor wind speed and volumetric flow rates for wind speeds 1m/s to 7m/s has been presented for the two cases in table 8-40 and figure 8.52. It is apparent that the volumetric airflow rates in case 16 are higher than case 1.

Table 8-39: Volumetric airflow rates for different velocities of cases 1 and 16

Openings	Volumetric flow rates for different velocities (m/s)													
	7.0		6.0		5.0		4.0		3.0		2.0		1.0	
	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16	Case-1	Case-16
W_Screen_1	-0.64	-0.97	-0.52	-0.78	-0.38	-0.58	-0.26	-0.40	0.16	-0.25	0.077	-0.117	0.023	-0.032
W_Screen_2	-0.68	-1.01	-0.55	-0.82	-0.40	-0.61	-0.27	-0.41	0.17	-0.26	0.080	-0.121	0.024	-0.033
W_Screen_3	-0.68	-1.01	-0.55	-0.82	-0.40	-0.61	-0.27	-0.41	0.17	-0.26	0.080	-0.121	0.024	-0.033
W_Screen_4	-0.64	-0.97	-0.52	-0.78	-0.38	-0.58	-0.26	-0.40	0.16	-0.25	0.077	-0.117	0.023	-0.032
W_Screen_5	0.68	0.53	0.55	0.43	0.40	0.32	0.27	0.22	0.17	0.14	0.080	0.067	0.024	0.023
W_Screen_6	0.64	0.43	0.52	0.35	0.38	0.26	0.26	0.18	0.16	0.12	0.077	0.057	0.023	0.021
W_Screen_7	0.64	0.43	0.52	0.35	0.38	0.26	0.26	0.18	0.16	0.12	0.077	0.057	0.023	0.021
W_Screen_8	0.68	0.53	0.55	0.43	0.40	0.32	0.27	0.22	0.17	0.14	0.080	0.067	0.024	0.023
W_Screen_9	-	0.52	-	0.42	-	0.31	-	0.21	-	0.13	-	0.058	-	0.010
W_Screen_10	-	0.50	-	0.40	-	0.30	-	0.20	-	0.12	-	0.056	-	0.011
W_Screen_11	-	0.50	-	0.40	-	0.30	-	0.20	-	0.12	-	0.056	-	0.011
W_Screen_12	-	0.52	-	0.42	-	0.31	-	0.21	-	0.13	-	0.058	-	0.010
Total volumetric flow rates	**2.64**	**3.96**	**2.14**	**3.20**	**1.56**	**2.38**	**1.06**	**1.62**	**0.66**	**1.02**	**0.31**	**0.48**	**0.09**	**0.130**

Table 8-40: Volumetric Airflow Rates (m3/s) for different Velocities (Cases 1 and 16)

Cases	Volumetric Airflow Rates (m^3/s) for different Velocities (Cases 1 and 16)						
	V-7 (m/s)	V-6 (m/s)	V-5 (m/s)	V-4 (m/s)	V-3(m/s)	V-2 (m/s)	V-1 (m/s)
Case-1	2.64	2.14	1.56	1.06	0.66	0.31	0.09
Case-16	3.96	3.20	2.38	1.62	1.02	0.48	0.13

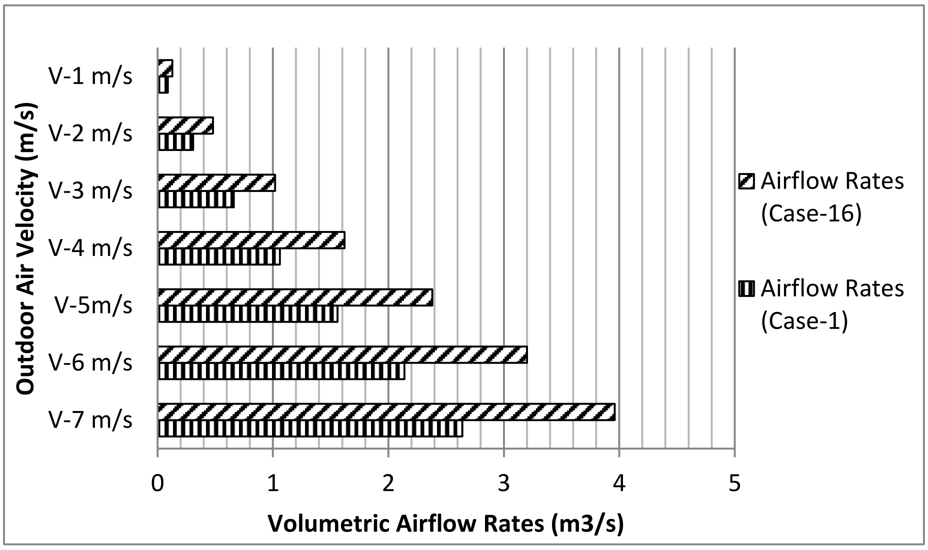


Figure 8.52: Volumetric Airflow Rates (m3/s) for different Velocities (Cases 1 and 16)

8.9.2 Air Change rates (ACR) and outdoor wind speed

The influence of outdoor air velocity on air change rate is similar with that of volumetric flow rates, the greater the outdoor wind velocity, the higher the air change rate in both cases 1 and 16. Hence, outdoor wind speed has considerable influence on the interior flow field and as a consequence on the ventilation rates (Bangalee 2012). The air change rates in case 16 are higher than in case 1. In case 1, the air change rates for simulation with outdoor air velocities between 4 m/s and 7 m/s have satisfied the ASHRAE requirements of 6 ach^{-1} in patient room, while those with outdoor velocities below 4 m/s have not fulfilled the ASHRAE standard. However, in case 16, air change rates for simulations with outdoor air velocity ranging from 3m/s to 7m/s have satisfied the ASHREA requirement while those with outdoor air velocity of less than 3m/s have not, as illustrated in table 8-41 and figure 8.53. Therefore case 16 is better in providing acceptable indoor air quality because of its potential of effective contaminant removal. Moreover, the result from this study implies that low outdoor wind speed has greater impact on air change rates. Gilkeson et al. (2013) in their study clearly confirmed the negative consequences of poor ventilation either through actively closing ventilation openings, or not accounting for circumstances such as low external wind speed at the design stage.

Table 8-41: Air Change Rates (ach^{-1}) for different Velocities (Cases 1 and 16)

Cases	Air Change Rates (ach^{-1}) for different Velocities (Cases 1 and 16)						
	V-7 (m/s)	V-6 (m/s)	V-5 (m/s)	V-4 (m/s)	V-3(m/s)	V-2 (m/s)	V-1 (m/s)
Case-1	20.8	16.9	12.3	8.4	5.2	2.4	0.8
Case-16	31.2	25.2	18.7	12.8	8.0	3.8	1.0

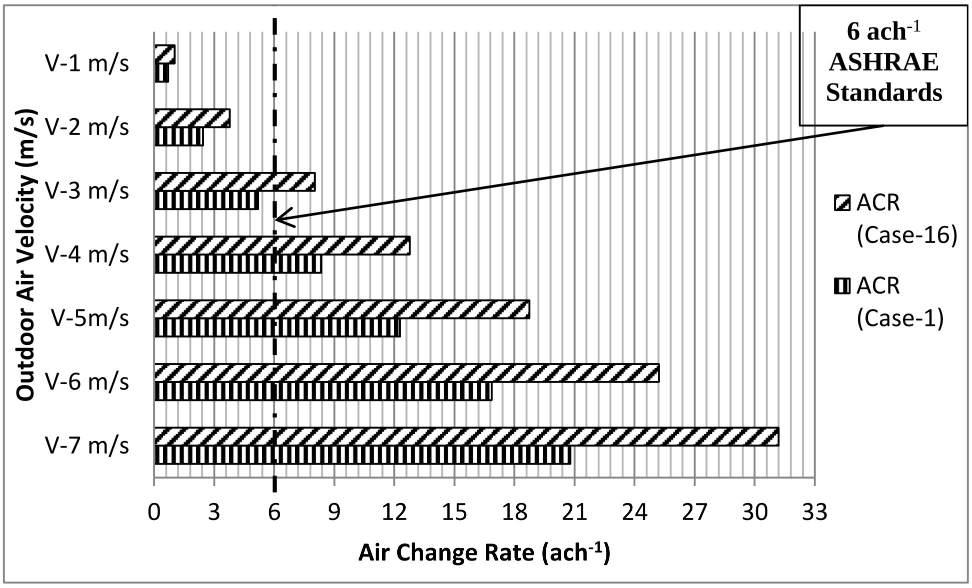


Figure 8.53: Air Change Rates (ach^{-1}) for different Velocities (Cases 1 and 16)

8.9.3 Average Indoor Air Velocity and outdoor wind speed

The influence of indoor air velocity in providing acceptable indoor air quality is crucial. The relationship between outdoor air speed and average indoor air velocity has been studied for both cases 1 and 16. The result shows that indoor air velocity increases with increase in outdoor air speed in both cases 1 and 16 as illustrated in table 8-42 and figure 8.54. Li et al. (2014) in their study established that, the indoor average velocity on the working planes increases from 0.25 to 0.74 m/s, when the outdoor wind speed increase from 0.51 to 1.00 m/s. This confirms that the indoor environment of a building has a rapid reaction to the outdoor climate, which is very vital for wind-driven naturally ventilated buildings. Gilkeson et al. (2013) also affirms that indoor air velocity increases linearly with outdoor wind speed in naturally or mechanically ventilated hospital environment.

Moreover, the indoor air velocities are higher in case 16 compared to case 1 for all levels of outdoor air speed simulated. All the indoor air speeds in both cases are below 0.15 except one in case 16 (indoor air velocity at 7m/s outdoor air speed) which is above 0.15. Studies have indicated that, in naturally ventilated buildings in the tropics occupants will be comfortable with indoor local air speed of 0.25m/s or less (Yau et al 2011). The trend line graph of indoor air velocity at different outdoor air speed shown in figure 8-55 suggest that, the difference is higher when the outdoor air speed is greater than 3m/s and lower in less than 3m/s. The trend line graph is stiff when the outdoor air speed is from

3m/s to 7m/s, and gentle when the outdoor air speed is between 3m/s and 1m/s as illustrated in figure 8.55. Hence, the effect of outdoor air speed on indoor air velocity is more significant at higher outdoor wind speed, compared to lower wind speed.

Table 8-42: Average indoor air Velocity for different Velocities (Cases 1 and 16)

Cases	Average indoor air Velocity for different Velocities (Cases 1 and 16)						
	V-7 (m/s)	V-6 (m/s)	V-5 (m/s)	V-4 (m/s)	V-3(m/s)	V-2 (m/s)	V-1 (m/s)
Case-1	0.099	0.077	0.055	0.035	0.024	0.023	0.021
Case-16	0.178	0.139	0.099	0.064	0.038	0.031	0.029

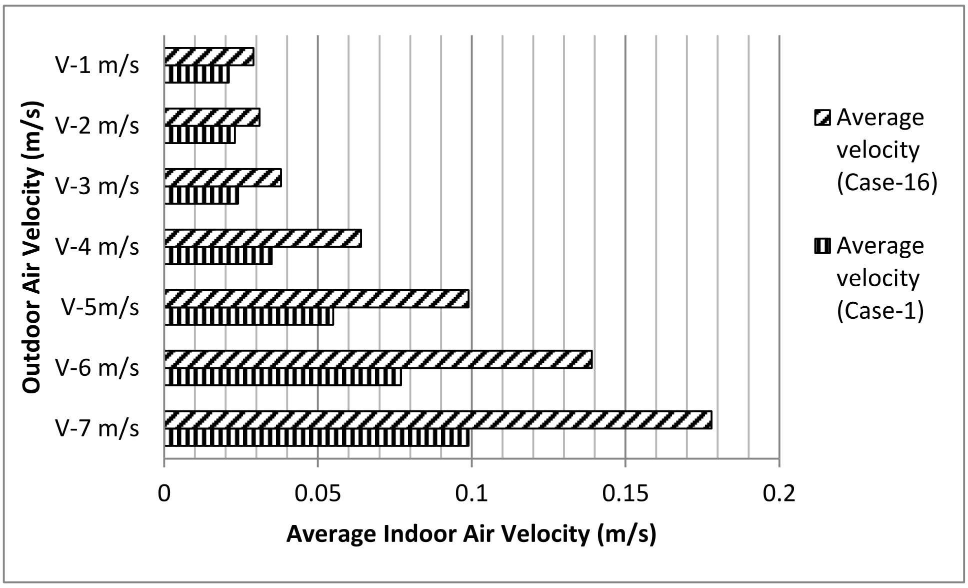


Figure 8.54: Average indoor air Velocity for different Velocities (Cases 1 and 16)

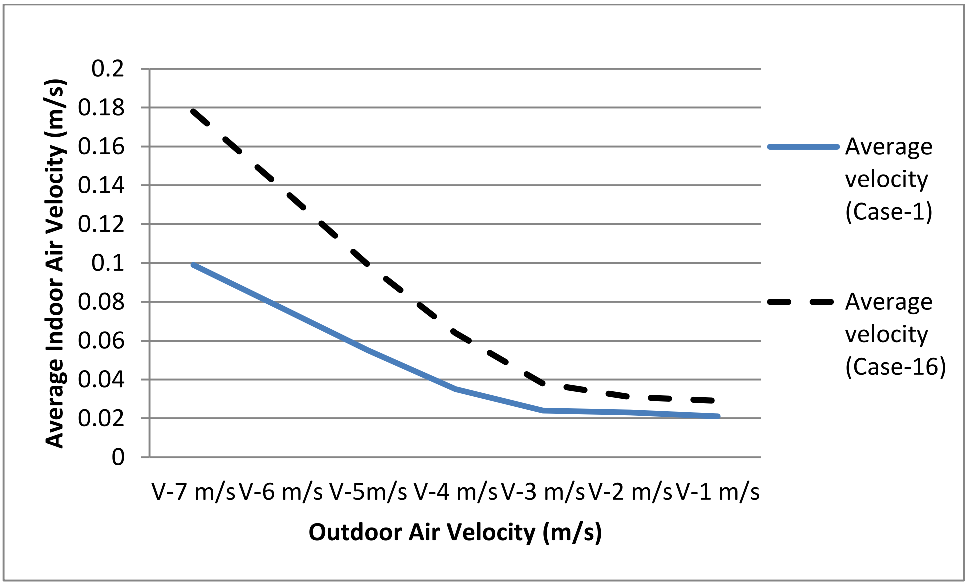


Figure 8.55: The Trend of Average indoor air Velocity for different Velocities (Cases 1 and 16)

8.9.4 Average Indoor Turbulent Intensity and outdoor wind speed

Turbulent intensity of indoor environment is one of the major factors that determine draught comfort. The effect of outdoor air speed on average indoor turbulent intensity is insignificant. This is apparent in the results shown in table 8-43 and figure 8.56 in which the variations in turbulent intensity between different outdoor air speeds is negligible. However, the turbulent intensities in case 1 are higher than in case 16. This implies that, turbulent intensity decreases as the indoor air velocity increases. Since case 16 has higher indoor air velocity than case 1 as illustrated in figure 8.54 and 8.55.

Table 8-43: Average indoor Turbulent Intensity (%) for different Velocities (Cases 1 and 16)

Cases	Average indoor Turbulent Intensity (%) for different Velocities (Cases 1 and 16)						
	V-7 (m/s)	V-6 (m/s)	V-5 (m/s)	V-4 (m/s)	V-3(m/s)	V-2 (m/s)	V-1 (m/s)
Case-1	4.59	4.60	4.63	4.64	4.57	4.40	4.40
Case-16	4.20	4.22	4.22	4.20	4.16	3.82	3.82

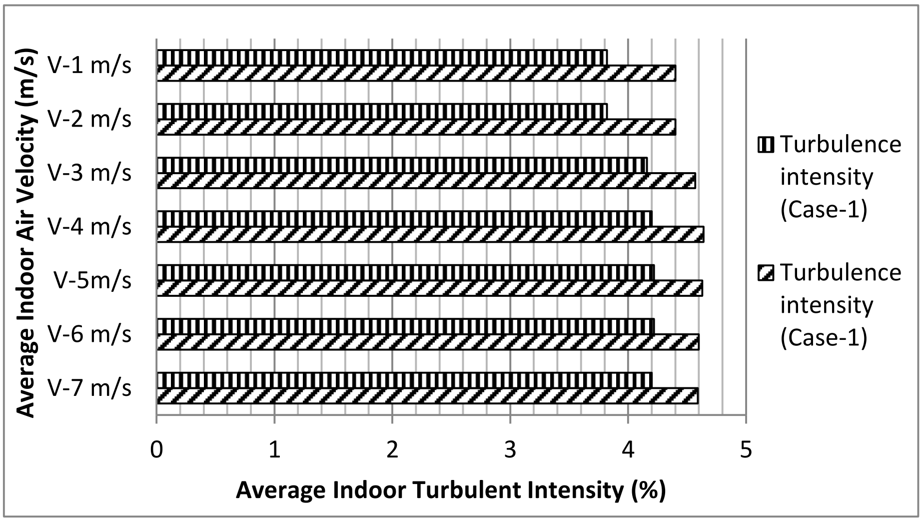


Figure 8.56: Average indoor Turbulent Intensity (%) for different Velocities (Cases 1 and 16)

8.10 Monthly evaluation of natural ventilation in hospital wards of semi-arid climates

In order to evaluate the ventilation rates of the different periods of the year, the base-case (Case 1) and the best-case (Case 16) has been simulated using the monthly average weather data of the study area, including the monthly outdoor wind speeds and air temperature. The assessment of the monthly air change rates, indoor air velocity and indoor air temperature is necessary in acquiring detailed information about the indoor air quality and ventilation of these hospital wards. The simulations are conducted with the assumption that, the angle of attack of the prevailing wind to the inlet openings is normal. The results indicate that, the highest airflow rates and air change rates are experienced in the months of March and June and the lowest airflow rates and air change rates are experienced in the month of September. The airflow rates and the air change rates are higher in case 16 (best-case) compared to case 1 (base-case). However, the air change rates in all the 12 months have satisfied the 6 ach^{-1} ASHRAE recommendation for hospital wards as illustrated in table 8.44, figures 8.57 and 8.58.

Table 8-44: The monthly volumetric flow rates and air change rates (Cases 1 and 16)

Months	Volumetric flow rates		Air Change Rates	
	Case 1	Case 16	Case 1	Case 16
January	1.64	2.38	12.92	18.75
February	2.12	3.10	16.70	24.42
March	2.20	3.20	17.33	25.21
April	2.12	3.10	16.70	24.42
May	2.12	3.10	16.70	24.42
June	2.20	3.20	17.33	25.21
July	2.00	2.92	15.75	23.00
August	1.46	2.12	11.50	16.70
September	1.40	2.04	11.03	16.07
October	1.46	2.12	11.50	16.70
November	1.70	2.46	13.39	19.38
December	1.46	2.12	11.50	16.70

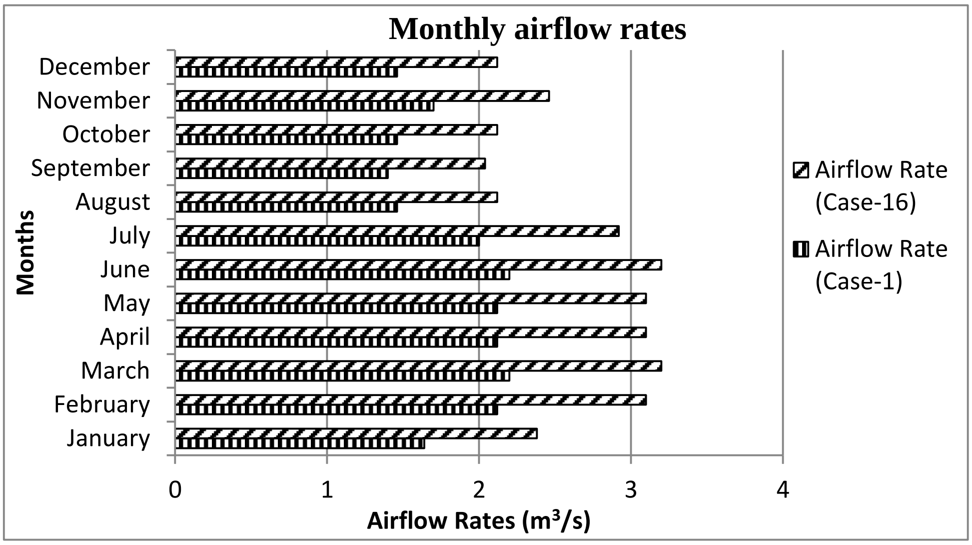


Figure 8.57: Monthly Airflow Rates in the simulated hospital wards

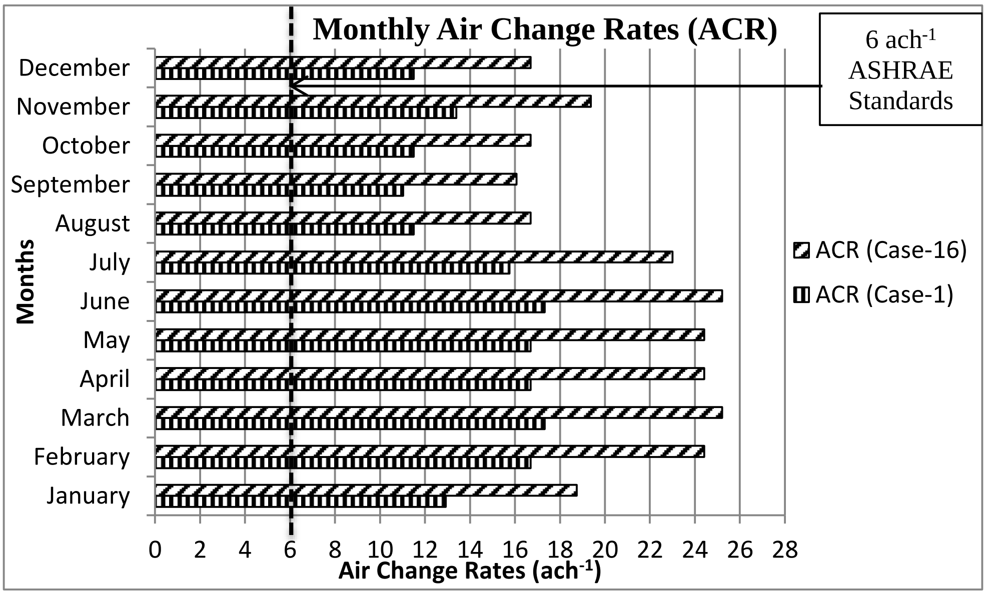


Figure 8.58: Monthly Air Change Rates in the simulated hospital wards

In this study, the influence of monthly outdoor climate condition on the average indoor air velocity, turbulent intensity and air temperature has been studied. The results indicate that indoor air velocity is higher in case 16 compared to case 1 (base-case) as illustrated in table 8-45 and figure 8.59. The monthly average indoor air velocity result is similar to the air change rates, as the highest average indoor air velocities are experienced in the months of March and June and the lowest average indoor air velocities are experienced in the month of September. Thus, higher indoor air velocity means the ventilation has greater efficiency in removing indoor air contaminants.

Table 8-45: The monthly average indoor air velocity and turbulent intensity (Cases 1 and 16)

Months	**Average air velocity (m/s)**		Turbulent intensity (%)		Average air temperature °C	
	Case 1	Case 16	Case 1	Case 16	Case 1	Case 16
January	0.059	0.099	4.15	4.22	22.0	22.1
February	0.080	0.134	4.15	4.21	24.7	24.8
March	0.083	0.139	4.14	4.22	28.5	28.6
April	0.080	0.134	4.14	4.22	31.7	31.8
May	0.080	0.134	4.14	4.22	32.2	32.3
June	0.083	0.139	4.14	4.22	30.2	30.3
July	0.075	0.125	4.15	4.22	27.8	27.9
August	0.052	0.086	4.14	4.23	26.9	27.0
September	0.050	0.082	4.14	4.23	27.8	27.8
October	0.052	0.086	4.14	4.23	28.3	28.4
November	0.062	0.103	4.15	4.22	24.8	24.9
December	0.052	0.087	4.10	4.22	22.4	22.5

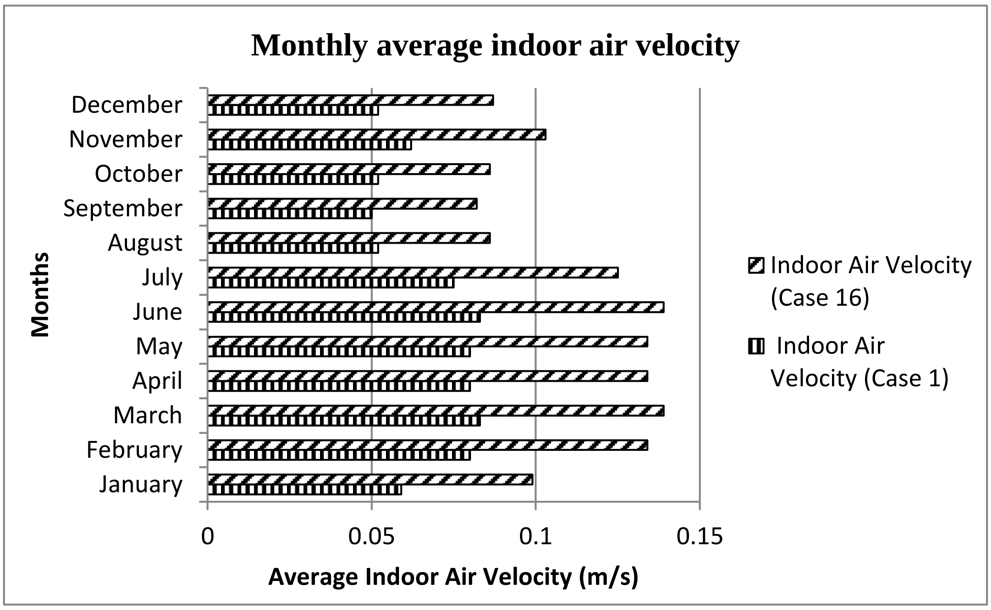


Figure 8.59: Monthly average indoor air velocity in the simulated hospital wards

The results about the indoor turbulent intensity indicate that, the turbulent intensity is higher in case 16 compared to case 1. This is because, case 16 has higher ventilation rates compared to case 1 (see figure 8.58). In a room with the same opening characteristics, indoor turbulent intensity increases with decreasing indoor air velocity and vice versa as illustrated in figures 8.59 and 8.60.

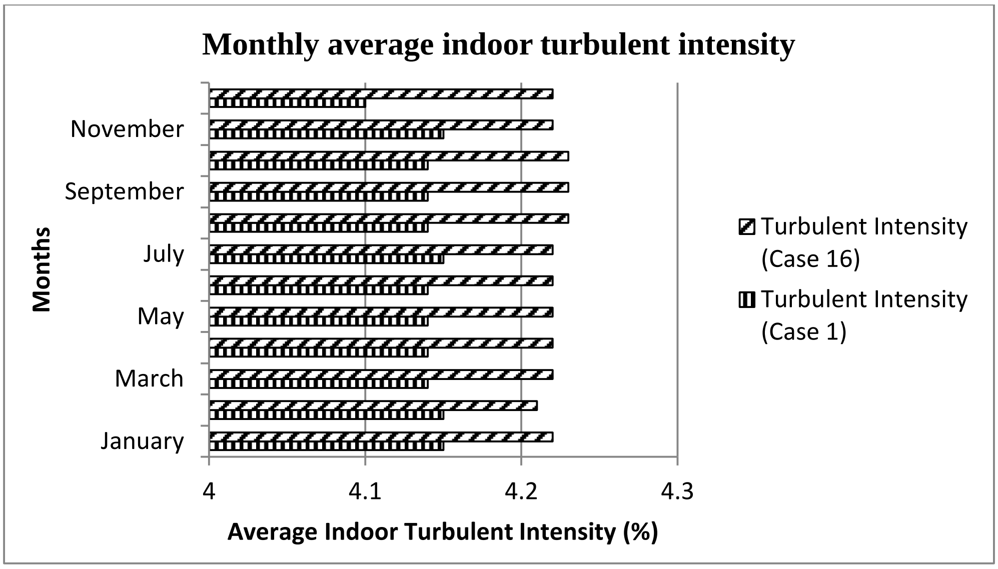


Figure 8.60: Monthly average indoor turbulent intensity in the simulated hospital wards

The average indoor air temperature for different months of the year has been simulated and analysed. The results indicate that, the highest indoor air temperature is experienced in the month of May and the lowest is experienced in the month of January, as illustrated in figure 8.61. The adaptive temperature calculated for the buildings of the study area by Mohammed et al. (2013a) indicate that, the comfort temperature is between 24.2^{o}C to 29.2^{o}C. The outcome of the simulation shows that, the temperatures in the months of April, May and June are slightly higher than the adaptive comfort temperature, because the months are the hottest in the study area. However, the temperatures in the months of January and December are slightly lower than the adaptive comfort temperature because, the months are the coldest months in the study area as illustrated in figure 8.61.

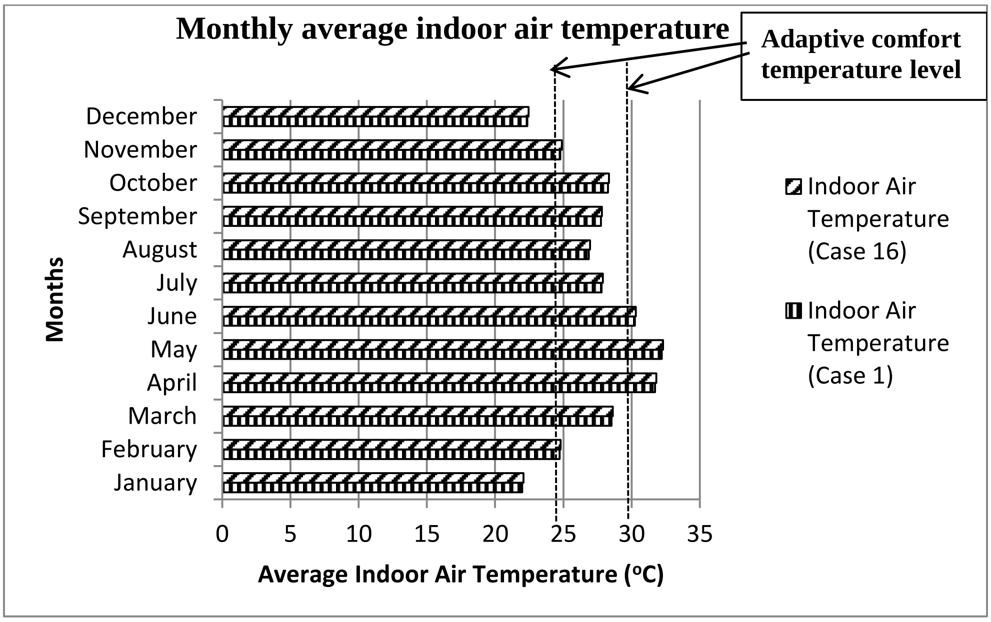


Figure 8.61: Monthly average indoor air temperature in the simulated hospital wards

Thus, the temperatures in the remaining 7 months including February, March, July, August, September, October and November are within the acceptable comfort temperature limits. Moreover, even the temperature in January and December are also good because they are cold season. The difference in temperature between cases 1 and 16 is insignificant as illustrated in figure 8.61.

8.11 Chapter Conclusion

The analysis of the simulation results lead to conclusions on various issues investigated including air change rates/airflow rates, air velocity and turbulence intensity in the hospital wards of the study area. With installed insect screens, the ventilation system will provide the required acceptable level of indoor air quality in hospital multi-bed wards of semi-arid climates. The inlet velocity of 2.6 m/s and insect screen porosity of 0.66 have been used for the investigation of the effect of various openings positions on ventilation rates, indoor air speed and indoor air circulation pattern. The chapter also investigated the influence of different ward orientations, insect screen porosities and outdoor wind speed and ventilation rates and indoor air speed in the hospital wards of the study area.

Case 16 with influence of both wind and buoyancy is the best in terms of airflow rates, circulation and distribution. The study also established that, air change rates/volumetric airflow rates alone will not measure ventilation efficiency and effectiveness, rather indoor air distribution and circulation are also essential, due to the influence of short circuiting. The effect of short circuiting airflow, which is as a result of the close proximity between the inlet and outlet openings leads to false estimation of air change rates and volumetric flow rates in indoor environment.

The highest percentage of dissatisfied (PD) due to indoor air quality for 30, 50, 70 and 90 standard persons occupancy level are 4.5, 7.4, 10 and 13% respectively. Hence the PD level in all the 17 cases is less than 15%. However, the best-case (Case 16) is among the cases with lowest dissatisfaction rates of 2.3, 4.5, 7.4 and 8.5 for 30, 50, 70 and 90 occupancy levels respectively.

The highest indoor local air speeds in the multi-bed wards studied are obtainable at the points opposite the inlets openings. In the points directly opposite the airflow openings, the local indoor air speeds are higher in the windward sides of the wards, and then followed by the centre and then the leeward side close to the outlet openings. In the points opposite the walls, the indoor local air speeds are higher in the leeward sides and then followed by the points at the centre of the ward, and then the windward positions. The highest indoor air velocities at the windward sides of the ward, opposite the inlet openings are 20% and 12% of the external incident wind velocity for levels 1.0 m and 0.6 m above floor level respectively. The indoor air speeds in the remaining positions at the centre and toward the outlet openings are less than or equal to 2% of the external incident wind velocity. The simulation results further show that, the higher the indoor air speed, the lower the turbulent intensity inside the ward. The highest draught risk estimated at 1.0 m occupancy level for case 1(base-case) and case 16 (best-case) is 10.2% and 16.8% respectively. However, the highest draught risk estimated at 0.6 m occupancy level for case 1(base-case) and case 16 (best-case) is 6.6% and 10.7% respectively.

The volumetric airflow rates and the air change rates are higher in cases with external wind incidents normal to the inlet openings (90^o), and then followed by angles 60^o, 30^o and 0^o respectively. In the best-case (case 16), the air change rates in wards with outdoor wind incidents angles of 90^o, 60^o and 30^o have satisfied the ASHREA standard of 6 ach^{-1} in a patient room, while angle 0^o did not. The study confirms that, the average indoor air speeds for wind flow with oblique angle of attack to the openings (30^o and 60^o) are higher compared to the cases with normal (90^o) angle of attack. Thus, the oblique orientations provide better airflow distributions compared to the cases with outdoor wind flow orientation normal to the inlet openings, were channel flow develops connecting the inlet and outlet.

The volumetric flow rates and the air change rates decreases, with decreasing insect screen porosity. In the best-case (case 16) the air change rates of openings with screen porosities ranging from 0.4 to 1.0 have satisfied the ASHREA standard of 6 ach^{-1} in hospital wards, while the remaining openings with porosities 0.1 to 0.3 did not fulfil the requirement. However, the results about the influence of outdoor wind velocity on ventilation rates shows that, the higher the outdoor air velocity, the higher the volumetric flow rates and air change rates and vice versa. In the best-case (case 16), the air change rates for simulation with outdoor air velocity ranging from 3 m/s to 7 m/s have satisfied the ASHREA standard of 6 ach^{-1} in patients room, when the ward’s opening orientation is normal to the wind flow direction.

However, for case 16, with outdoor wind velocities less than 3 m/s did not fulfil the ASHRAE requirement. Taking the monthly average wind speeds in table 2-2 (page 21) and simulating air change rates for case 16, in all months the ASHRAE standard was achieved. And the indoor air temperatures in 9 out of the 12 months in a year have satisfied the adaptive comfort requirements except the months of April, May and June, in which the temperatures are slightly higher than the adaptive comfort level.

Owing to its better performance, Case 16 was used as the starting point for the pollutant dispersion studies in the next chapter (Chapter 9). The hospital ward description together with their air change rates and the effect of short circuiting airflow of all the 17 cases simulated is shown in table 8-46.

Table 8-46: The summary of the simulated case studies showing air change rates and short-circuiting effects

Cases	Description	Air Change Rates (ach^{-1})	Short-circuiting
Case 1	**Inlets centre & outlets centre**	*9.14*	*No*
Case 2	**Inlet centre & outlet up**	*9.30*	*No*
Case 3	**Inlet centre & outlet down**	*8.98*	*No*
Case 4	**Inlet high & outlet down**	*9.30*	*No*
Case 5	**Inlet down and outlet high**	*8.51*	*No*
Case 6	**Inlet high and outlet high**	*9.61*	*No*
Case 7	**Inlet down and outlet down**	*8.20*	*No*
Case 8	**Inlet centre and outlet side**	*8.51*	*Yes*
Case 9	**Inlet centre & outlet roof leeward**	*10.40*	*No*
Case 10	**Inlet centre & outlet roof centre**	*12.45*	*Yes*
Case 11	**Inlet centre & outlet roof windward**	*14.65*	*Yes*
Case 12	**Inlet centre & outlet roof_parallel_2_windward**	*12.29*	*Yes*
Case 13	**Inlet centre & outlet roof_parallel_2 Leeward**	*10.24*	*Yes*
Case 14	**Inlet centre & outlet roof_parallel_3**	*11.19*	*Yes*
Case 15	**Inlet centre & outlet Tower**	*10.00*	*No*
Case 16	**Inlet centre & outlet both roof and leeward wall**	*13.55*	*No*
Case 17	**Inlet centre & outlet both Tower and leeward wall**	*11.14*	*No*

Chapter Nine

Pollutant Dispersion in Hospital Wards

Chapter Structure

9.1 Introduction

9.2 Indoor pollutant dispersion prediction in hospital wards

9.3 Discrete Phase Model (DPM)

9.4 DPM Boundary Conditions

9.5 The effect of screen porosity on dust particles deposition in hospital wards

9.6 The effect of outdoor wind speed on dust particles deposition in hospital wards

9.7 The effect of plenum on dust particles concentration and deposition in hospital wards

9.8 Chapter Conclusion

9 Chapter Nine: Pollutant Dispersion in Hospital Wards

9.1 Introduction

The effects of different opening configurations, insect screen porosity, building orientation and outdoor wind speed on ventilation rates in hospital multi-bed wards has been analysed and presented in the previous chapter (chapter 8). The chapter confirms the influence of the above mentioned parameters on indoor air quality and ventilation efficiency in hospital wards. In this chapter (chapter 9), the effects of screen porosity, incorporation of plenums and outdoor wind speed on indoor pollutant dispersion will be discussed and presented. The term Plenum is used in this research as a form of double skin façade, but without any glazing on the openings.

Owing to the influence of Harmattan dust on indoor air quality in the study area, the consideration of particle dispersion is necessary in any natural ventilation studies. The results of the psycho-social perception presented in chapter 5, shows the dissatisfaction of hospital wards occupants on indoor air quality especially the level of Harmattan dust indoors and ventilation efficiency of the studied wards. The outcome of the psychosocial perception survey further shows that, the availability of dust particles within hospital wards has consequences on the patients' health condition. The result of the survey conducted to ascertain the level of dust within the hospital wards, by asking the respondents "Do you normally experience dust problem in the wards?" about 97% of the respondents have agreed they experience dust problems in the wards. Moreover, the pollutant dispersion study presented in this chapter is mainly those with outdoor sources, thereby simply analysing the amount of particles reaching the indoor spaces. Pollutants with indoor sources are not considered and the main objective of this study is not to study the particles behaviour within the indoor environment in detail, but rather to ascertain the quantity of outdoor particles reaching the indoor environment, distinguishing between deposited and suspended particle tracks. This chapter (Chapter 9) and the previous chapter (Chapter 8) were intended to achieve objective number 4, which is *"To explore the potentials of using natural ventilation strategies for achieving acceptable indoor air quality with the presence of Harmattan dust and Mosquitoes"*

The initial parts of this chapter comprising sections 9.2 to 9.4, introduces dust particle studies including indoor pollutant dispersion in hospital wards. Discrete Phase Model (DPM) and DPM boundary conditions were used to study the influence of dust particles concentration, deposition and suspension in different cases. Section 9.5 discusses the influence of insect screen porosity on dust particle concentration, deposition and suspension, section 9.6 presents the effect of outdoor wind speed on dust particles concentration, deposition and suspension and section 9.7 discusses the influence of introducing Plenum on indoor dust particle concentration, deposition and suspension. The final section (9.8) of this chapter is the conclusion.

9.2 Indoor pollutant dispersion prediction in hospital wards

Zhao et al. (2004b) in their study assert that, people spend 80 – 90% of their lifetime in an indoor environment. Therefore, owing to the significant consequences of dust particles on indoor air quality in indoor environments and the great influence of particle concentration or number of particles on indoor air quality, the assessment of airflow pattern, particle dispersion and movement is essential (Tian et al. 2009). There are two sources of indoor air contamination that affects indoor air quality including; indoor (internal) sources and outdoor (external) sources. The indoor sources represent all kind of materials for construction, painting, furniture, cleaning products, combustion, etc. while the outdoor sources includes vehicles, industrial activities ,waste water treatment plants and other sources that can discharge air contaminants which penetrate into the indoor environments (Santos et al. 2011). These pollutants are mainly suspended particles in air, such as dusts, smoke, fumes, and mists (ASHRAE Fundamentals, 1997). However, the interest of this research lies with the effect of the pollutants with outdoor sources, such as Harmattan dust and Mosquitoes on indoor air quality. Thus, both Harmattan dust and Mosquitoes are outdoor pollutants with sources outdoors. Other type of pollutants with indoor sources are not considered in this study due to time constraints, simplification and computational power and hence out of scope of this research. The impact of outdoor pollutant sources on the levels of indoor concentration and distributions is determined by factors such as atmospheric dispersion or concentration patterns around the buildings, the building surfaces and the opening characteristics and hence the level of outdoor pollutants penetration into the indoor environment. Therefore, the sustainable method of enhancing indoor air quality is the reduction and/or elimination of external sources of indoor air contaminants, whereas a more effective approach is the management of ventilation systems efficiently. (Santos et al. 2011).

Furthermore, there are many consequences of indoor air pollution. Nararoff (2004) confirms that, the availability of aerosol particles indoors will lead to adverse health consequences and are considered as significant pollutants in an indoor building environment. Outdoor air contaminants such as dust particles penetration indoors, apart from creating discomfort in terms of furniture and other surfaces dirtying, it is also strongly associated with working efficiency and health of building occupants (Fanger, 2006; Wyon, 2004). It is acknowledged that the inhalation of suspended aerosol particles by the inhabitants of populated indoor environment will lead to the deposition of these particles on nasal passage with potential harmful consequences (Zhao et al. 2004a). Likewise, aerosol particles could be deposited on internal surfaces, triggering a soiling problem and consequently leading to damages (Lu et al. 1996). Furthermore, since the particle behaviour and spatial concentration are strongly linked to surrounding airflow pattern, the perfect prediction of airflow characteristics in and around the building is necessary and vital for particle assessments (Jiang and Wang, 2012). Therefore, ventilation systems should enhance the exchange of air between indoors and outdoors to exhaust the air pollutants produced by internal sources and consistently dilute the indoor air pollutants produced by external sources, to prevent the accumulation of contaminants at areas with stagnant air in the building indoor environment (Santos et al. 2011).

The employment of state-of-the-art tool with the capacity of reliably predicting airflow pattern and particle dispersion and distribution in buildings is important to design an efficient ventilation system. This is because, the system of ventilation used in buildings defines the airflow pattern in the indoor space, and subsequently, the airflow pattern determines the particle distribution and dispersion (Béghein et al. 2005). Numerical simulation plays a significant part in examining the characteristics of pollutant dispersion in indoor environment (Xia and Leung 2001). Owing to its capacity to rapidly provide comprehensive information on airflow, particle concentration, deposition and movement in different ventilated spaces with relatively low cost, the employment of CFD for indoor air quality studies is growing in the recent years (Jiang and Wang, 2012). It is acknowledged that indoor air quality is largely dependent on the building ventilation rates and the patterns of airflow inside the building (Santos et al. 2011). In this study the effect of Harmattan dust on indoor air quality in the study area (Maiduguri) has been simulated and analysed, using Fluent 13.0 CFD code. The simulation was conducted to ascertain the particles penetration to the indoor environment under different circumstances including installation of insect screen with various porosities, different levels of outdoor wind speeds and introduction of plenums.

In order to simplify the simulation process and further reduce computational power effectively, the following assumptions are used for the purpose of this study which is also used in previous studies (see Zhao et al. 2004a; Lu et al. 1996; Tian et al. 2009):

a) Heat and mass transfer between air and particles are neglected;
b) No particle rebounds on solid surfaces, such as walls, floors and ceilings;
c) No particle coagulation in the particle deposition process;
d) All particles are in spherical solid shape.

In the present study, one-way coupling approach was used in treating the interaction between the carrier air and the particles. The assumption made by Béghein et al. (2005) was adopted, which presumed that the influence of the particles on the turbulent flow is insignificant owing to low solid loading and relatively low particle settling velocity, and that there is no coagulation of particles. On the issue of assumption (b) above that 'No particles rebounds on solid surfaces, previous studies have shown that there is a possibility of particles rebound especially with smaller size particles (Abadie et al., 2001), but their effects are negligible. However, simulating particles rebounds using CFD requires enormous computational power and this assumption was adopted in this study to simplify the model and subsequently reduce the computational power. The same assumptions were used in previous ventilation studies (see Tian et al., 2009; Lu et al. 1996; Zhao et al. 2004a).

9.3 Discrete Phase Model (DPM)

In this study the Lagrangian discrete particle model was used for tracking the number particles penetration into the indoor environment. This method has been employed in many previous studies. Lu et al. (1996) applied Lagrangian particle transport model in tracking the deposition and concentration of sample particles in a ventilated room with different particle sizes. Béghein et al. (2005) applied Lagrangian method in studying particle dispersion for two ventilation circumstances in a ventilated cavity with a simplified geometry. Jiang and Wang (2012) in their investigation of particle dispersion and spatial distribution of full-scale forced ventilated room compared four different multiphase models including passive scalar model, discrete particle phase model, mixture model and Eulerian model and concluded that the Lagrangian discrete phase model is the best by predicting particle concentration distribution more closer to experimental values.

The Lagrangian approach divides the particle phase into a representative set of individual particles and tracks these particles individually within the flow domain by solving the particle movement equation (Lu et al. 1996). Basically, in this study, the problem was initially solved for the single phase flow, and then the discrete phase model (DPM) was enabled. There are two methods of computing the pollutant concentration when using Lagrangian Particle Dispersion (LPD) approach (Xia and Leung 2001).

1. Statistical method: The pollutant concentration is established by counting the number of particles in an imaginary sampling volume.
2. Kernel method: Every particle is considered as a pollutant mass and the concentration at a given point is estimated as the sum of contributions from all particles by a kernel density estimator.

In this study, the first approach was adopted, because of its capacity to provide the required information of establishing the number of particles entering the indoor environment through the provided openings. However, the major constraint of the DPM is that its needs higher computational power compared to other methods such as Passive Scalar Model (PSM) and Modified Passive Scalar Model (MPSM) (Jiang and Wang, 2012). Moreover, the employment of computational particles to represent a packet of real particles suggests that DPM model could only be appropriate for very much diluted particle flows (Elghobashi, 1994).

The Discrete Phase Model (DPM) calculates the individual particles trajectories by taking into account the influences of all forces on particles in the Lagrangian frame. The governing equation for each particle is given in equation (23) as follows (Jiang and Wang, 2012):

$$\frac{du_P}{dt} = F_D\left(u - u_p\right) + g\,\frac{\rho_P - \rho}{\rho_P} + F \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(23)$$

where u_p and u are particle and airflow velocities respectively, $F_D(u - u_p)$ is drag force per unit particle mass, F is any additional acceleration term, ρ_p is particle density, ρ is fluid density, and g ($\rho_p - \rho / \rho_p$) is gravity force.

The drag coefficient is calculated using equation (24) as follows:

$$\mathrm{F_D} = \frac{18\mu}{\rho_P d_P^2 C_c} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(24)$$

Where μ is fluid viscosity, d_p is particle diameter and C_c is (Cunningham correction factor). The Cunningham correction factor is calculated using the formula in equation (25) as follows:

$$C_c = 1 + \frac{2\lambda}{d_p}\left(1.257 + 0.4e^{-1.1d_p/_{2\lambda}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

Where λ is the molecular mean free path

9.4 DPM Boundary Conditions

It is generally acknowledged that in CFD simulations, accurate settings of boundary conditions are required for successful predictions (Jiang and Wang, 2012). In this study boundary conditions were specified based on available best practice guidelines, literature and full-scale measurement data. The consequences of applying inappropriate boundary conditions have been previously studied. Lee et al. (2002) in their research established that profiled inlet profile from experiments revealed better agreement with measured particle concentration both qualitatively and quantitatively than uniform inlet velocity.

When a Lagrangian Particle Dispersion (LPD) method is implemented, the methodology of obtaining the pollutant concentration can be generalised into three steps (Xia and Leung 2001):

1. Solving the wind field from the governing equations;
2. Determining the trajectories of pollutant particles in the computed wind field;
3. Calculating the pollutant concentration according to the position of emitted particles

9.4.1 Particles injection and properties

In the present study the inert particles were injected using surface injection, in which the injection surface was placed outside the building in the windward side opposite the inlet openings. The particles were injected in the direction normal to the face of the injection surface (inject using face normal direction), while the flow rate was scaled by the injection face area (scale flow rate by face area). The particles diameter distribution used was a normal distribution. All other necessary initial conditions of the individual particles tacking have been defined including the starting positions and the initial velocities of the particles as enshrined in Lu et al. (1996). The particles used have the density equivalent to dry sand of 2700 kg/m^3.

According to Hinds (1982) particles diameter remains the most significant parameter influencing the movement of particle. The particles with diameters 1, 2.5, 5, and 10μm were used in indoor aerosol particle concentration and disposition by Tian et al. (2009) and Zhao et al. (2004a). The particles of these sizes are employed because of their special importance for indoor air quality, as they are generally acknowledged as inhaled particles (Zhao et al. 2004a). Therefore, in this study the particle tracking was implemented to include the particles of diameters 1, 2.5, 5, and 10μm and beyond. Cooke et al. (1993) established that, the median dust particle diameter in Maiduguri (the study area) is 74.3μm. Moreover, McTainsh and Walker (1982) in their studies also established that the dust particles median diameter in Maiduguri is 68μm. The detailed characteristics of the Harmattan dust have been presented in chapter 4. In the present study, taking into account the dust median diameters in the study area as presented above, larger particles sizes of 20, 30, 40, 50, 60, 70, 80, 90 and 100μm are also considered in the simulation. The selected sizes will provide the required information on particle dispersion in hospital wards of the study area.

9.4.2 Turbulence in particle dispersion

Owing to the typically turbulent nature of airflow in buildings, the instantaneous velocity field will considerably affect particle dispersion (Armenio et al., 1999). Since the solution of the steady RANS modelling is limited only to mean velocity field, a stochastic model is employed to create a fluctuating flow field, to account for the effect of the turbulent fluctuations on the particle motions (Béghein et al. 2005). In this study, the stochastic tracking was employed, together with Discrete Random Walk model (DRW) to account for the effect of turbulence in particle dispersion. Tian et al. (2009) also used the Discrete Random Walk (DRW) model to account for the random effects of turbulence on the particle dispersion.

Moreover, the accuracy of pollutant concentrations estimated through the Statistical Method is determined by the sampling size and the number of particle utilised in the computations. When using the Statistical Method, acceptable outcomes are achieved through increasing the number of discharged particles or through the expansion of the sampling volume dimensions (Xia and Leung 2001). In this study to increase the number of discharge particles, the number of tries has been increased until there is no change in result when the same calculation is repeated. The number of tries was set at 20, and the time scale constant was allowed at the default value of 0.15.

9.4.3 Building Surface DPM boundary conditions

Generally, there are three (3) different categories of boundary conditions for solid particles moving in a ventilated room, including reflect, trap, and escape (Tian et al.

2009). The trap-type boundary conditions have been applied previously in several studies (See Tian et al. 2009; Zhao et al. 2004a; Béghein et al. 2005; Jiang and Wang 2012). In order to use the trap-type boundary condition a fine grid resolution is required near the wall regions (Jiang and Wang, 2012). Since the grid resolution used is sufficiently fine near the wall regions, in the present study the trap-type boundary condition was applied when a particle collides with interior wall surfaces (wall, ceiling and floor). There is no particle rebound when it reaches or collide with the walls (Zhao et al. 2004a), the particles will be trapped on the wall due to low velocity of the flow particles and hence, it is very difficult for the particles to be re-suspended again into the indoor air (Béghein et al. 2005). The escape boundary condition was specified for all the exterior walls and the interior type boundary condition were specified for both inlets and outlets openings, meaning once particles reach the outlet, they will escape from the room.

However, the fates of particles in ventilated rooms are generally divided into three classes including suspend, deposit, and escape (Tian et al. 2009). In this study, all particles trapped on the floor surface are considered deposited particles. Likewise, particles that are trapped on the interior wall surfaces other than the floor surface are regarded as suspended particles, while all particles that have not entered the room or exhausted though the outlet openings are considered escaped particles.

9.4.4 DPM Tracking parameters

The setting of appropriate maximum number of steps in Lagrangian Particle Dispersion (DPM) model is essential. As the default maximum time steps value is set to 500 time steps in Fluent, which may be inadequate to finish the trajectory calculation. Once this maximum number of steps is exceeded, the FLUENT software will automatically end the trajectory calculation for that particle injection and reports the fate of the trajectory as "incomplete'' (FLUENT, 2006). Therefore, to avoid this phenomenon in the present study, the maximum number of steps was set to a higher number of 5,000,000, and the step length factor was allowed at the default value of 5. The limit on the number of integration time steps eradicates the likelihood of a particle being held in a recirculating region of the continuous phase flow field and being tracked infinitely (FLUENT, 2006).

However, appropriate setting of the particle shape is also essential. The physical characterization of sampled dust particles obtained from North-Eastern Nigeria revealed that, the dust particles obtained are mixture of different shapes and sizes (Mohammed, 2013b). The particle shape adopted for the present study is spherical shape for simplification. In FLUENT the particle shape is set through the drag parameter which was also allowed at the default type “Spherical”. Béghein et al. (2005) also employed sphere particle shape for simplification.

9.5 The effect of screen porosity on dust particles deposition in hospital wards

The effect of insect screens on indoor air pollution has been studied, with dust particles of sizes 1.0µm, 2.5µm, 5.0µm 10µm, 20µm, 30µm, 40µm, 50µm, 60µm, 70µm, 80µm, 90µm and 100.0µm. The simulation was conducted using Case 16, using outdoor wind speed of 2.6 m/s (Local wind speed). In the first phase the effect of smaller sizes dust including 1.0µm, 2.5µm, 5.0µm and 10µm were simulated. These smaller sizes were considered because of their special importance for indoor air quality, as they are generally acknowledged as inhaled particles (Zhao et al. 2004a). Moreover, the larger particles dust (10.0µm, to 100.0µm) was simulated to consider the dust particle size characteristics in the study area as presented in chapter 4. To accomplish this, 18800 particle trajectories have been injected. The result shows that, there is a significant influence of screen porosity on the infiltration of dust particles to the interior part of the building. The number of particle trajectories received inside the ward increases as the screen porosity increases as illustrated in figures 9.1, 9.2 and 9.3. The detailed results of the particle trajectories have been presented in tables 12-1 to 12-13 in the Appendices section 12.3.1. However, the difference in terms of particle size is not well pronounced with particles of less than 10µm as shown in figure 9.1 and 9.3. However, the difference in concentration due to particle size is well pronounced with larger size particles as illustrated in figures 9.2 and 9.3. Hence, the larger the particle size, the fewer the particles concentration indoors.

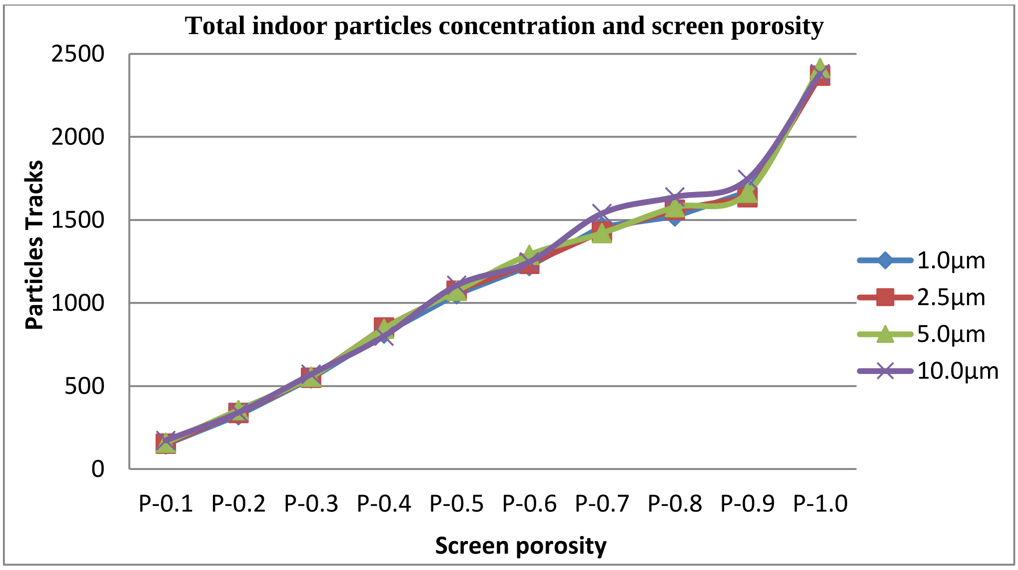


Figure 9.1: Concentration characteristics of dust particles for different insect screen porosities (1µm-10µm)

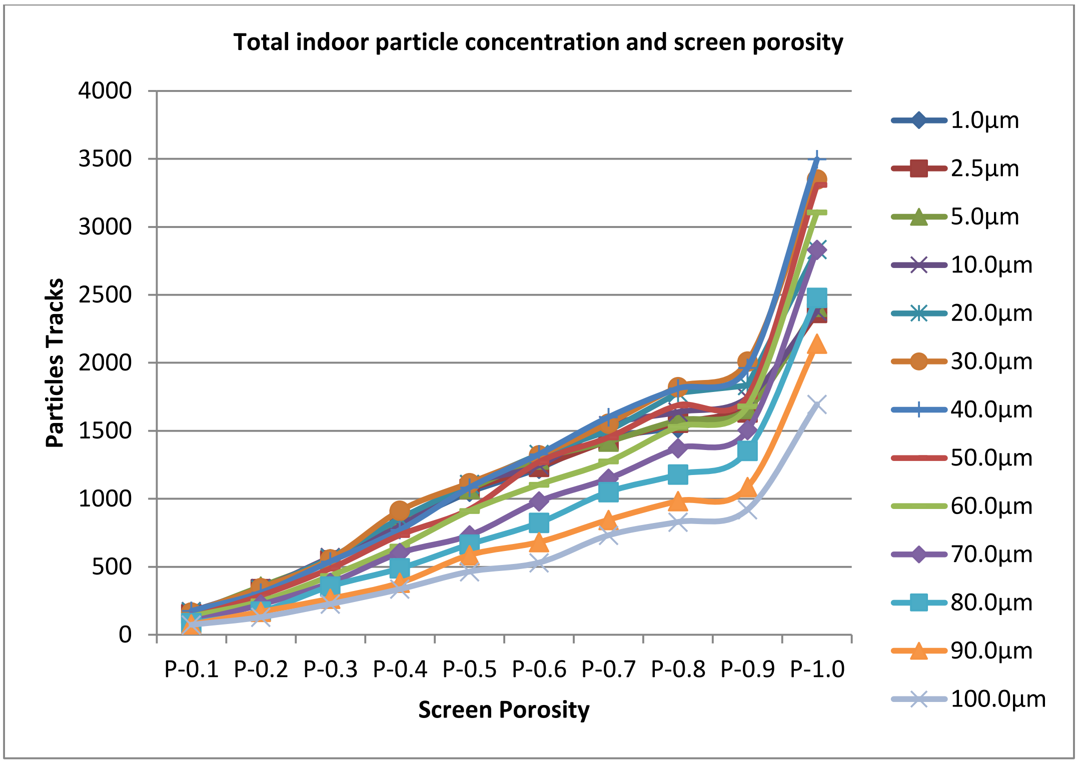


Figure 9.2: Concentration characteristics of dust particles for different insect screen porosities (1µm-100µm)

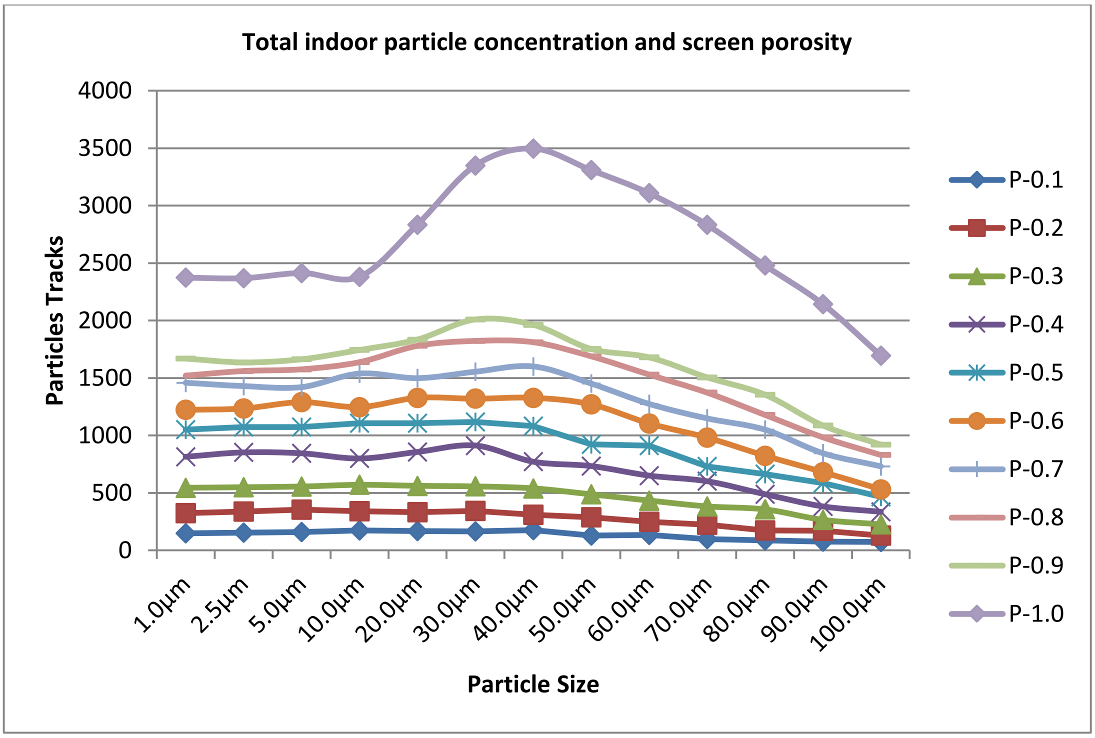


Figure 9.3: Concentration characteristics of dust particles for different particle sizes (1µm-100µm)

The results also shows that the number of particles that escaped through the outlet openings increases with growing screen porosity as illustrated in figure 9.4 and 9.5. This is because, as the screen porosity increases, higher number of particles will leave the indoors. The amount of particles escaped through the outlet openings decreases with increasing dust particle size, as illustrated in figure 9.5. This is because it is difficult for larger size particles to escape through the outlets, because of their size and reducing air speed indoors.

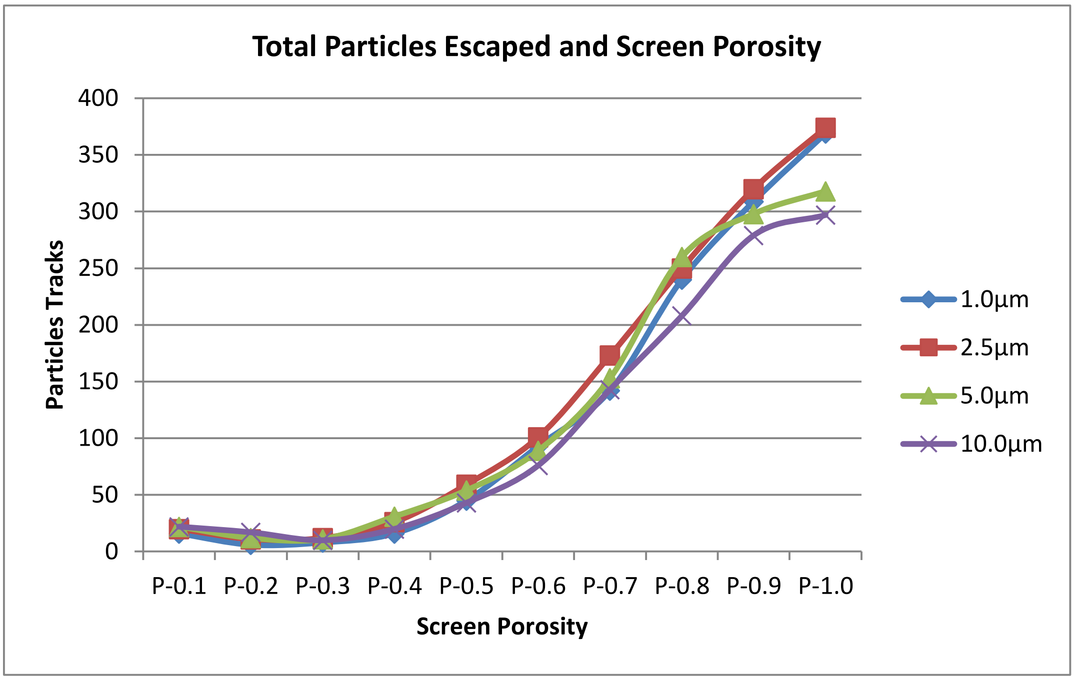


Figure 9.4: Dust particles prevention characteristics of different insect screen porosities (1µm-10µm)

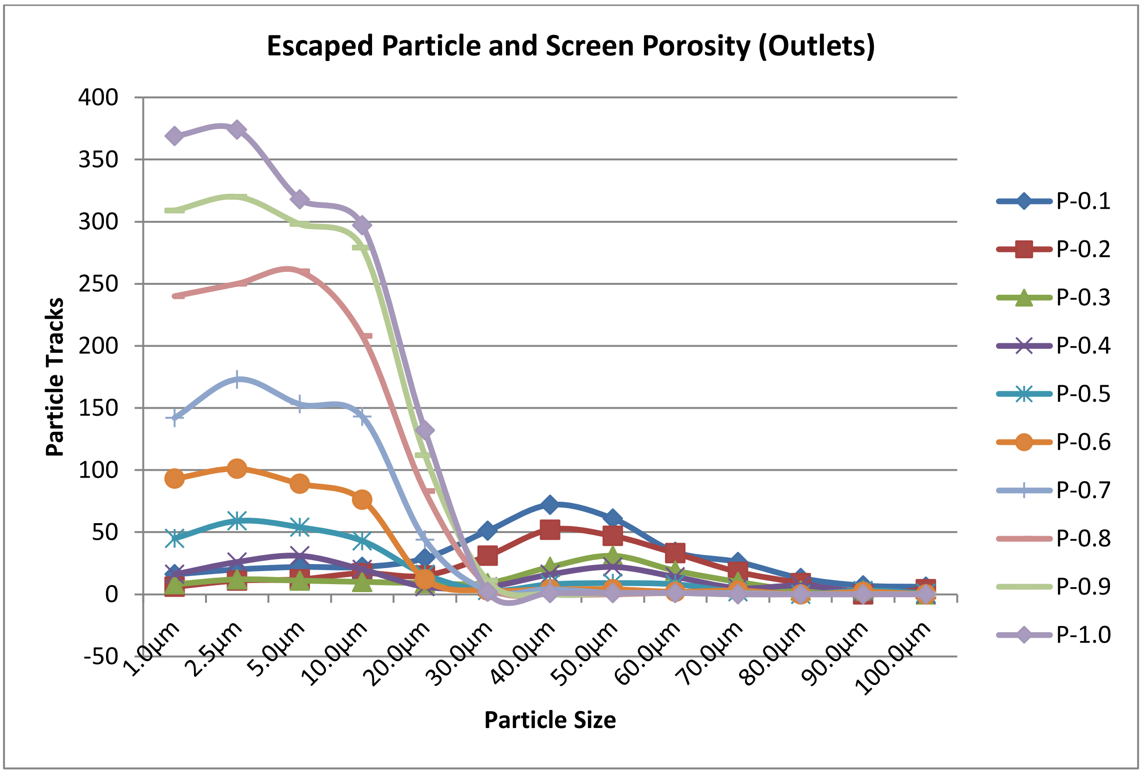


Figure 9.5: Dust particles prevention characteristics of different insect screen porosities (1µm-100µm)

The quantity of particles deposited on the floor of indoor space plays a significant role in the particle deposition process (Tian et al. 2009). The effect of screen porosity on the quantity of particles deposited on the surface of the floor has been studied. The quantity of particles deposited on the floor increases with the increasing screen porosity. Likewise, the result indicates that, deposition level increases with increasing particle size as illustrated in figure 9.6 and 9.7. This result agreed with findings of Zhao et al (2004a) which reported that, when the particle size increases, fewer particles escape and more deposited in a room. Béghein et al. (2005) in their research have revealed that light particles in indoor spaces follow the airflow pattern in the room and many particles are exhausted, whereas the larger particles deposit to the floor surface.

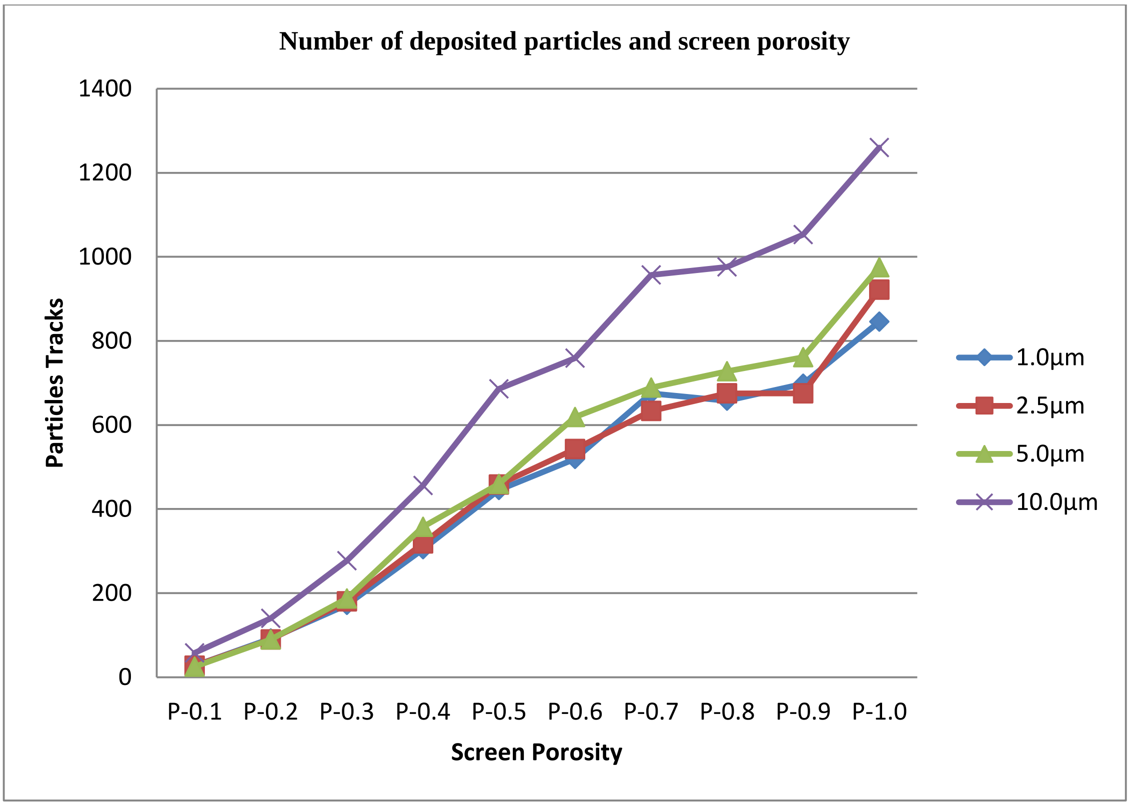


Figure 9.6: The effect of screen porosity and particle size on particle deposition (1µm-10µm)

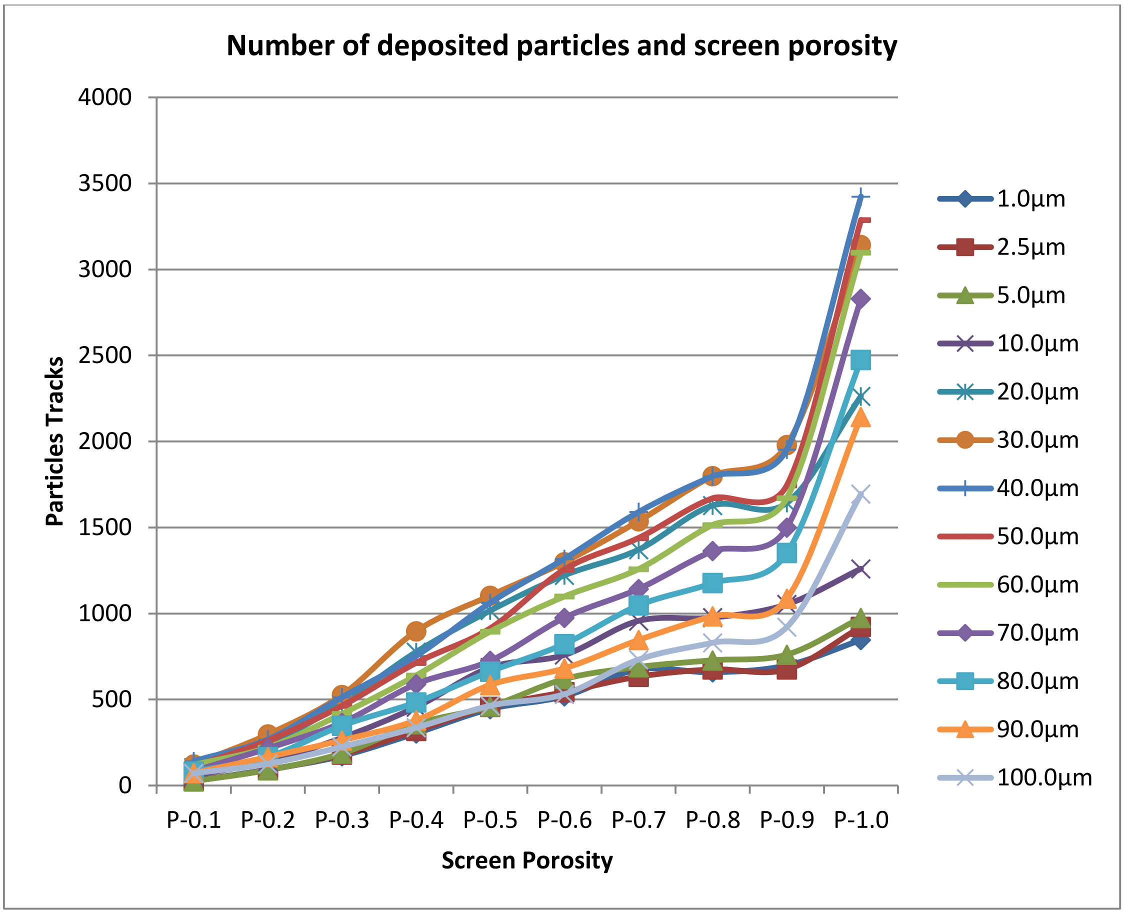


Figure 9.7: The effect of screen porosity on particle deposition for different particle sizes (1µm-100µm)

The deposition level is higher with medium size particles of between 20µm to 70µm. This is because it is easier for smaller size particles of diameter 1µm to 10µm to leave the room through the outlet openings, which is responsible for the lesser deposition of smaller size particles. In terms of larger particles of diameter 80µm to 100µm, due to their size and weight fewer particles penetrate through the inlet openings into the room from the outside, which eventually reduces their deposition level. However, for medium level particles of 20µm to 70µm, the amount of particles reaching the indoors through the inlet opening is higher than the larger size particles and due to their size the amount of particles that escapes through the outlet openings is fewer than smaller size particles. Hence, the quantity of particle deposition will be higher with medium size particles compared to both smaller and larger size particles as illustrated in figure 9.8.

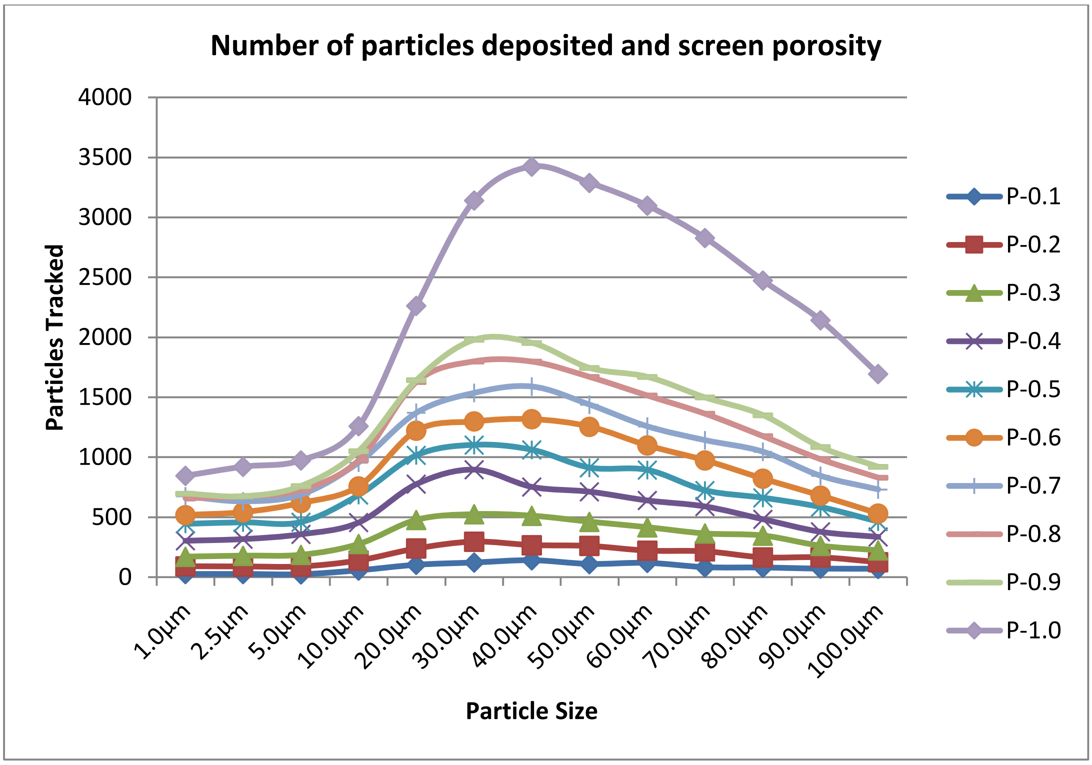


Figure 9.8: The effect of particle size on particle deposition for different screen porosity (1µm-100µm)

Unlike the deposited particles, the number suspended particles in the hospital ward decreases with growing particle size as illustrated figure 9.9 and 9.10. This is due to the fact that larger particles have larger settling velocity, and the drift of the particles between fluids is more significant (Zhao et al. 2004a). The level of suspension in smaller size particles of 1.0µm to 5.0µm is higher and the lowest level of suspended particles indoors is obtainable with larger size particles of 30.0µm to 100.0µm sizes as illustrated in figure 9.10. The variation between particles of sizes ranging from 10.0µm to 30.0µm is wider because they are not too light to be suspended and too heavy to be deposited. The results of the effects of screen porosity on number of particle tracked, escaped and trapped together with detailed indoor surfaces trajectories for the considered particle sizes is presented in tables 12-1 to 12-13 of the appendices section 12.3.1.

The level of dust particle suspension with larger size particles of greater than 40.0µm is low and insignificant as illustrated in figure 9.11. Consequently, since suspended particle are the ones susceptible to human inhalation as they move at the occupancy level, smaller particles of less than 40.0µm have the potential of causing health problems compared to larger size particles.

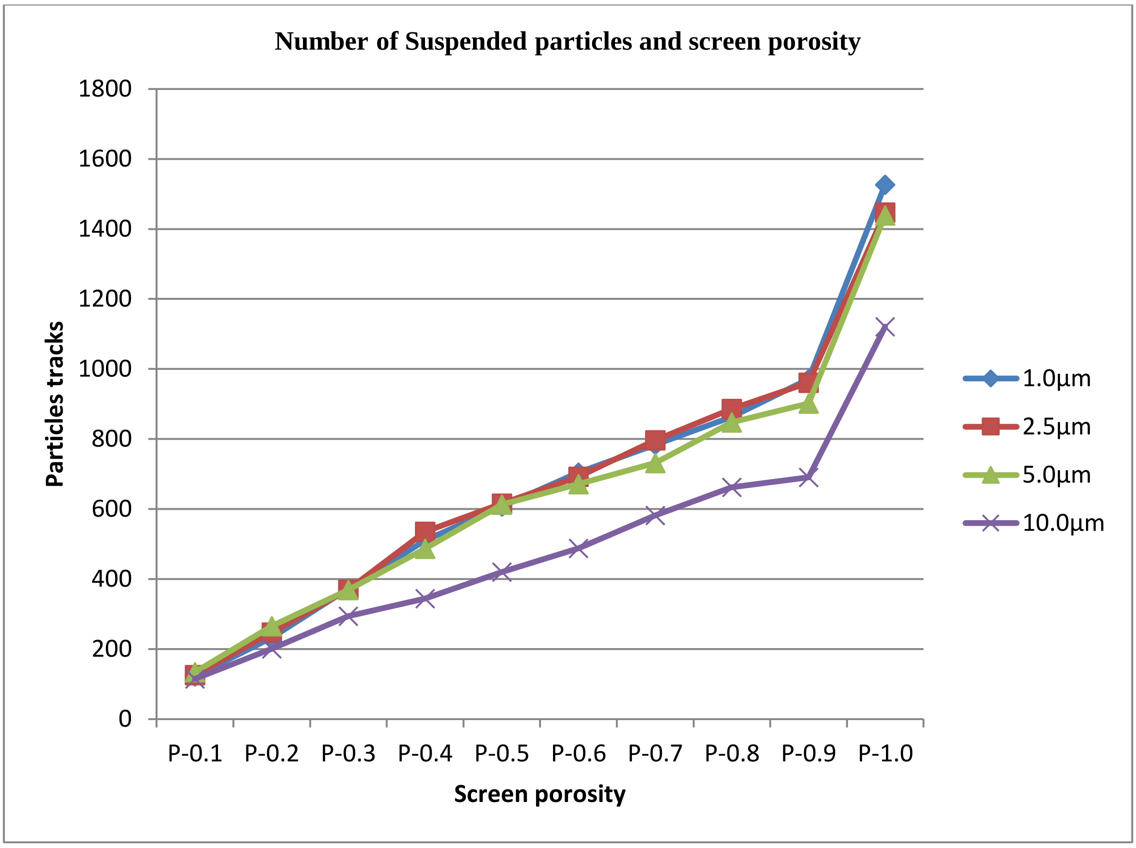


Figure 9.9: The effect of screen porosity and particle size on particle suspension (1µm-10µm)

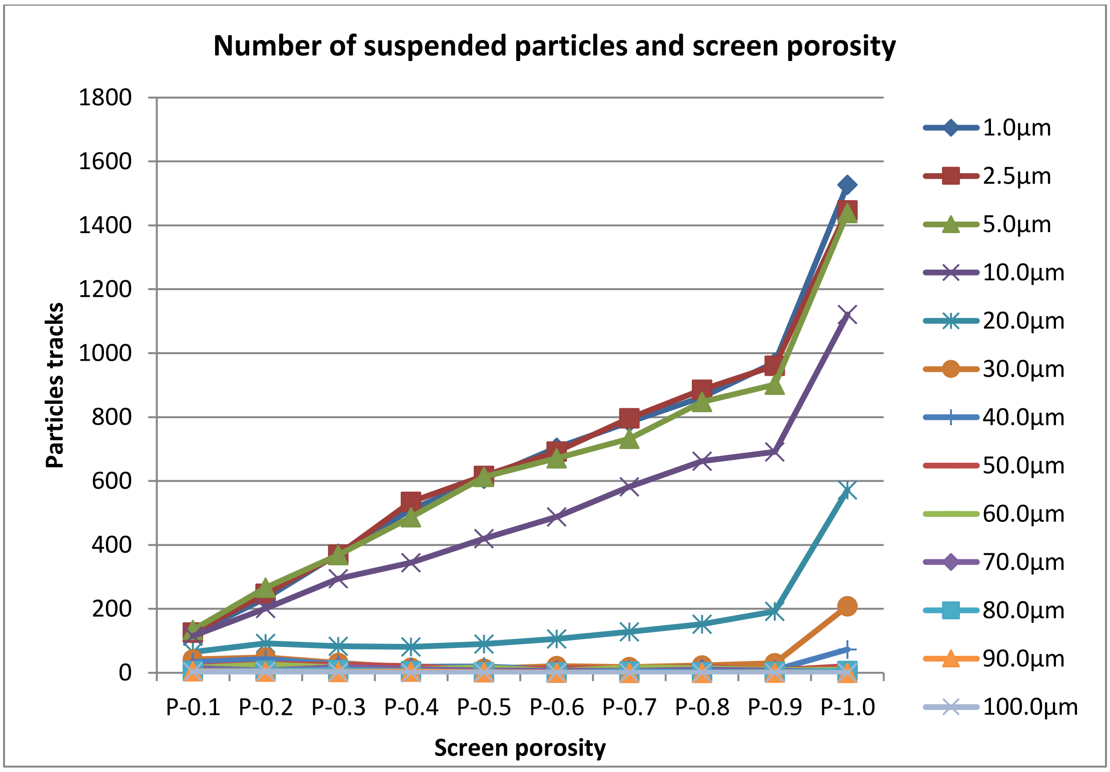


Figure 9.10: The effect of screen porosity on particle suspension for different particle size (1µm-100µm)

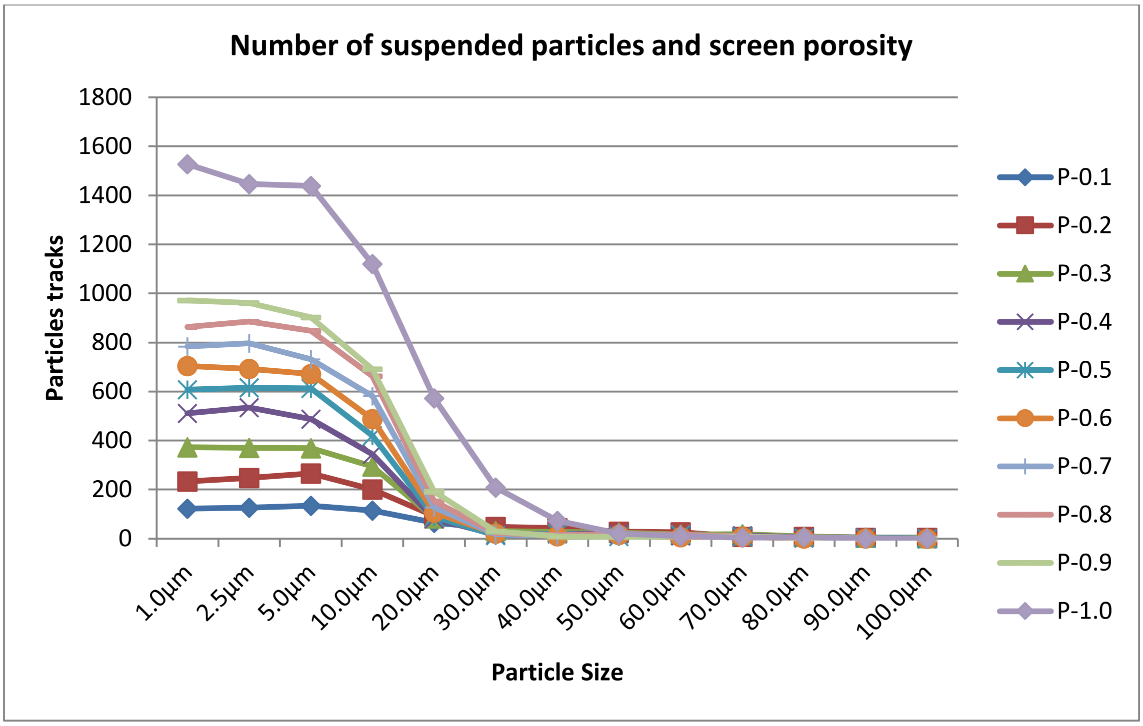


Figure 9.11: The effect of particle size on particle suspension for different screen porosity (1µm-100µm)

9.6 The effect of outdoor wind speed on dust particles deposition in hospital wards

The effect of outdoor prevailing wind speed on dust particles concentration and deposition in indoor environment of hospital multi-bed ward has been simulated and analysed. Outdoor wind speeds ranging from 1m/s to 7m/s (airport values) have been used in simulating different particle sizes of 1.0µm, 2.5µm, 5.0µm 10.0µm, 20.0µm, 30.0µm, 40.0µm, 50.0µm, 60.0µm, 70.0µm, 80.0µm, 90.0µm and 100.0µm. The simulation was conducted using an insect screen porosity of 0.66. The results show that the concentration of particles in the room increases with growing outdoor wind speed as illustrated in figure 9.12 and 9.13. The difference between particle sizes is insignificant with smaller particle size. However, the difference in terms of particle size is more pronounced with larger particle sizes of greater than 30.0µm, as illustrated in figure 9.13 and 9.14. The concentration of particle indoors decreases as the particle size increases (see figure 9.14).

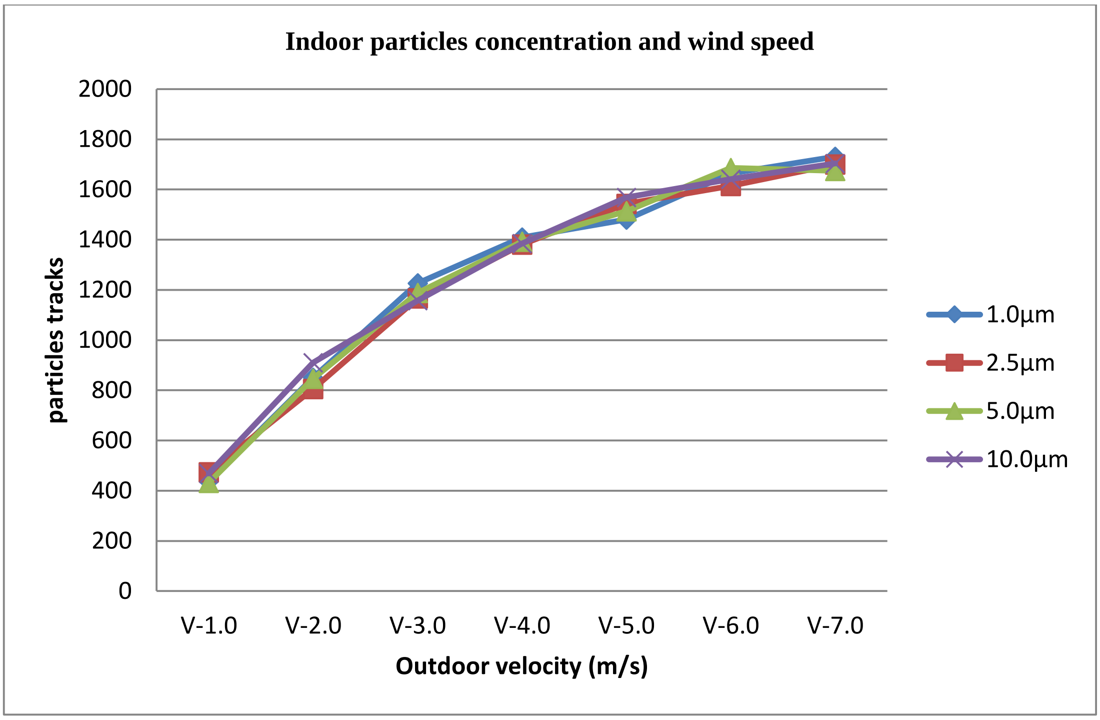


Figure 9.12: The effect of outdoor wind speed on dust particle concentration of different particle sizes (1µm-10µm)

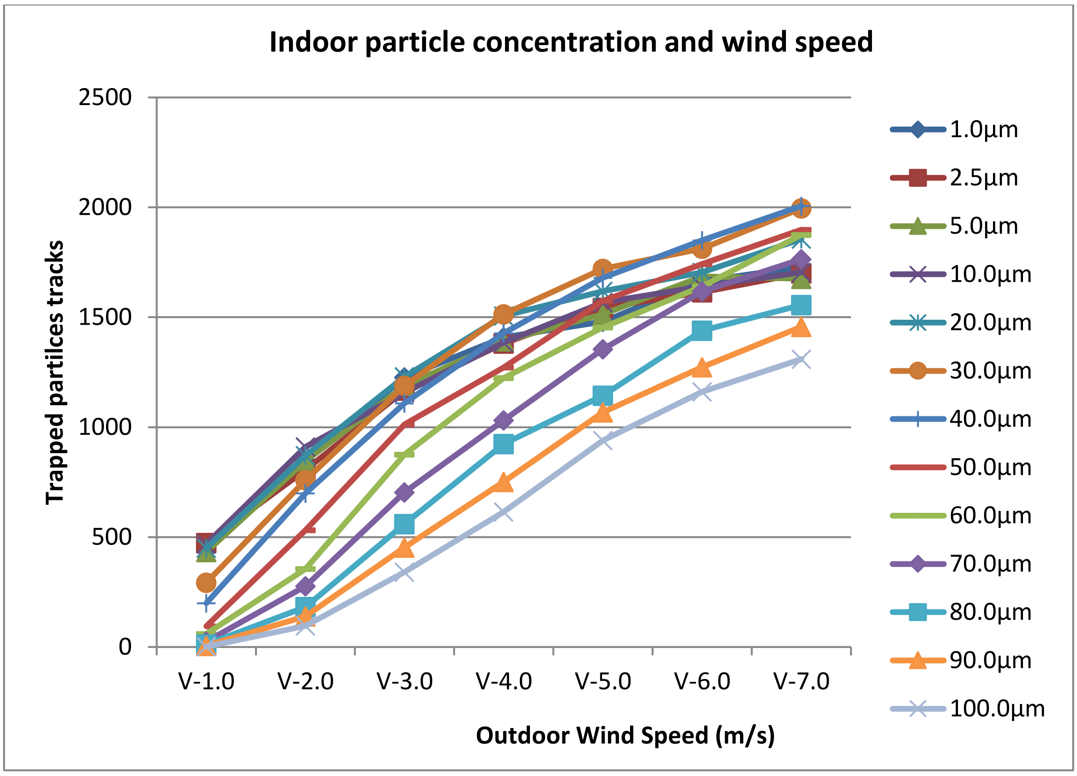


Figure 9.13: The effect of outdoor wind speed on dust particle concentration of different particle sizes (1µm-100µm)

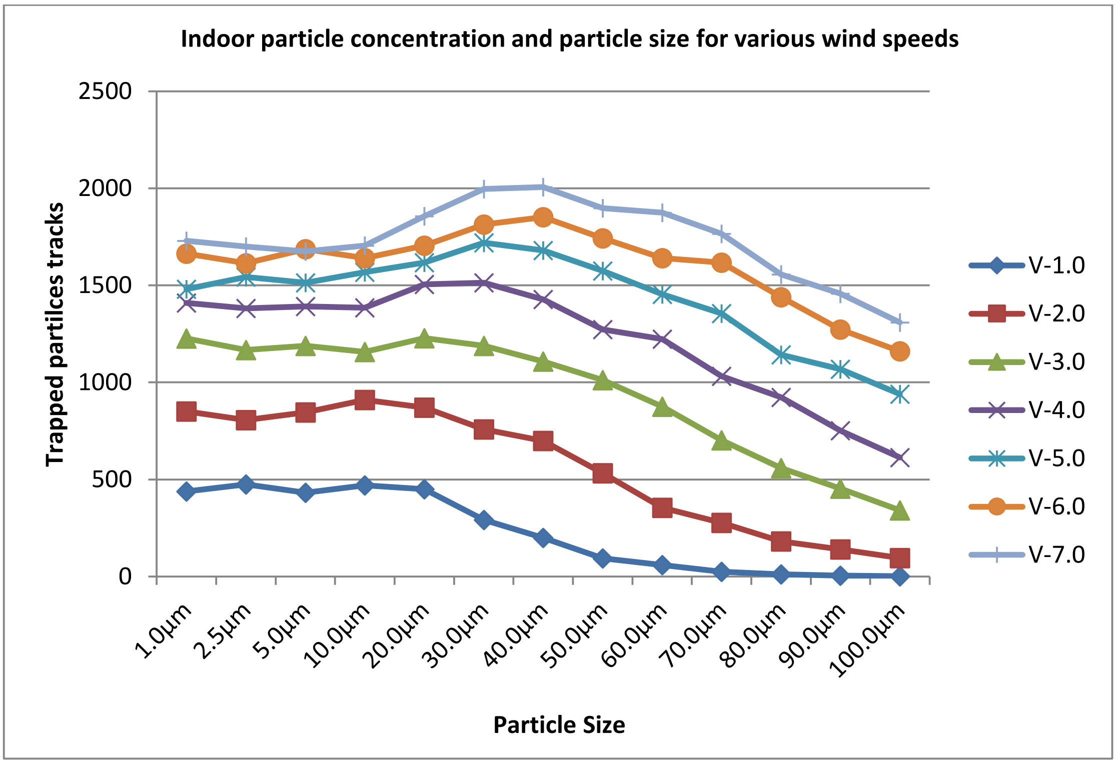


Figure 9.14: The effect of particle sizes on dust particle concentration of different outdoor wind speeds (1µm-100µm)

Similar to the total indoor concentration, the quantity of escaped particles increases with increasing outdoor prevailing wind velocity, as illustrated in figure 9.15 and 9.16. This is because, with lower wind speeds, fewer particles will reach the indoor space and consequently there will be lower particle concentration indoors and hence fewer particles will escape through the outlet openings. But, this situation is not well pronounced with larger particle sizes of greater than 40µm as illustrated in figure 9.16

The effect of particle size on particle escape level is more pronounced with smaller particles of sizes less than 40.0µm as illustrated in figure 9.17. The possible explanation for the above scenario is that, larger size particles are more difficult to penetrate and escape through the outlet openings, when the indoor air speed has been reduced by the effect of the installed insect screens. Furthermore, the level of escape with larger particle sizes is also affected by the inlet openings with installed insect screen by restricting the amount of particles reaching the indoor environment.

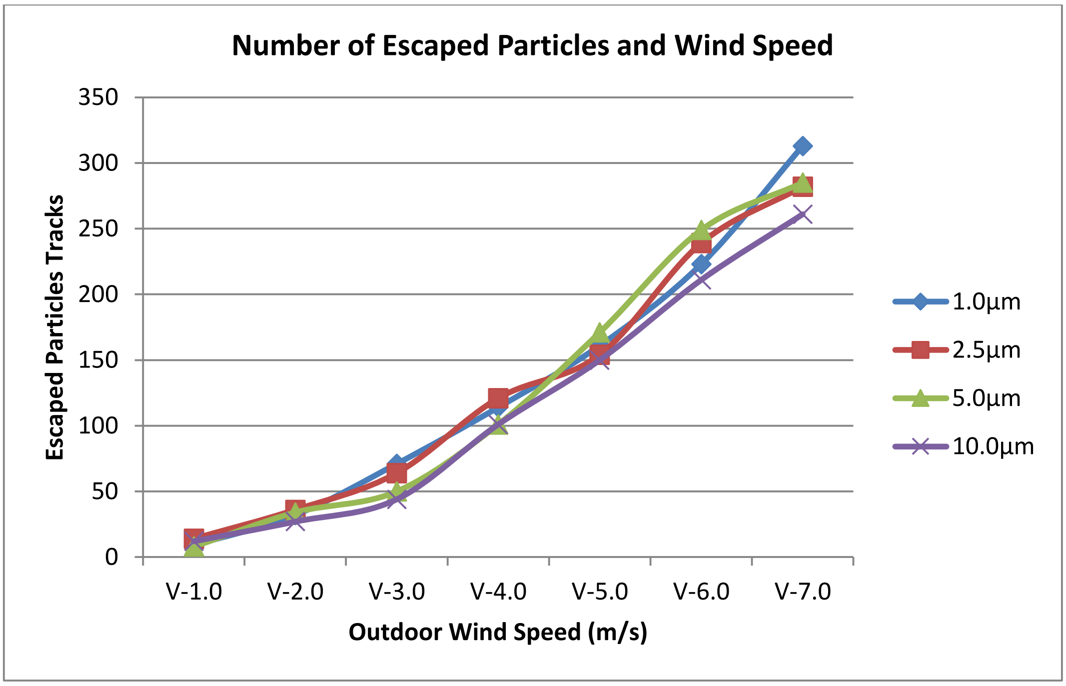


Figure 9.15: The effect of outdoor wind speed on dust particle prevention (escaped particles) of different particle sizes (1µm-10µm)

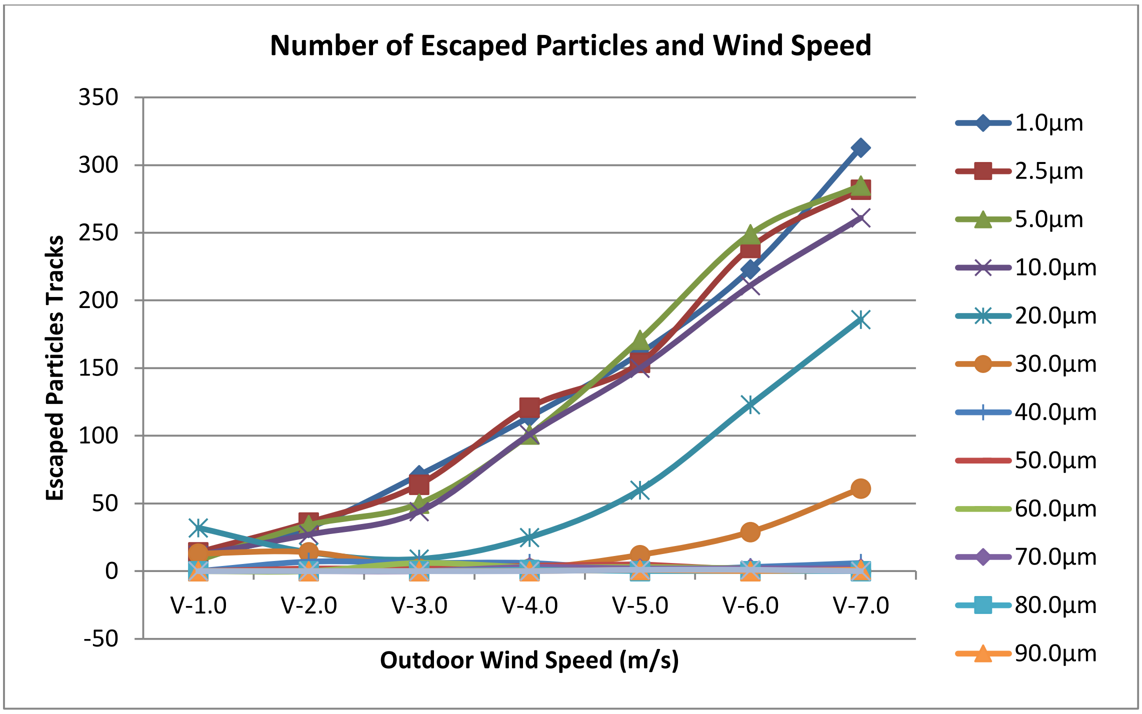


Figure 9.16: The effect of outdoor wind speed on dust particle prevention (escaped particles) of different particle sizes (1µm-100µm)

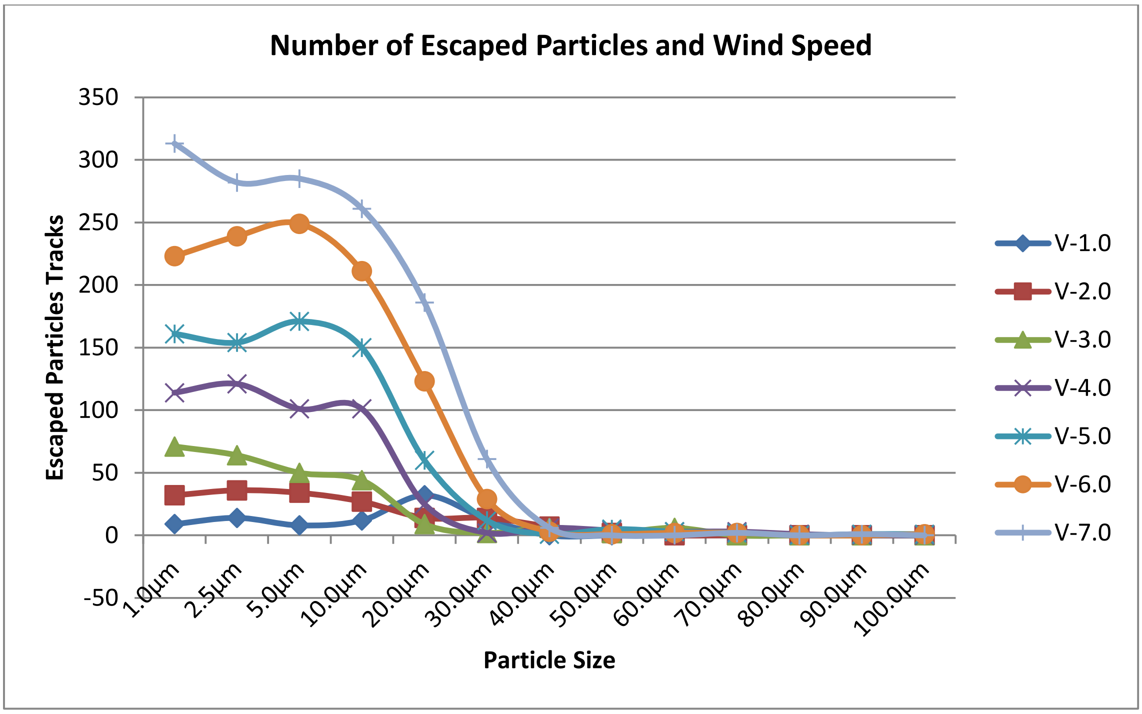


Figure 9.17: The effect of particle sizes on dust particle prevention (escaped particles) of different outdoor wind speed (1µm-100µm)

Likewise, the study also indicated that dust particle deposition increases with growing outdoor wind speed. However, the deposition level is higher with larger size particles compared to smaller size particles as illustrated in figure 9.18, 9.19 and 9.20. It can be observed from the result that there is a significant difference in deposition level between particles of different sizes. This difference is insignificant with particle sizes of less than 5.0µm, but considerable with larger particle sizes as illustrated in figures 9.18, 9.19 and

9.20. Therefore, both outdoor wind speed and particle size are influential factors in determining particle deposition characteristics in indoor environment.

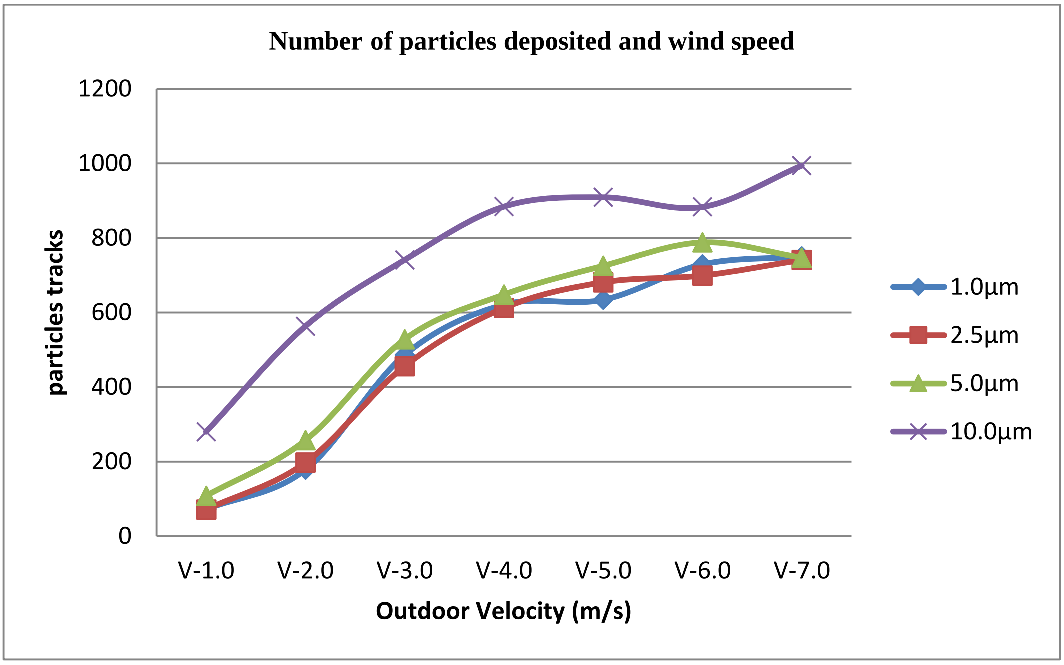


Figure 9.18: The effect of outdoor wind speed on dust particle deposition of different particle sizes (1µm-10µm)

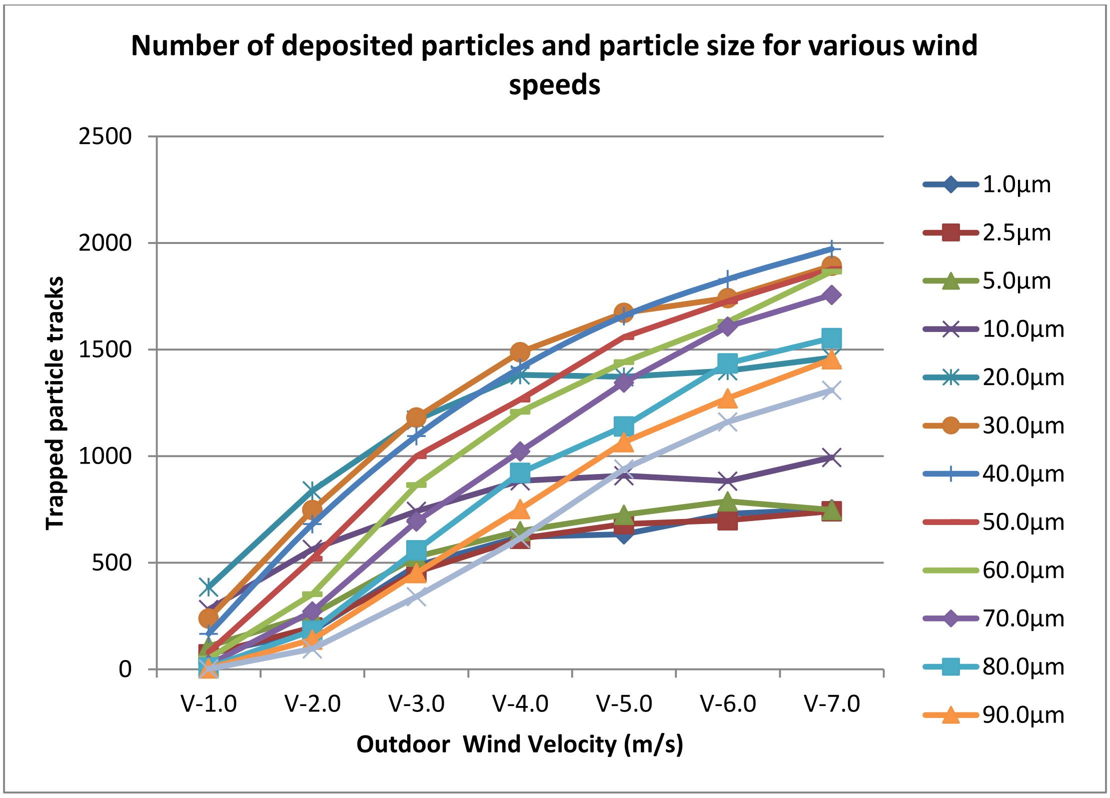


Figure 9.19: The effect of outdoor wind speed on dust particle deposition of different particle sizes (1µm-100µm)

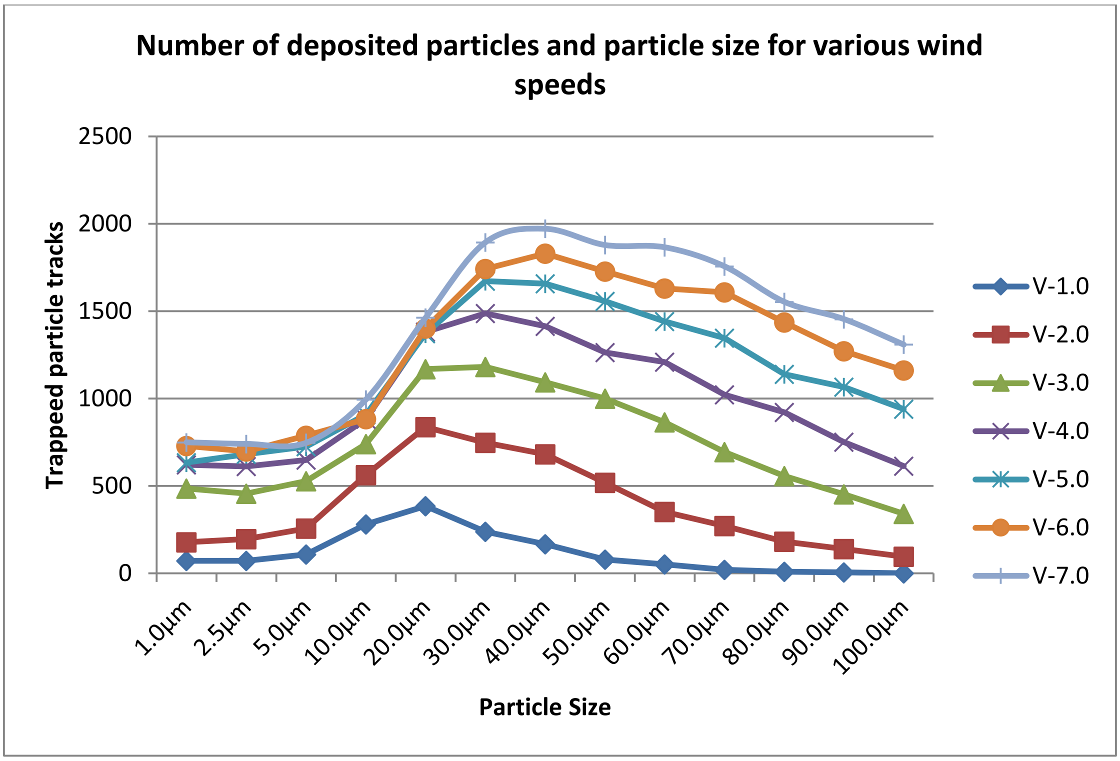


Figure 9.20: The effect of particle sizes on dust particle deposition of different outdoor wind speeds (1µm-100µm)

On the question of the effect of outdoor wind speed on quantity of particles suspended in the indoor environment, this study found that number of suspended particles increases with increasing outdoor wind speeds as illustrated in figure 9.21 and 9.22. According to Béghein et al. (2005) the ventilation situation in buildings influences the percentage of particles suspended in the air in an indoor environment. Moreover, on the effect of particle size on indoor particle suspension, the result revealed that number of suspended particles decreases with growing particle size. This could be observed from figures 9.21, 9.22 and 9.23 that, with larger size particles greater than 40µm size, the level of dust particle suspension is insignificant with all the wind speed levels simulated. The results of the effects of outdoor wind speed on number of particle tracked, escaped and trapped together with detailed indoor wall surfaces trajectories for all the considered particle sizes is presented in tables 12-14 to 12-26 of the appendices section 12.3.2.

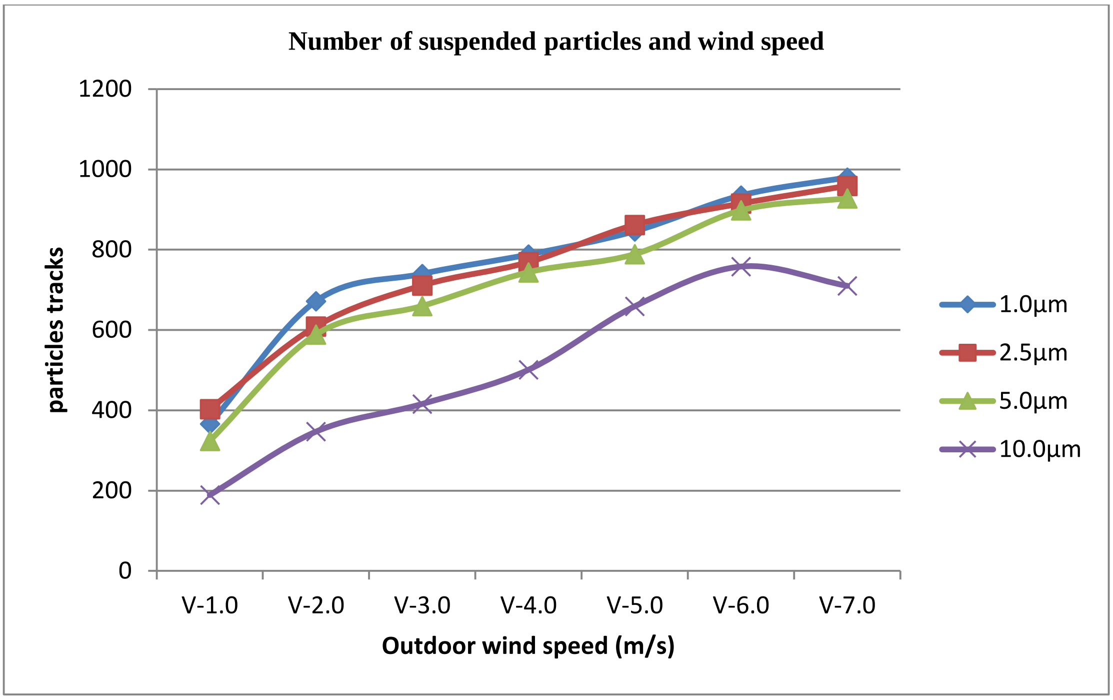


Figure 9.21: The effect of outdoor wind speed on dust particle suspension of different particle sizes (1µm-10µm)

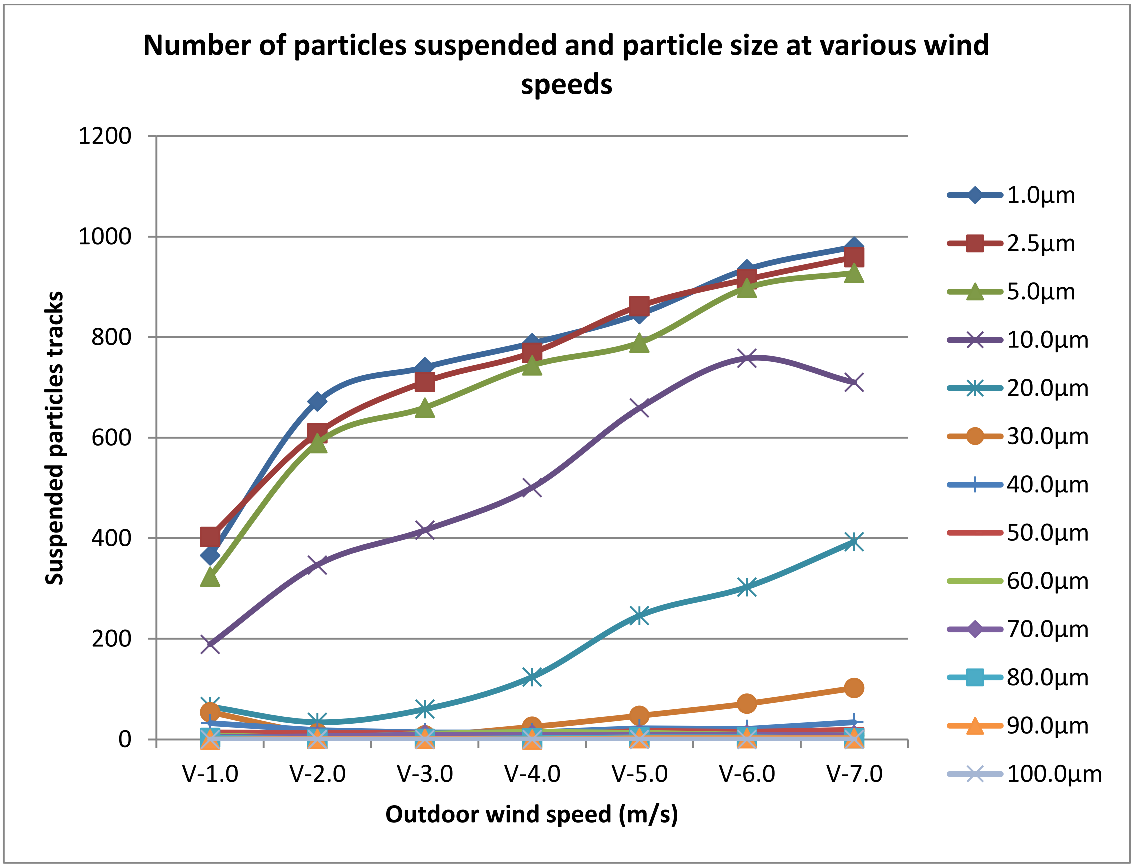


Figure 9.22: The effect of outdoor wind speed on dust particle suspension of different particle sizes (1µm-100µm)

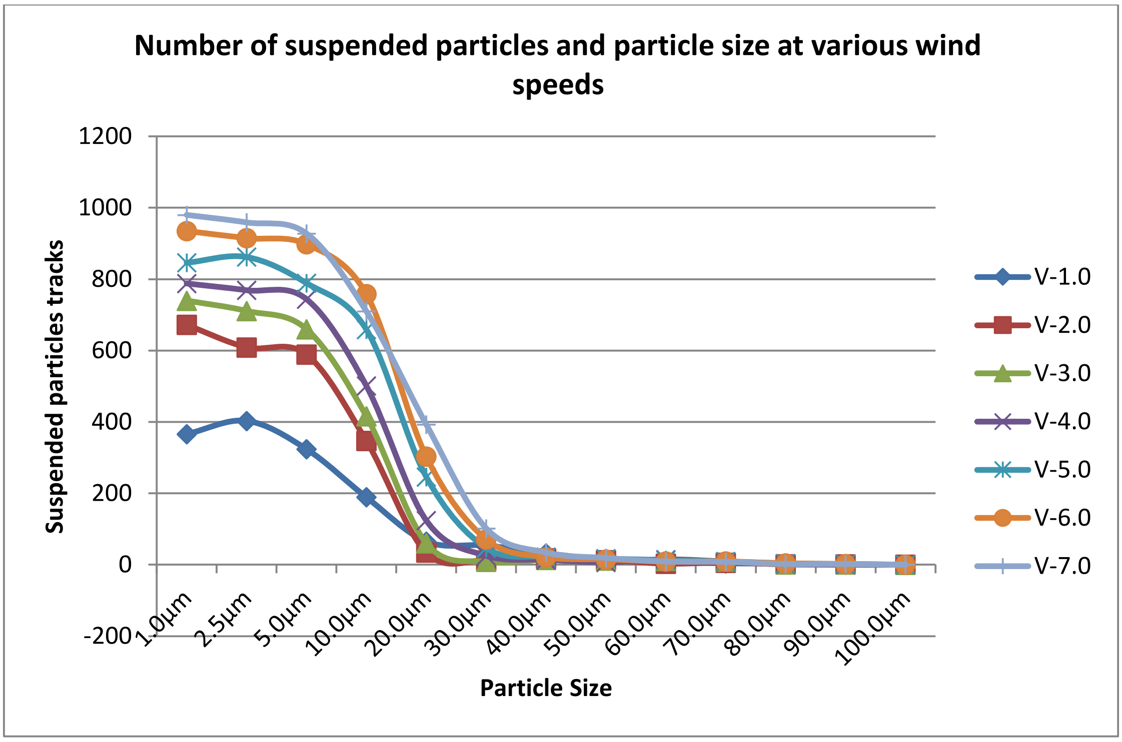


Figure 9.23: The effect of particle sizes on dust particle suspension of different outdoor wind speed (1µm-100µm)

9.7 The effect of plenum on dust particles concentration and deposition in hospital wards

There are many factors affecting particles movement in ventilated rooms including; airflow pattern, particle properties, geometry configurations, ventilation rates, supply and exhaust locations, internal partitions, thermal buoyancy etc. (Zhao et al. 2004a). In the present research, the influence of providing plenums on dust particle penetration to the interior part of the wards has been studied. Three different cases have been considered for the simulation including case 18 with one plenum at the windward side of the ward; case 19 with two plenums at the windward and leeward sides of the ward and case 20, which is the same with case 19 but the roof openings are included inside the leeward side plenum. The plenums have 2.0m width and its height is the same with the ward, as illustrated in table 9-2. The insect screens are moved away from the window openings and positioned on the plenum opening. The simulation was conducted using an insect screen porosity of 0.66. The result shows that, dust particle concentration indoors increases with increasing airflow rates and air change rates. Lu et al. (1996) in their research also reported that, particle deposition, exchange and extraction rates increases with growing ventilation rates in indoor environment. The volumetric flow rates of individual openings and the total volumetric flow rates of the wards simulated are shown in table 9-1. According to Zhao et al. (2004a), the movement of particles in ventilated rooms is strongly affected by the airflow pattern. Hence, the particle concentration and deposition rate may vary largely between different types of ventilation, even if the air supply volume and particle properties are the same.

Table 9-1: The Volumetric flow rates of individual openings and total volumetric flow rates of cases 16, 18 and 19

Openings	**Volumetric airflow rates**			
	Case 16	**Case 18**	**Case 19**	**Case 20**
W_Screen_1	-0.42	0.79	0.98	1.01
W_Screen_2	-0.44	0.79	0.98	1.00
W_Screen_3	-0.44	0.79	0.98	1.00
W_Screen_4	-0.42	0.79	0.98	1.01
W_Screen_5	0.23	0.40	-0.65	-0.48
W_Screen_6	0.19	0.38	-0.67	-0.54
W_Screen_7	0.19	0.38	-0.67	-0.54
W_Screen_8	0.23	0.40	-0.65	-0.48
W_Screen_9	0.22	0.40	0.32	-0.47
W_Screen_10	0.22	0.40	0.32	-0.52
W_Screen_11	0.22	0.40	0.32	-0.52
W_Screen_12	0.22	0.40	0.32	-0.47
Volumetric airflow rates	**1.72**	**3.16**	**3.92**	**4.02**

The results further indicate that, the introduction of plenum to the windward (Case_18) resulted in 83.7% increase in air change rates; establishment of plenums to both the windward and leeward sides of the ward (Case_19) resulted in 127.9% increase in air change rate; and the inclusion of the roof openings into the leeward plenum (Case_20) resulted in 133.7% increase in air change rate compared to the case without plenum (Case 16). The air change rates obtained in cases 18, 19 and 20 are far above the ASHREA standard requirement of 6 ach^{-1} in patient rooms. Table 9-2 presents different indoor airflow parameters and comparative analysis of cases 18, 19 and 20 with the case without plenum (Case_16). Likewise, the average indoor air speed also followed the same pattern with the air change rate. The indoor air speed is higher in case 20 and followed by case 19, and then case 18, while the case without plenum (Case 16) has the lowest air speed as shown in table 9-2.

Therefore, based on the above results, the possibility of achieving acceptable indoor air quality with low outdoor wind speed, and lower insect screen porosity is high. This is coupled with the finding in this research that, dust particle concentration in indoor environment decreases with deceasing screen porosity. Hence, for effective reduction of dust particles concentration indoors, the opening screen porosity in cases 19 and 20 could be reduced from the present value of 0.66 to lower value without compromising air quality standards of 6 ach^{-1} air change rates in patient rooms as enshrined in ASHRAE standard.

Moreover, the introduction of plenums (cases 18, 19 and 20) has effectively improved the airflow distribution in the simulated hospital multi-bed ward compared to the case without plenums (case 16). Table 9-3 illustrates the horizontal and vertical sections of velocity magnitude at 1.0m and 0.6 m occupancy levels and 3D velocity streamline of the room volume.

Table 9-2; Indoor air flow characteristics of ventilation strategies with and without plenums

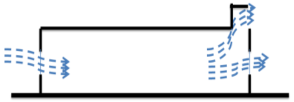
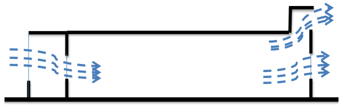
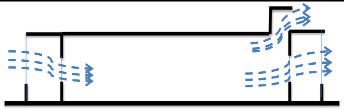
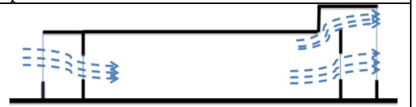
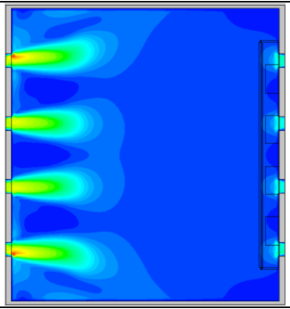
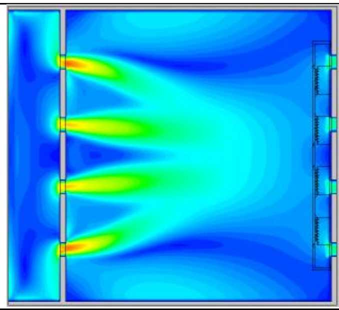
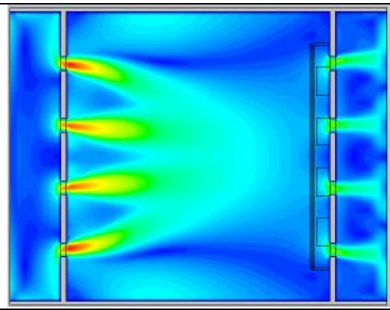
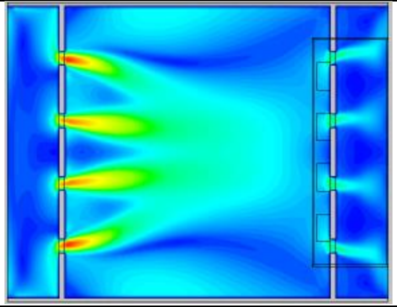
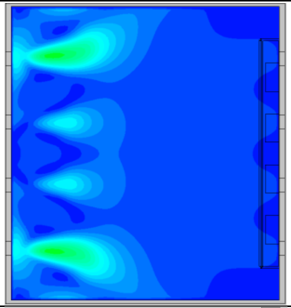
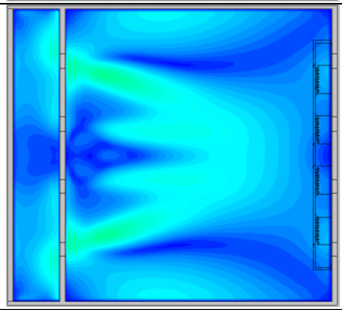
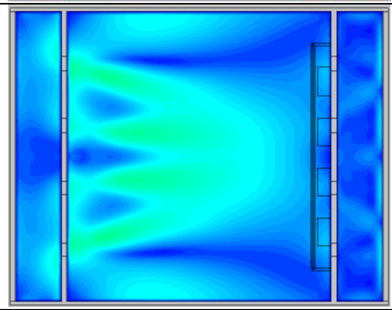
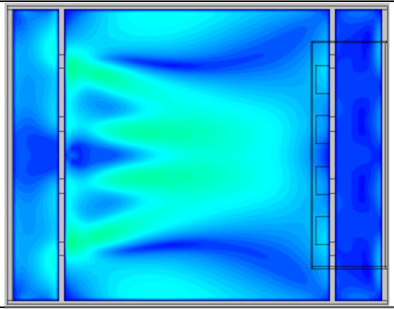
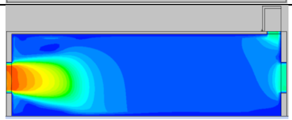
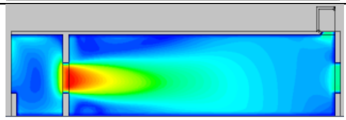
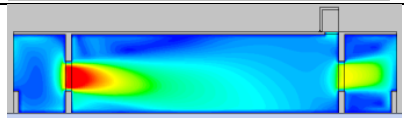
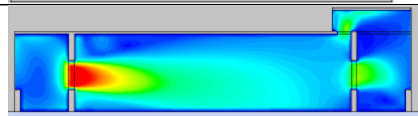
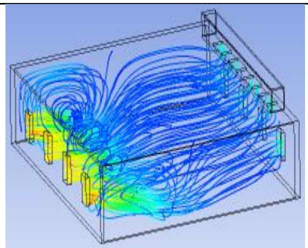
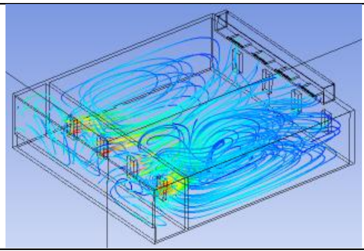
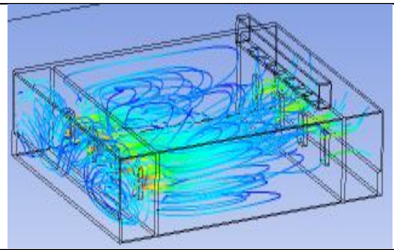
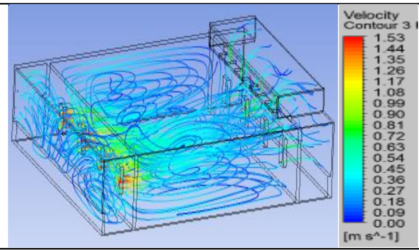
Cases	**Case 16**	**Case 18**	**Case 19**	**Case 20**
Description	Inlet centre & outlet both roof and leeward wall	Case 16 with plenum at the wind ward side	Case 16 with plenum at both windward and leeward sides	Case 19 with roof windows inside the plenum box
Diagram				
Volumetric airflow rates	1.72	3.16	3.92	4.02
Air change rates (ACR) ach^{-1}	13.55	24.89	30.88	31.67
% Increase in ACR on case 16	0%	83.7%	127.9%	133.7%
Average indoor air velocity	0.069	0.219	0.265	0.294
Average indoor turbulent intensity	4.0	4.1	4.7	4.34%
Average indoor air temperature	27.5	27.6	27.6	27.6

Table 9-3: Contours showing airflow pattern (Velocity magnitude) and 3D streamlines of cases 16, 18 and 19.

Cases	**Case 16**	**Case 18**	**Case 19**	**Case 20**
Description	Inlet centre & outlet both roof and leeward wall	Case 16 with plenum at the wind ward side	Case 16 with plenum at both windward and leeward sides	Case 19 with roof windows inside the plenum box
Horizontal Section – Velocity Magnitude (1.0m)				
Horizontal Section – Velocity Magnitude (0.6 m)				
Vertical section of the Velocity Magnitude				
3D Streamline of the Velocity Magnitude				

The simulation results also indicated that, the dust particle concentration in the simulated hospital multi-bed ward decreased with the introduction of single plenum at the windward side of the ward (Case_18) and double plenums at both windward and leeward sides (Case_19 and 20) of the ward. However, the reduction in particle concentration compared to case 16 is higher in the Case_18 with single plenum, compared to both Cases 19 and 20, with double plenums as illustrated in figure 9.24 and 9.25. This is due to the effect of airflow rate or air change rate on dust particle concentration indoors. The result shows that, the concentration of dust particles indoors increases with growing airflow rate or air change rate. Lu et al. (1996) in their research also reported that, particle deposition, exchange and extraction rates increases with the growth of ventilation rates in indoor environment.

Furthermore, the dust particle concentration is higher with smaller size particles and lower with larger size particles. The explanation for this condition is that, larger size particles due to their size trapped in the plenums before reaching the inlet openings. The introduction of the plenums with installed insect screen, results in pressure drop within the plenums and subsequently decreasing the indoor air velocity within the plenum and the building. This situation results in settlement of more large size particles due to their size compared to smaller particles within the plenum before reaching the indoor space. Hence, the dust particle concentration indoors is lower with larger size particles compared to smaller size particles as illustrated in figure 9.24 and 9.26. The study also established the percentage of particles trapped (concentration) within the hospital wards.

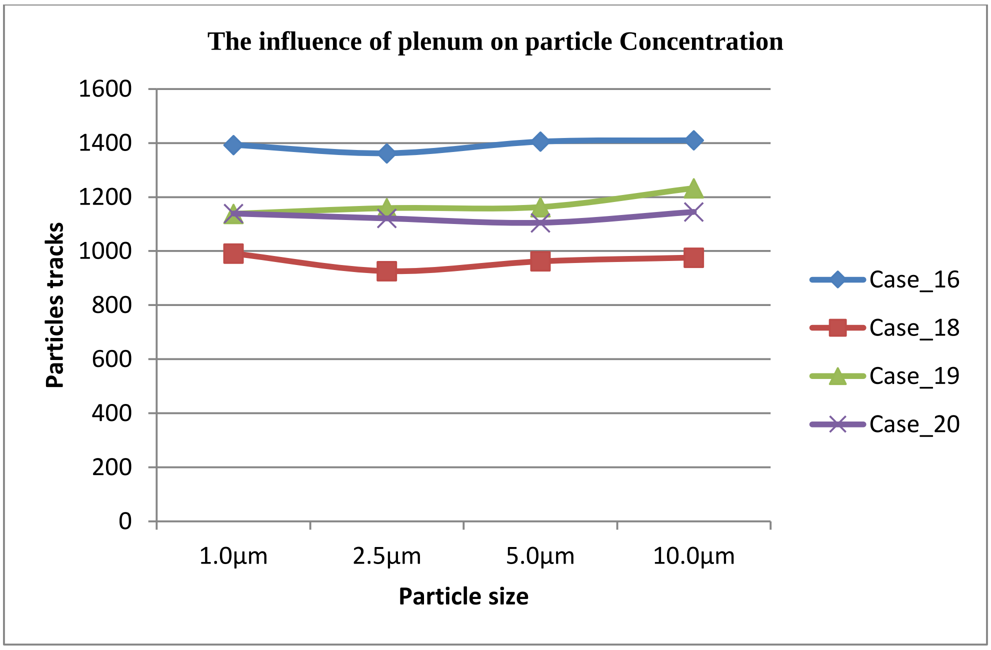


Figure 9.24: The influence of plenum on different sizes of dust particle concentration (1µm-10µm)

The percentage of particles concentration is higher in the case without the plenum (Case 16) and lower in the cases with the plenum (Cases 18, 19 and 20) as illustrated in figures 9.25 and 9.27. Thus, the introduction of plenums in the wards has reduced the amount of Harmattan dust concentration in the hospital wards and hence improves the indoor air quality.

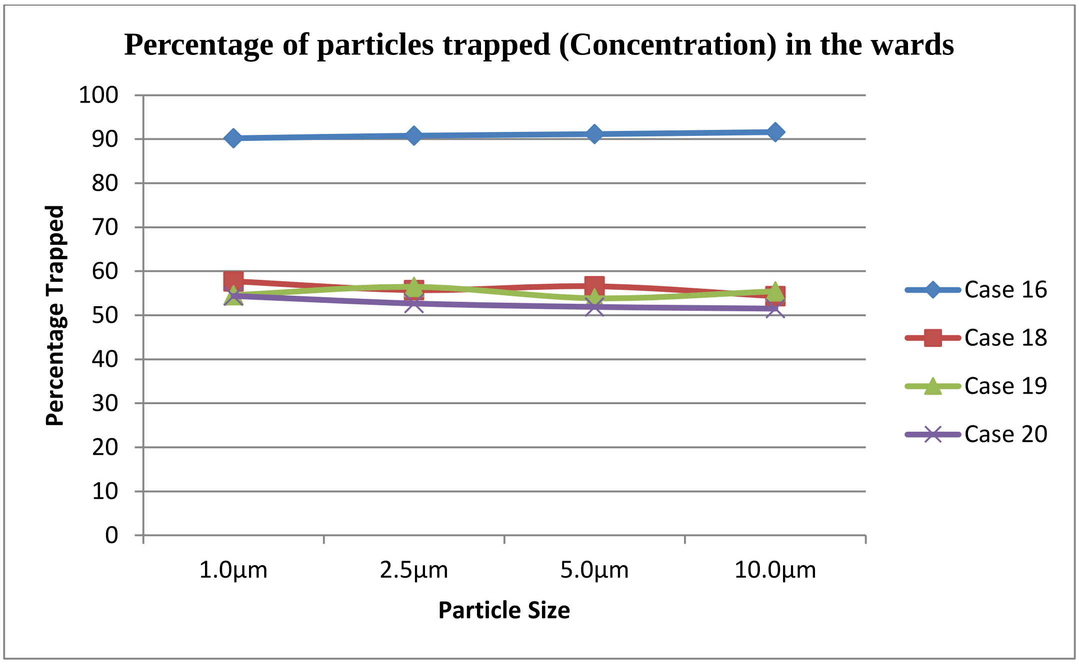


Figure 9.25: The influence of plenum on different sizes of dust particle concentration (1µm-10µm)

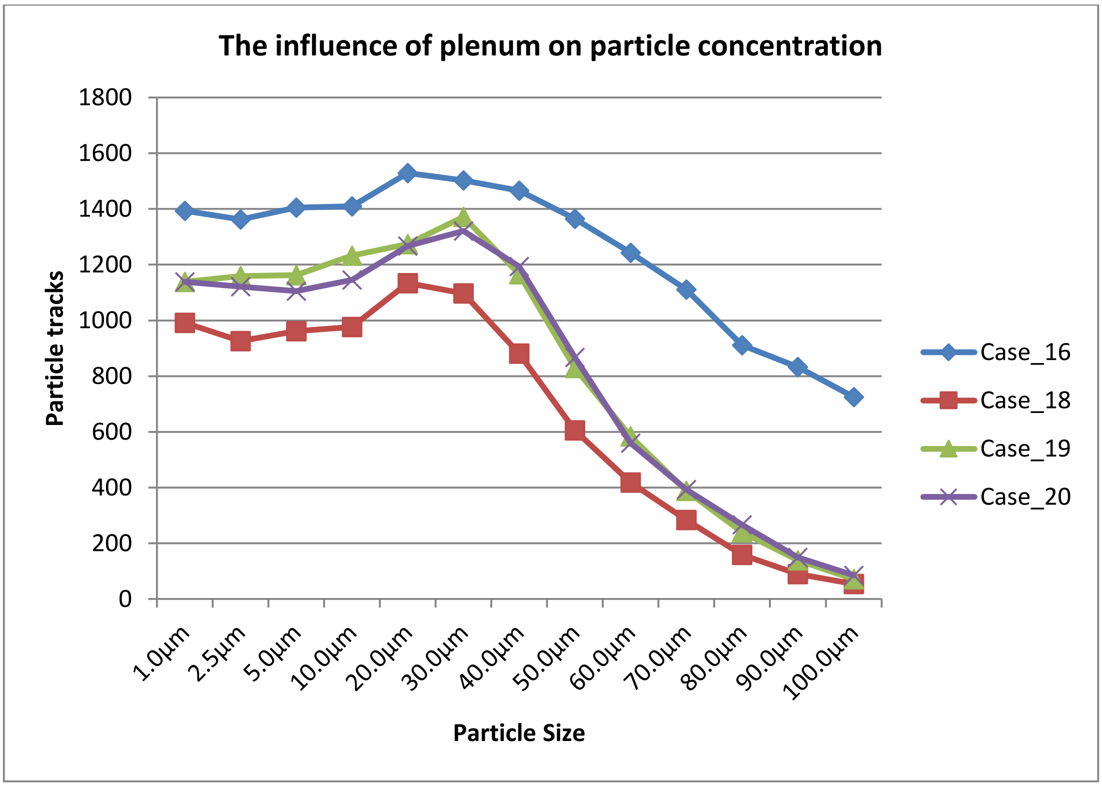


Figure 9.26: The influence of plenum on different sizes of dust particle concentration (1µm-100µm)

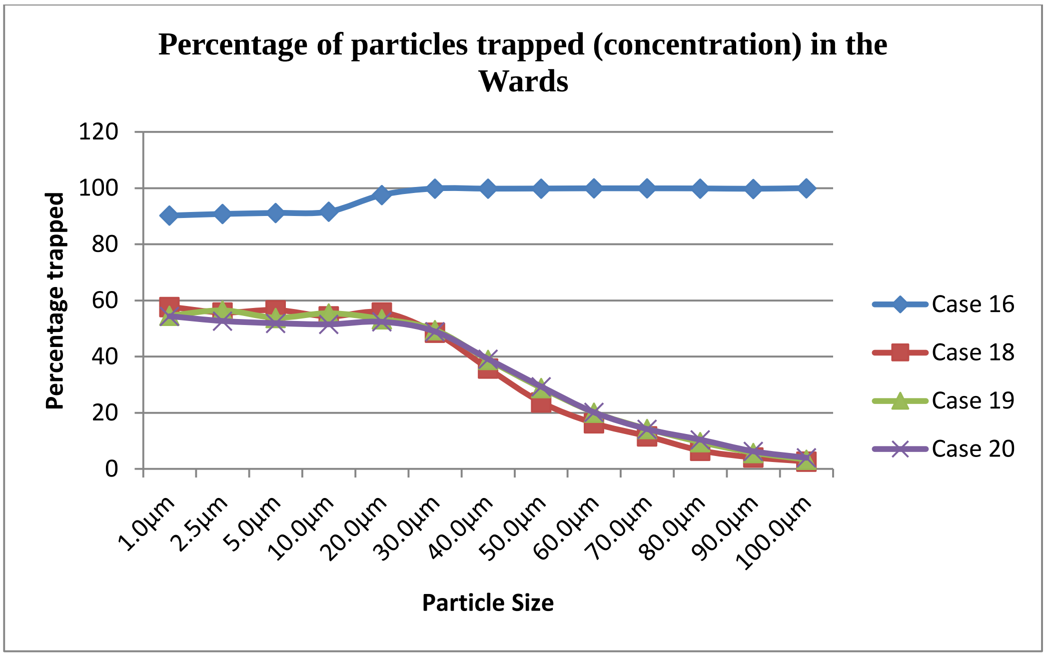


Figure 9.27: The influence of plenum on different sizes of dust particle concentration (1µm-100µm)

In terms of escaped particles through the outlet openings, case 20 has the highest number of escaped particles followed by case 19 and then case 18, while the case without plenum (case 16) has the lowest particle escape rate as illustrated in figure 9.28 and 9.30. The higher the number of particles escaped, the better the ventilation system, because higher escape means lower concentration indoors. Moreover, with smaller particles of sizes ranging from 1.0µm to 20.0µm, the effect of particle sizes on the number of particle escaped is insignificant until particle size of 20.0µm. However, with larger particles of sizes above 20.0µm the number of particles escaped increases with decreasing particle size in all the cases as illustrated in figure 9.28 and 9.30. The decrease in quantity of escaped particles with growing particles size in particle with sizes between 20.0µm to 100.0µm is due to the bigger size of the particle. These types of particle will find it difficult to escape through the outlet openings with installed insect screen due to their larger sizes and reduced indoor air velocity that could not be able to transport them out. However, with smaller size particles it is easy for the particle to leave with lower air velocity.

Tian et al. (2009), in their findings confirmed that, due to the greater influence of gravity on particles of 10µm diameter compared to smaller diameters particles. The particles do not completely follow the airflow paths. Consequently, the escaped particle mass for larger particles (10µm diameter) is smaller than particles of other diameters.

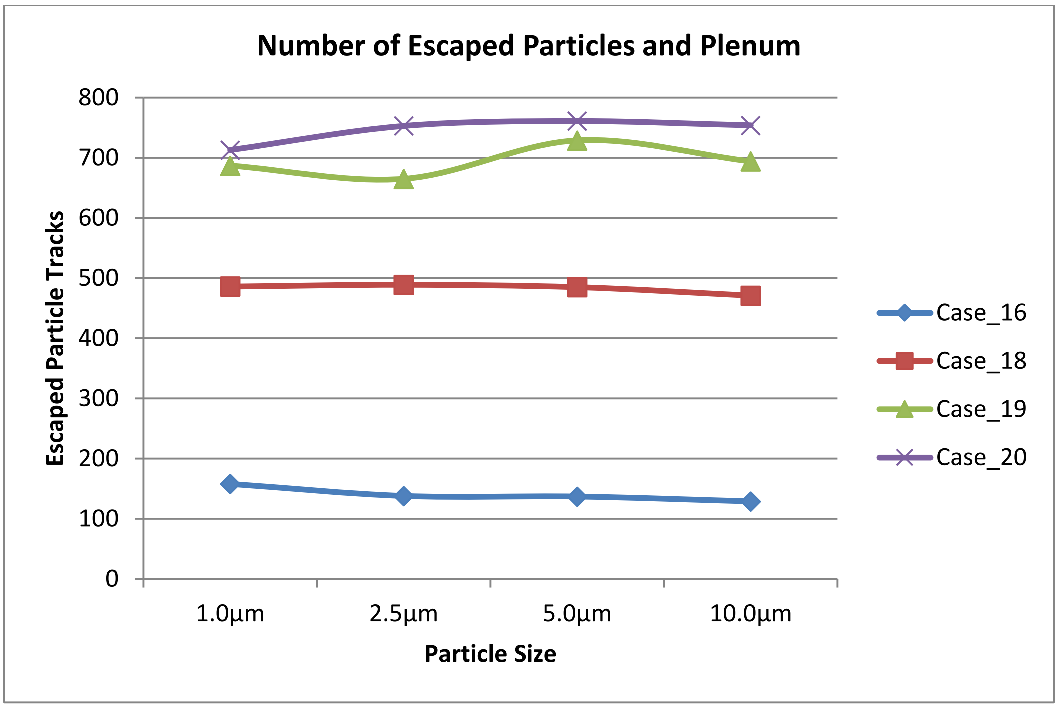


Figure 9.28: The influence of plenum on preventing different sizes of dust particle (1µm-10µm)

The study also investigated the percentage of particle escaped through the outlet openings. The result indicates that, the percentage of particle escaped for the wards is higher in cases with plenum (20, 19 and 18 respectively) and lower in the case without plenum (Case 16) as illustrated in figures 9.29 and 9.31. The percentage of escaped particles is higher with smaller particle sizes compared to larger particles sizes as shown in figure 9.31. Thus, the introduction of plenums to the hospital wards will improve the percentage of particles exhausted through the outlet openings.

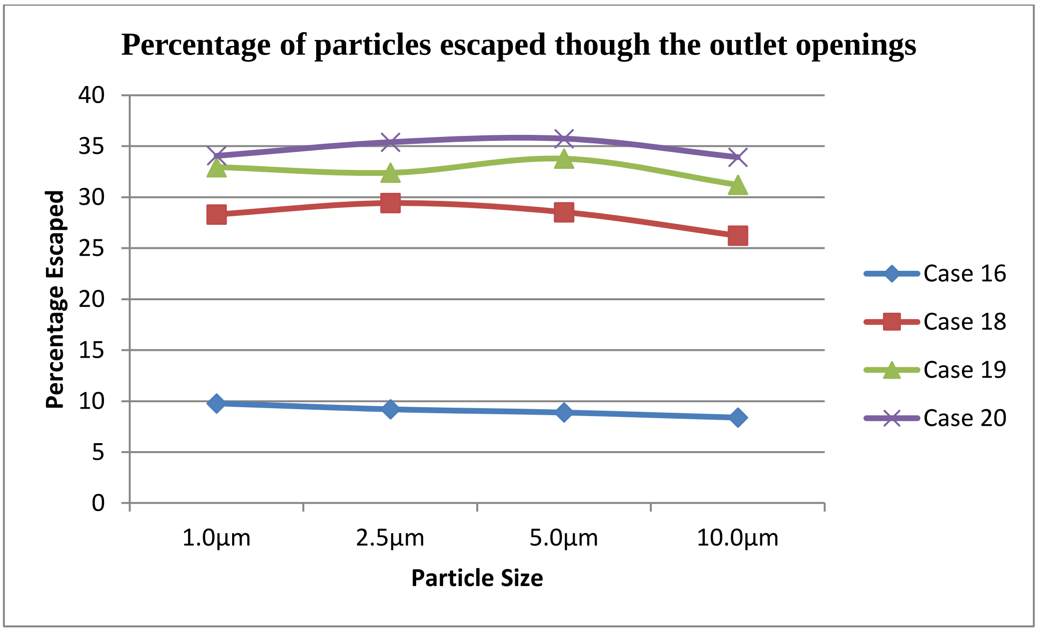


Figure 9.29: The influence of plenum on removing dust particle of different sizes (1µm-10µm)

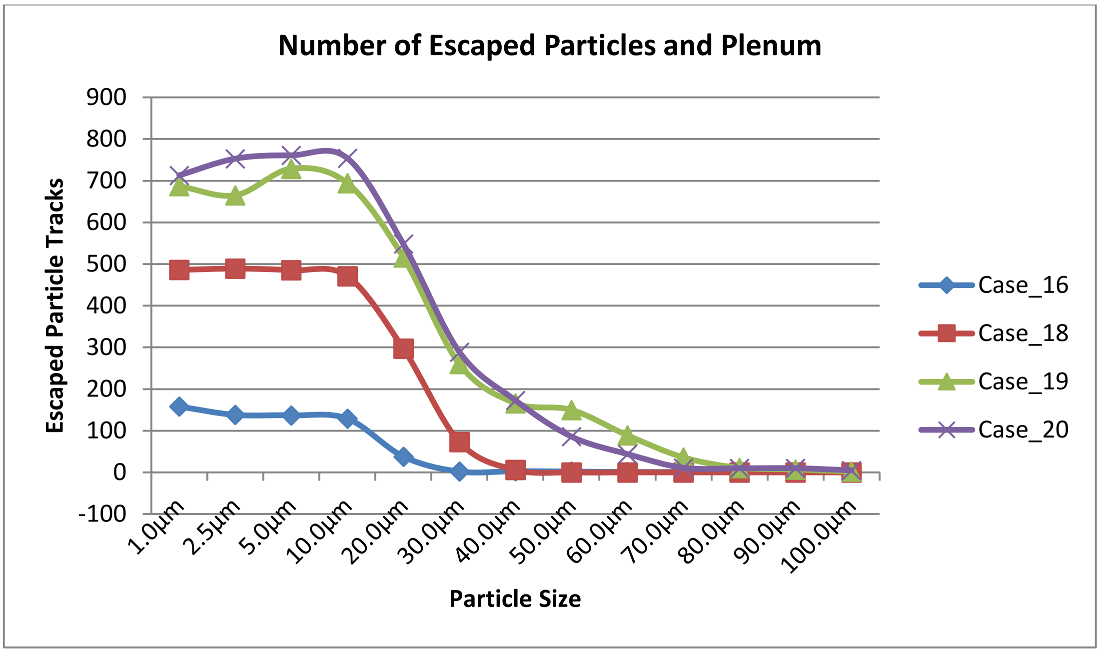


Figure 9.30: The influence of plenum on preventing different sizes of dust particle (1µm-100µm)

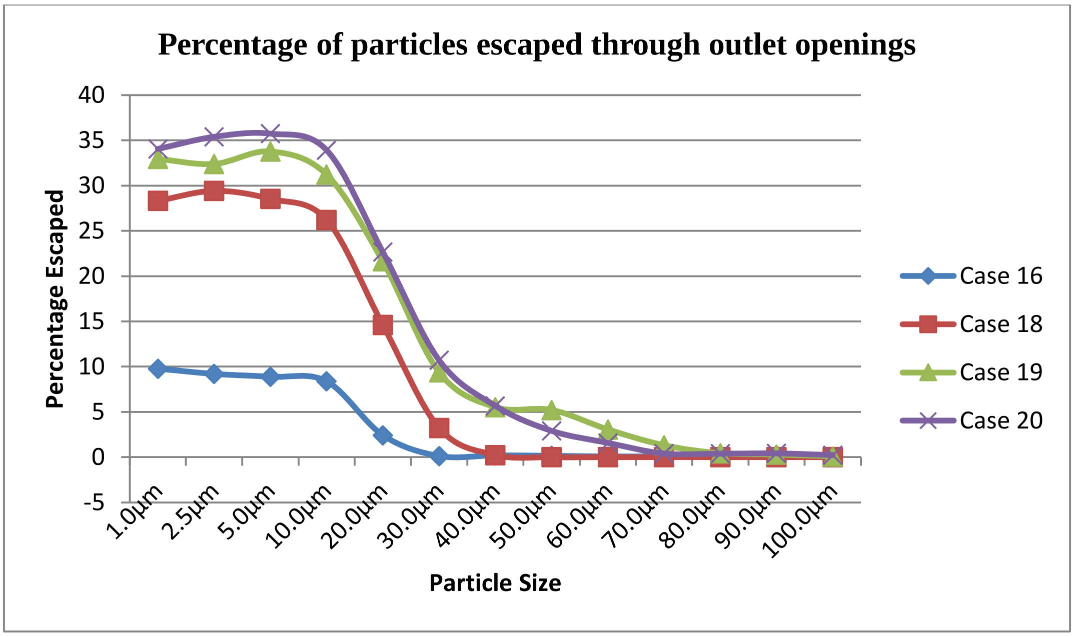


Figure 9.31: The influence of plenum on removing dust particle of different sizes (1µm-100µm)

The influence of introducing plenums on dust particle deposition in the hospital multi-bed ward has been simulated and analysed. The results indicate that, the case without plenum (case 16) has the highest number of deposited particles, and then followed by cases with plenum (Case 18, 19 and 20). Among the cases with plenum, Case 19 has the highest deposition rates, and then followed by case 20 and case 18 has the lowest deposition rate in the wards as illustrated in figures 9.34 and 9.36. Although, Lu et al. (1996) in their research reported that, particle deposition rates increases with the growth of airflow rates in indoor environment. However, this is not the case in this study due to the introduction of plenums in cases 18, 19 and 20, which altered the uniformity of the building configuration compared to the case without plenum (Case 16). The particle deposition rate in cases with double plenums (Cases 19 and 20) is higher than case 18 with single plenum, which is consistent with previous findings in this study. Therefore, the introduction of plenums to the hospital multi-bed wards has decreased the quantity of particles deposited indoors.

Furthermore, the result also shows that, with smaller particles of sizes between 1.0µm to 30.0µm the deposition rates increases with growing particle size. This is because, it is easier for smaller size particles (1.0µm to 30.0µm) to infiltrate the inlet openings with installed insect screen and eventually settles down as the particle size increase up to 30.0µm. However, with larger particle size greater than 30.0µm, the deposition rate decreases with growing particle sizes as shown in figures 9.34 and 9.36. This is because, due to their size, it is difficult for larger size particles of greater than 30.0µm to penetrate through the inlet openings with installed insect screen. Hence, the larger the particle size the fewer the infiltration rates and consequently the lower the deposition rate. This is because larger particles are trapped in the plenum and do not enter the ward/room volume as illustrated in figure 9.32. The percentage of particles deposited on the floor of the plenums before reaching the wards increases with increasing particles size as illustrated in figure 9.33.

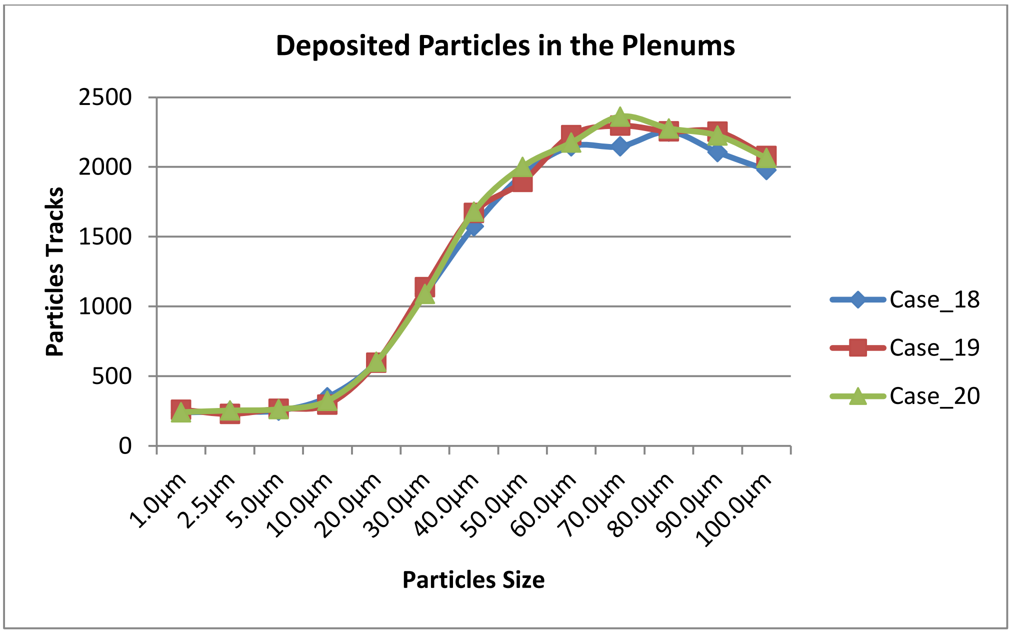


Figure 9.32: Quantity of Particles Deposited in the Windward Plenums

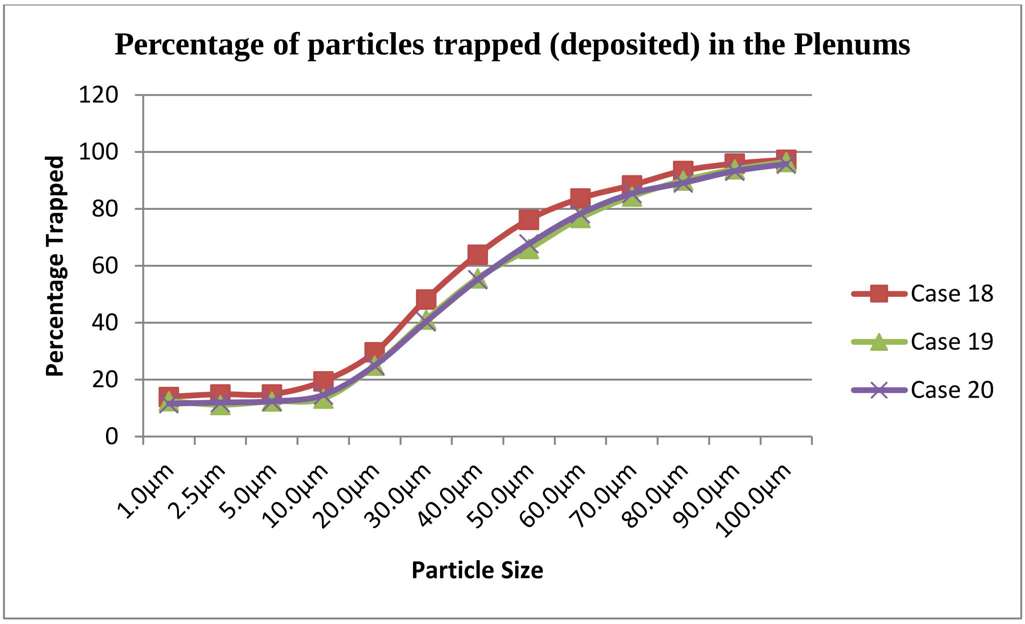


Figure 9.33: Quantity of Particles Deposited in the Windward Plenums

According to Zhao et al. (2004a) as the particle size increases the particle escape rate decreases and the deposition rate increases. But in this study, this assertion is only applicable for particles with sizes less than 30.0µm. The movement and deposition of aerosol particle are largely affected by the particle properties and airflow patterns. The smaller particle movements are influenced by both deposition procedure and airflow pattern while deposition process dominates the movements of the larger particles.

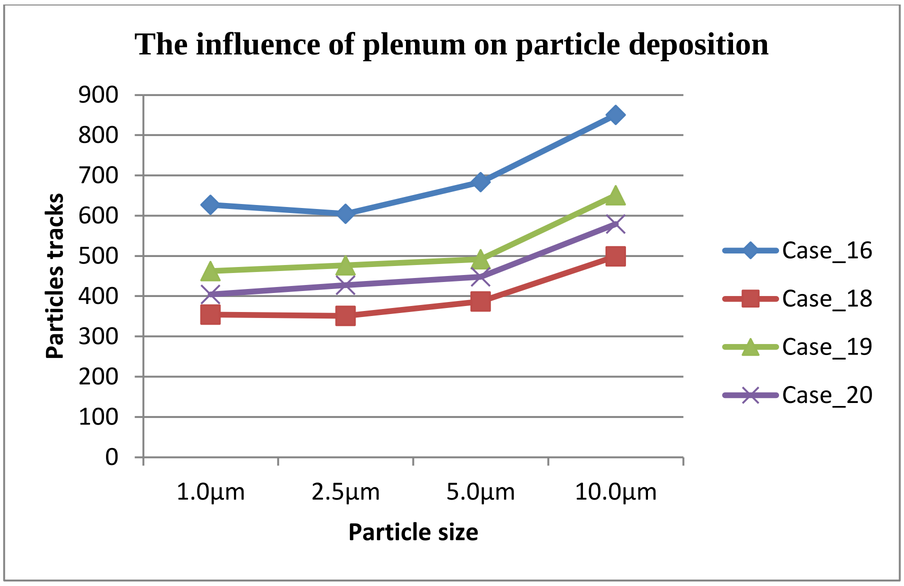


Figure 9.34: The influence of plenum on different sizes of dust particle deposition (1µm-10µm)

With smaller particles sizes of 1.0µm to 30.0µm, the percentage of particles deposited in the wards increases with increasing particle size as illustrated in figures 9.35 and 9.37. But with larger particle sizes of greater than 30.0µm, the percentage of particle deposited in the wards decreases with increasing particle size, especially in the cases with plenums

(18, 19 and 29) as illustrated in figure 9.37. This is because the larger size particles most have been deposited in the plenums before reaching the wards' indoor environment. It could be observed from figure 9.37 that, with larger particles, the effect of particle size on deposition percentage is insignificant in the case without plenum (Case 16).

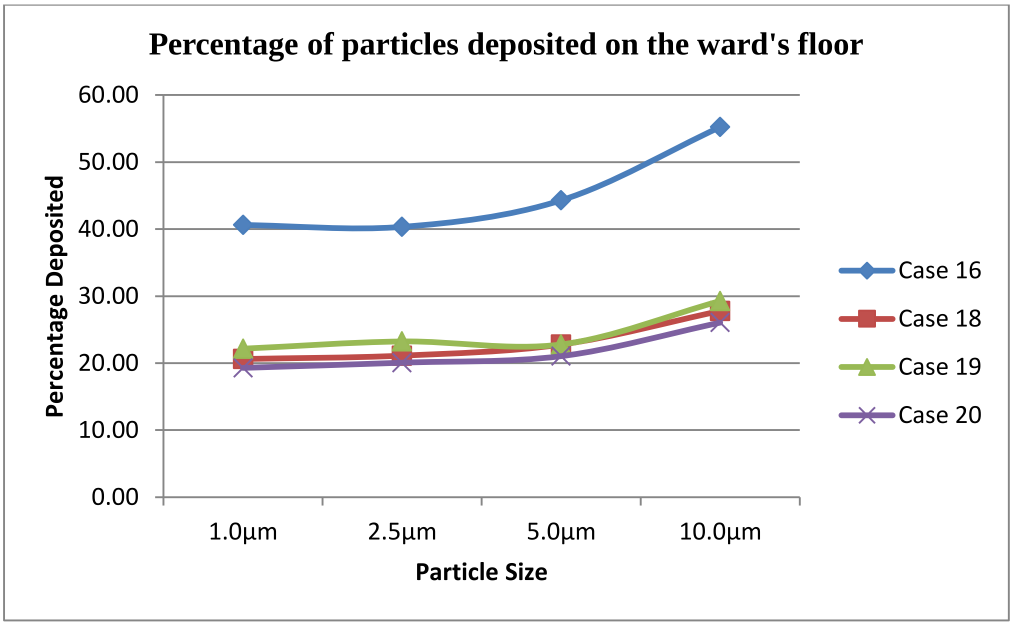


Figure 9.35: The influence of plenum on different sizes of dust particle deposition (1µm-10µm)

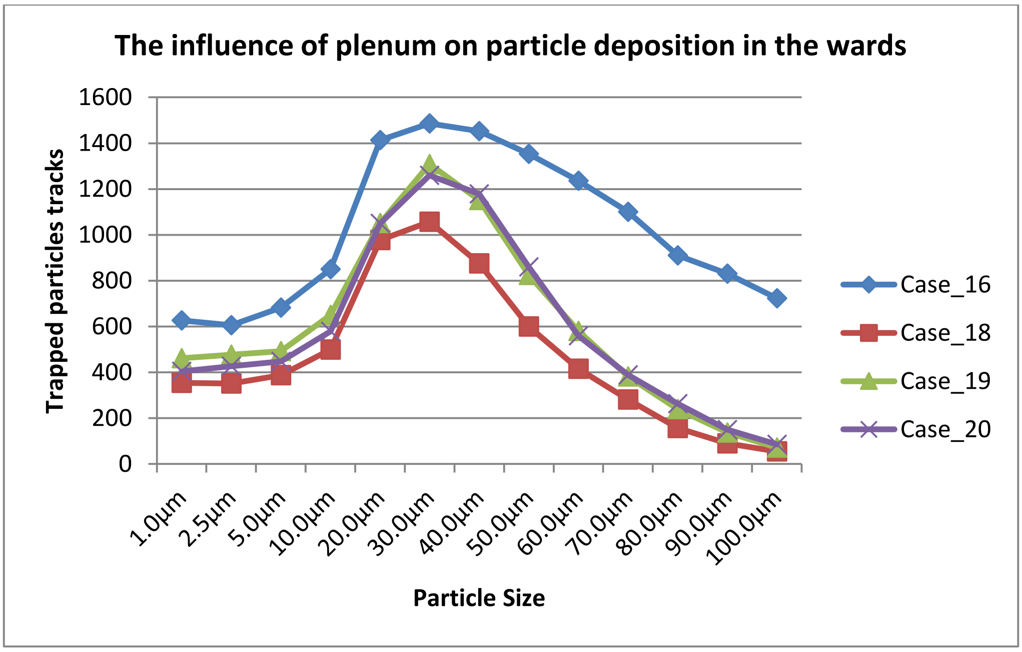


Figure 9.36: The influence of plenum on different sizes of dust particle deposition (1µm-100µm)

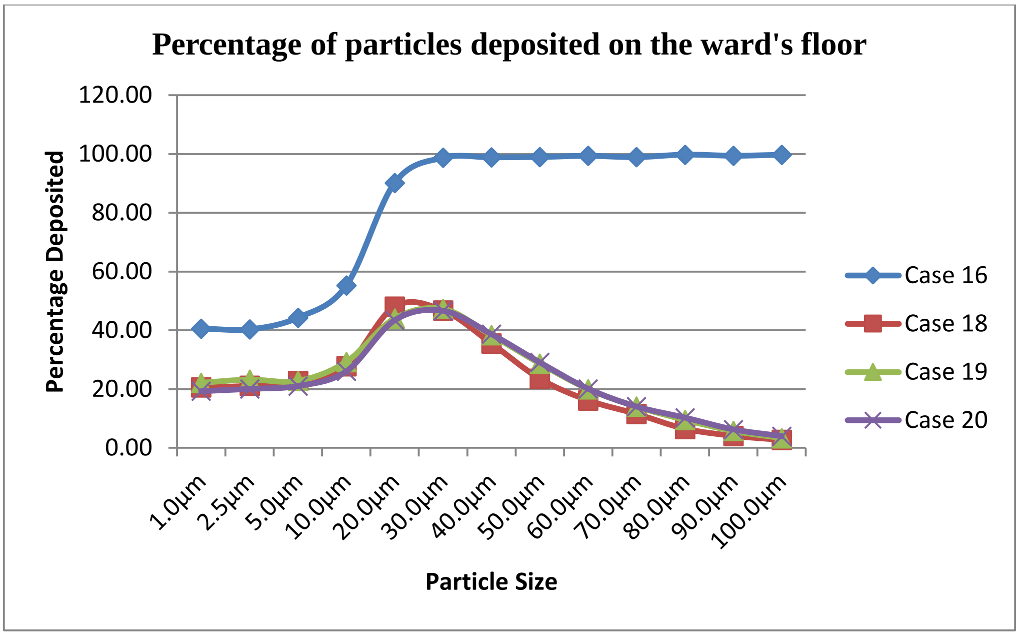


Figure 9.37: The influence of plenum on different sizes of dust particle deposition (1µm-100µm)

The influence of plenums on suspended particles in the hospital multi-bed ward has been studied and analysed. The results revealed that the number of suspended particles is higher in the case without plenum (Case16) and then the cases with plenum (Case 18, 19 and 20) as illustrated in figures 9.38 and 9.40. Among the cases with plenum, case 19 and 20 have the highest suspension rates and the followed by case 18 with the lowest suspension rate. The difference in suspension level between cases 19 and 20 is insignificant. Owing to their sizes, the suspension rate is insignificant with particles of sizes greater than 40.0µm as illustrated in figure 9.40. Consequently, based on the above results and considering the occupancy level in hospital ward which is usually above the floor level, cases with lower suspended particles are the best option for hospital wards. Moreover, the result also indicates that, as the particle size decreases, the quantity of suspended particles increases as illustrated in figure 9.40. This is because smaller particles can easily follow the air movement compared to larger particles (Béghein et al. 2005). Owing to the more time smaller particles spend suspended in ventilated spaces, their influence on the pollutant concentration and indoor air quality is considerable (Lu et al. 1996). The results of the effects of plenums on number of particle tracked, escaped and trapped together with detailed indoor wall surfaces trajectories for the considered particle sizes is presented in tables 12-27 to 12.32 of the appendices section 12.3.3.

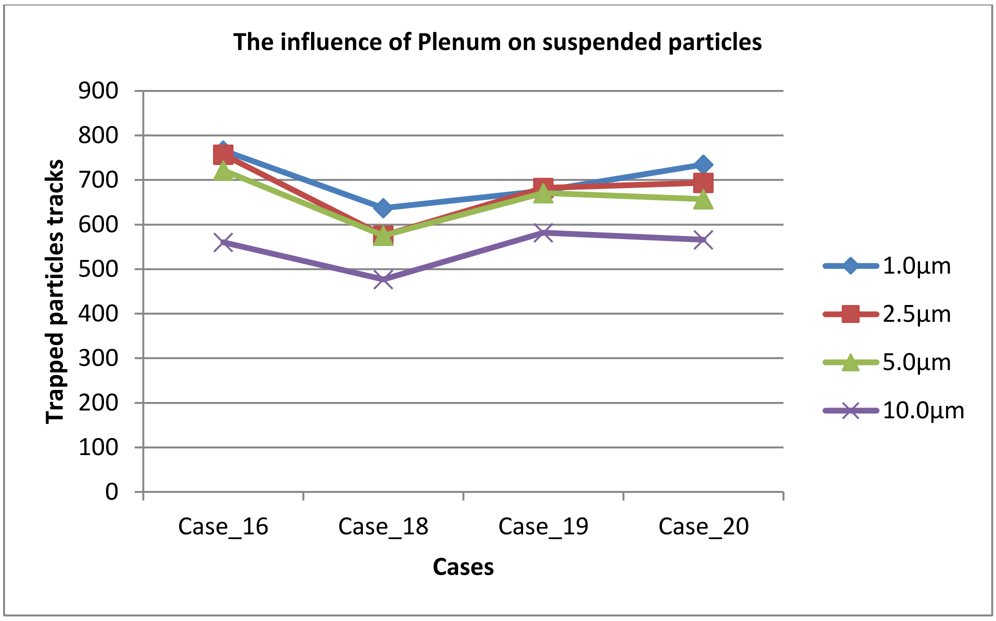


Figure 9.38: The influence of plenum on different sizes of dust particle suspension (1µm-10µm)

The results also indicate that the percentage of particles suspended in the wards decreases with increasing particle sizes as illustrated in figures 9.39 and 9.41. This phenomenon is well pronounced with particles of smaller sizes between 1.0µm and 30.0µm and less pronounced particles larger than 30.0µm as illustrated in figure 9.41. This is because the larger size particles are too dense to remain suspended in the air, compared to smaller size particles.

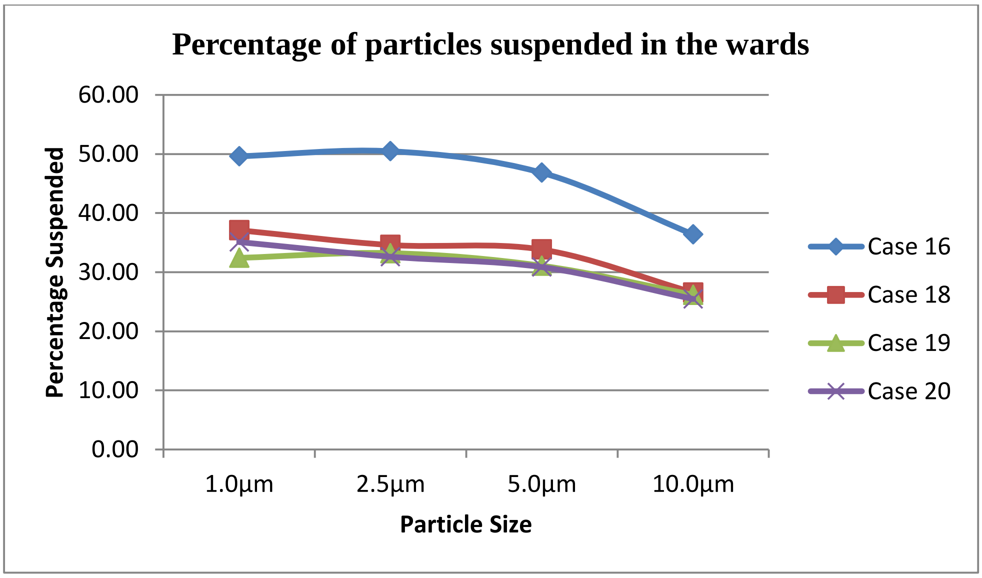


Figure 9.39: The influence of plenum on different sizes of dust particle suspension (1µm-10µm)

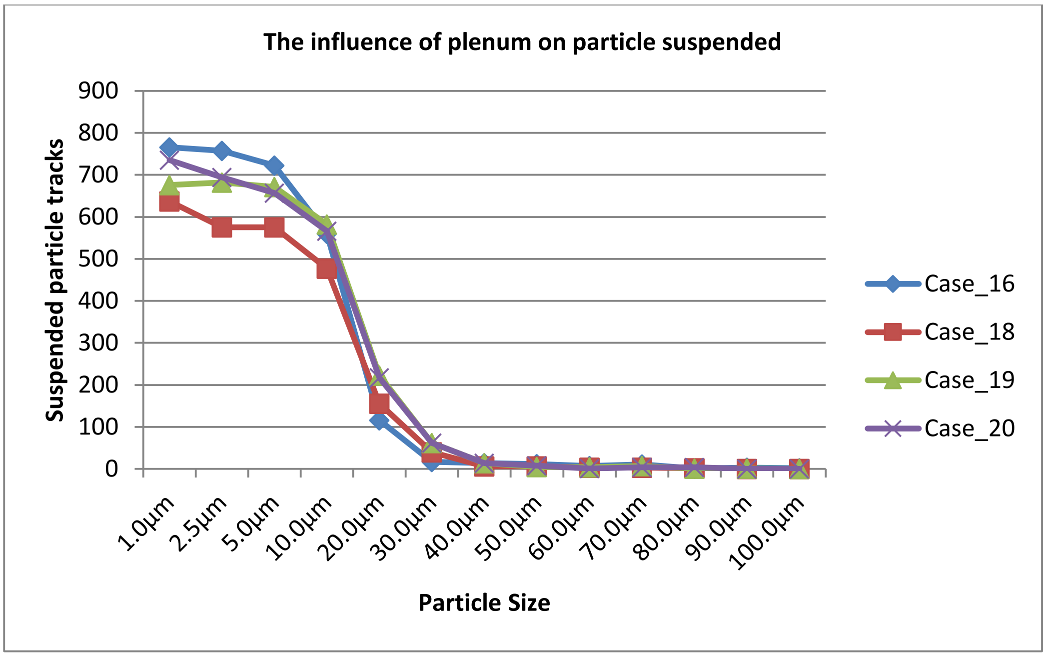


Figure 9.40: The influence of plenum on different sizes of dust particle suspension (1µm-100µm)

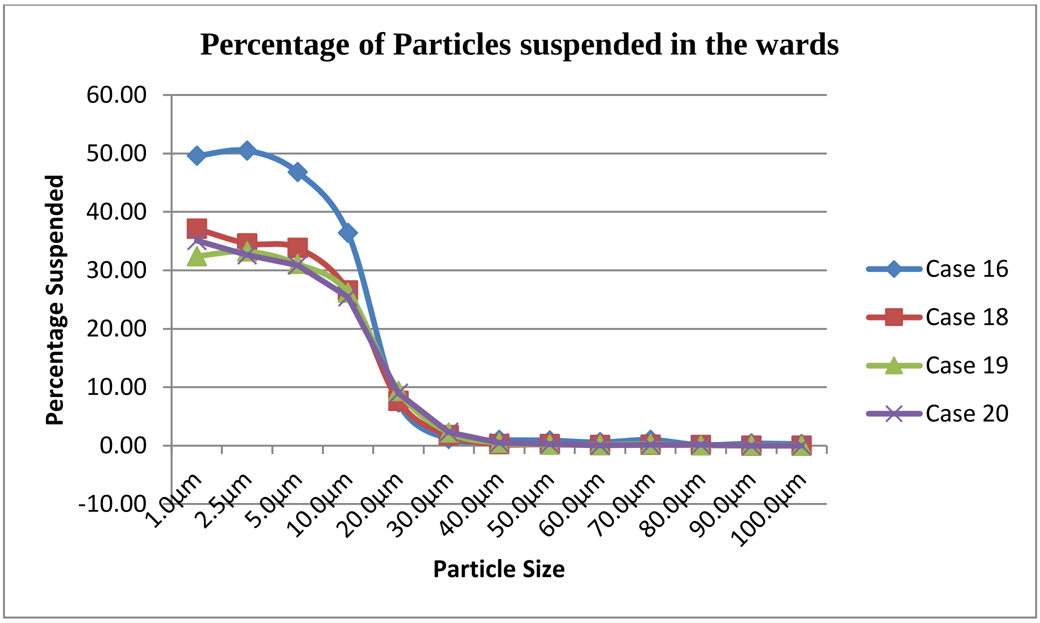


Figure 9.41: The influence of plenum on different sizes of dust particle suspension (1µm-100µm)

Owing to the introduction of plenums in cases 18, 19 and 20 and subsequent realisation of higher air change rates, especially with cases 19 and 20, lower screen porosities between 0.1 and 0.3 has been investigated. This is because the present study has revealed that, lower particle infiltration will be achieved with lower screen porosity. The original insect screen porosity used in the present study is 0.66. The volumetric airflow rates of cases 19 and 20 with different screen porosities (0.1 to 0.3) are shown in table 9.4 and 9.5. The inclusion of cases 19 and 20 with 0.66 screen porosity is to compare with the lower screen porosities of 0.1, 0.2 and 0.3 and assessed the level of reduction in terms of air change rates. Because, as the air change rates decreases, the amount of particles infiltrations indoors will be less.

Table 9-4: The Volumetric flow rates of individual openings and total volumetric flow rates of different porosities of Case 19

Openings	Volumetric airflow rates (Case_19)			
	Case 19_P-0.66	**Case 19_P-0.3**	**Case 19_P-0.2**	**Case 19_P-0.1**
W_Screen_1	0.98	0.68	0.47	0.18
W_Screen_2	0.98	0.67	0.47	0.17
W_Screen_3	0.98	0.67	0.47	0.17
W_Screen_4	0.98	0.68	0.47	0.18
W_Screen_5	-0.65	-0.54	-0.40	-0.16
W_Screen_6	-0.67	-0.55	-0.40	-0.15
W_Screen_7	-0.67	-0.55	-0.40	-0.15
W_Screen_8	-0.65	-0.54	-0.40	-0.16
W_Screen_9	0.32	0.13	0.07	0.02
W_Screen_10	0.32	0.13	0.07	0.02
W_Screen_11	0.32	0.13	0.07	0.02
W_Screen_12	0.32	0.13	0.07	0.02
Volumetric airflow rates	**3.92**	**2.70**	**1.88**	**0.7**

Table 9-5: The Volumetric flow rates of individual openings and total volumetric flow rates of different porosities of Case 20

Openings	Volumetric airflow rates (Case_20)			
	Case 20_P-0.66	**Case 20_P-0.3**	**Case 20_P-0.2**	**Case 20_P-0.1**
W_Screen_1	1.01	0.72	0.49	0.18
W_Screen_2	1.00	0.71	0.49	0.17
W_Screen_3	1.00	0.71	0.49	0.17
W_Screen_4	1.01	0.72	0.49	0.18
W_Screen_5	-0.48	-0.35	-0.26	-0.12
W_Screen_6	-0.54	-0.38	-0.24	-0.11
W_Screen_7	-0.54	-0.38	-0.24	-0.11
W_Screen_8	-0.48	-0.35	-0.26	-0.12
W_Screen_9	-0.47	-0.34	-0.24	-0.06
W_Screen_10	-0.52	-0.36	-0.24	-0.06
W_Screen_11	-0.52	-0.36	-0.24	-0.06
W_Screen_12	-0.47	-0.34	-0.24	-0.06
Volumetric airflow rates	**4.02**	**2.86**	**1.96**	**0.7**

The air change rates of cases 19 and 20 with lower screen porosities (0.1, 0.2 and 0.3) have been compared with cases 19 and 20 with the original used porosity of 0.66. The result shows that, in case 19, the reduction in air change rate in relation to opening with

0.66 screen porosity is 31.02%, 52.07% and 82.19% for porosities of 0.3, 0.2 and 0.1 respectively as shown in table 9-6. However, in case 20, the decrease in air change rate in relation to opening with 0.66 screen porosity is 28.95%, 51.25% and 82.63% for porosities of 0.3, 0.2 and 0.1 respectively. Hence the difference between cases 19 and 20 is low as illustrated in figure 9-42. The air change rates in cases with screen porosity of 0.2 and 0.3 in both cases 19 and 20 have satisfied the ASHRAE standards requirement of 6 ach^{-1} for hospital wards. However in both cases 19 and 20, the cases with 0.1 screen porosity have not satisfied the ASHRAE requirement, but very closed to satisfy the requirement as presented in tables 9-6 and 9-7.

Table 9-6: Indoor air flow characteristics of case 19 with different screen porosities

Parameters	**Case 19**			
Porosity	P-0.66	P-0.3	P-0.2	P-0.1
Volumetric airflow rates	3.92	2.70	1.88	0.7
Air change rates (ach^{-1})	30.88	21.30	14.80	5.50
% Reduction in ACR on case 19 with P-0.66	0	31.02%	52.07%	82.19
Average indoor air velocity	0.265	0.164	0.088	0.024
Average indoor turbulent intensity	4.70%	4.04%	3.84%	3.79%
Average indoor air temperature	27.6	27.6	27.5	27.2

Table 9-7: Indoor air flow characteristics of case 20 with different screen porosities

Parameters	**Case 20**			
Porosity	P-0.66	P-0.3	P-0.2	P-0.1
Volumetric airflow rates	4.02	2.86	1.96	0.7
Air change rates (ach^{-1})	31.67	22.50	15.44	5.50
% Reduction in ACR on case 20 with P-0.66	0	28.95%	51.25%	82.63%
Average indoor air velocity	0.294	0.198	0.108	0.026
Average indoor turbulent intensity	4.34%	3.68%	3.34%	3.16%
Average indoor air temperature	27.6	27.6	27.5	27.2

Moreover, the difference in terms of average indoor air velocity, case 20 has higher indoor velocity compared to case 19 as illustrated in figure 9.43. Therefore, based on the analysis of air change rates and indoor air velocity between case 19 and 20, their particle dispersion characteristics have been analysed. The particle dispersion analysis considered the characteristic of particle concentration, deposition and suspension in the hospital ward.

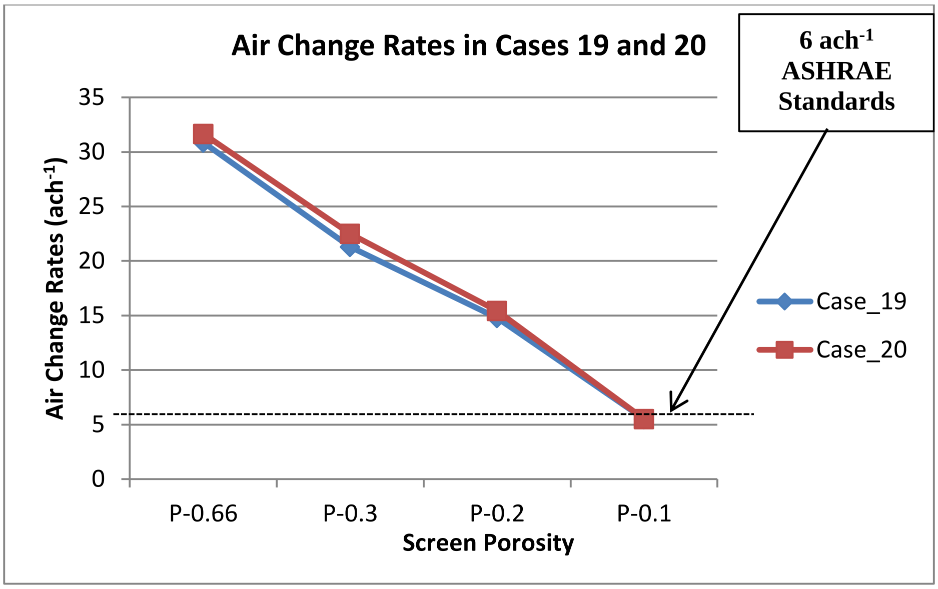


Figure 9.42: The effect of Plenum on Air Change Rates in Cases 19 and 20

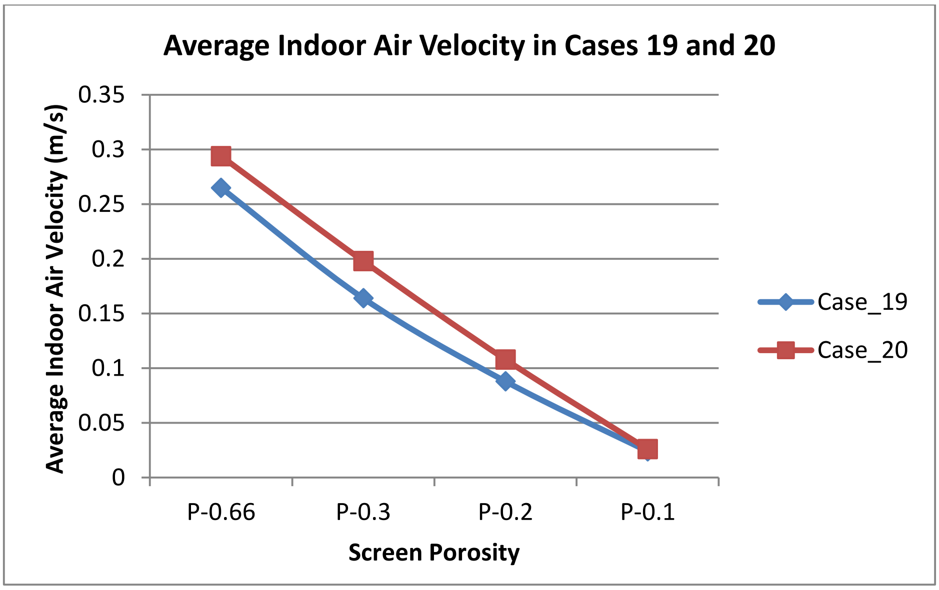


Figure 9.43: The effect of Plenum on Indoor Air Velocity in Cases 19 and 20

The variation in particle concentration between the particles of different sizes has been simulated and analysed. The results indicate that, the indoor particle concentration level is higher in cases with 0.3 screen porosity, followed by 0.2 and then 0.1 for both case 19 and 20 as illustrated in figure 9.44. However, the difference between the two cases (case 19 and 20) is not significant as could be observed in figure 9.44. The higher the screen porosity, the greater the percentage of particles concentration in the wards as illustrated in figure 9.45 (Figure 9.45 was split into figures 9.46 and 9.47 for proper understanding by plotting Case 19 and 20 separately). Although cases with screen porosity of 0.1 have shown better results in preventing particle concentration indoors, they have not satisfied the ASHRAE standard air change rates requirement of 6 ach^{-1}. But it is closed to satisfying the requirement, as the difference is too closed, that could be fulfilled by employing screens with porosity of a little bit higher than 0.1 and not up to 0.2.

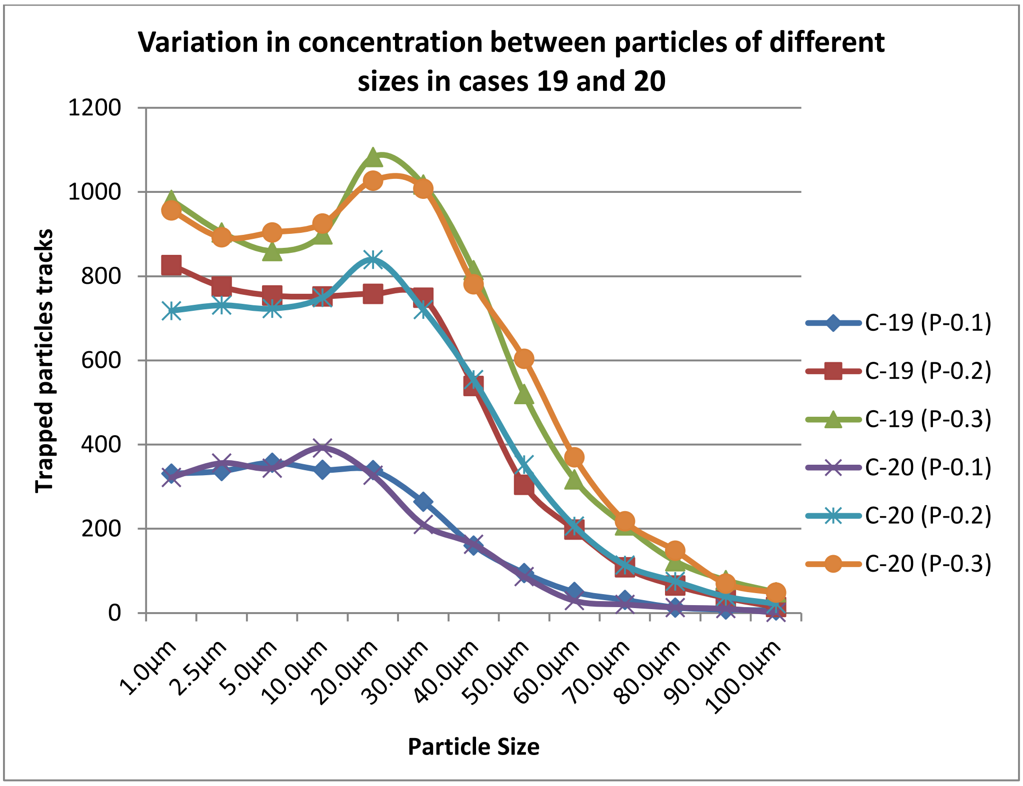


Figure 9.44: The variation in particle concentration between particles of different sizes in cases 19 and 20

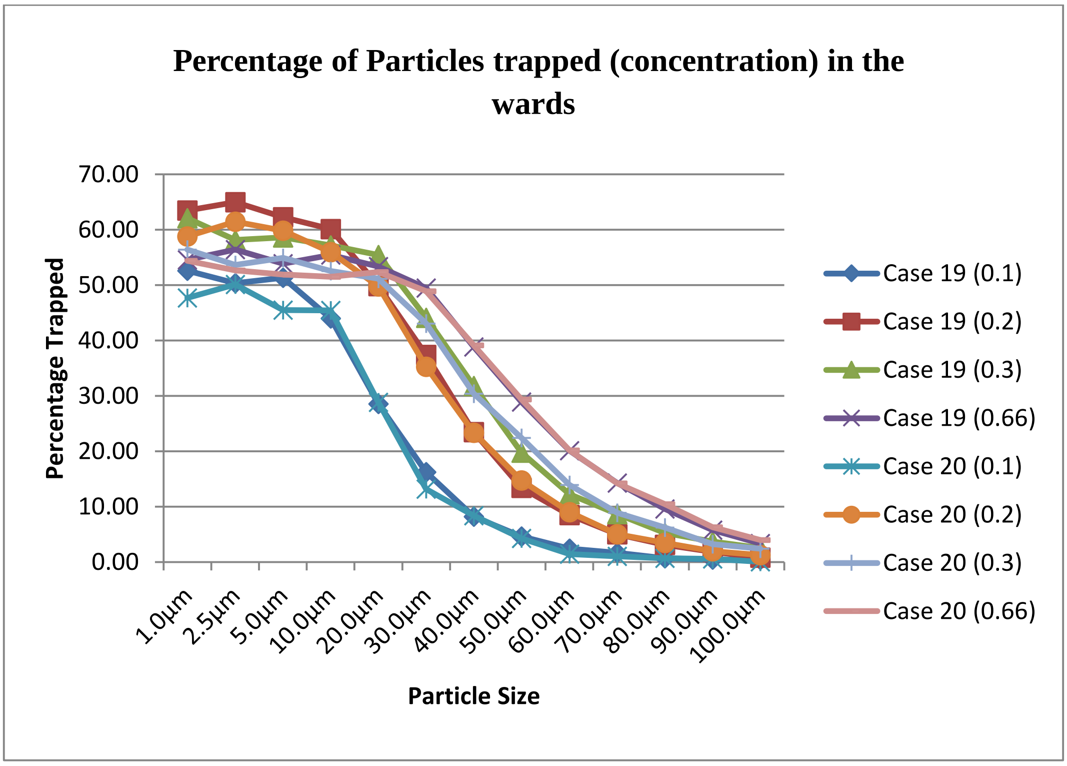


Figure 9.45: The variation in percentage of particle concentration between particles of different sizes in cases 19 and 20

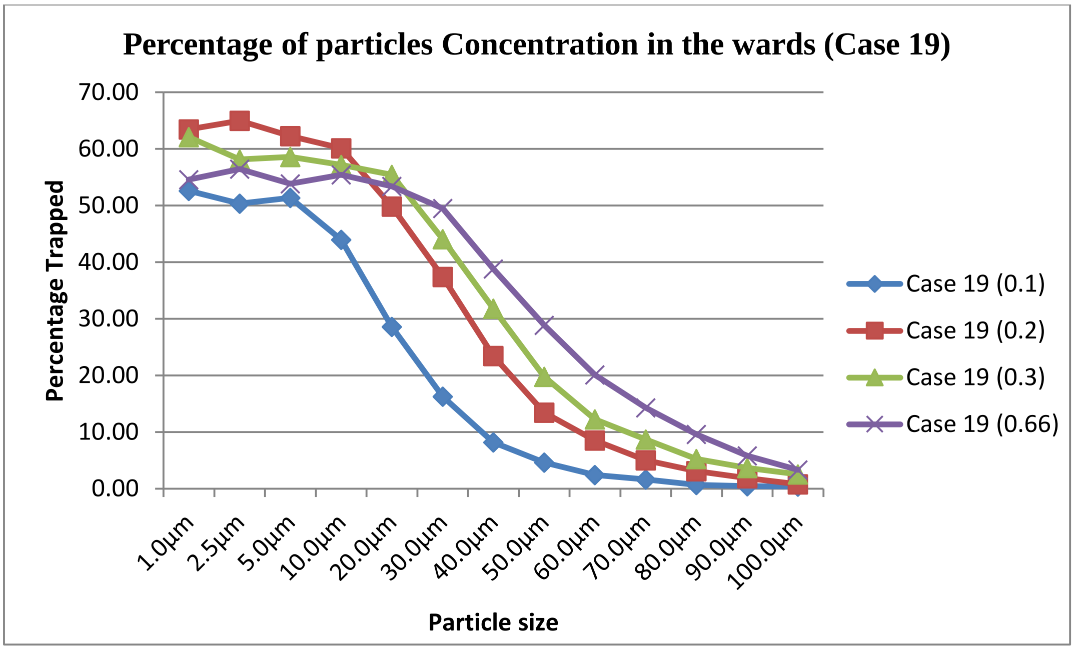


Figure 9.46: The variation in percentage of particle concentration between particles of different sizes in cases 19

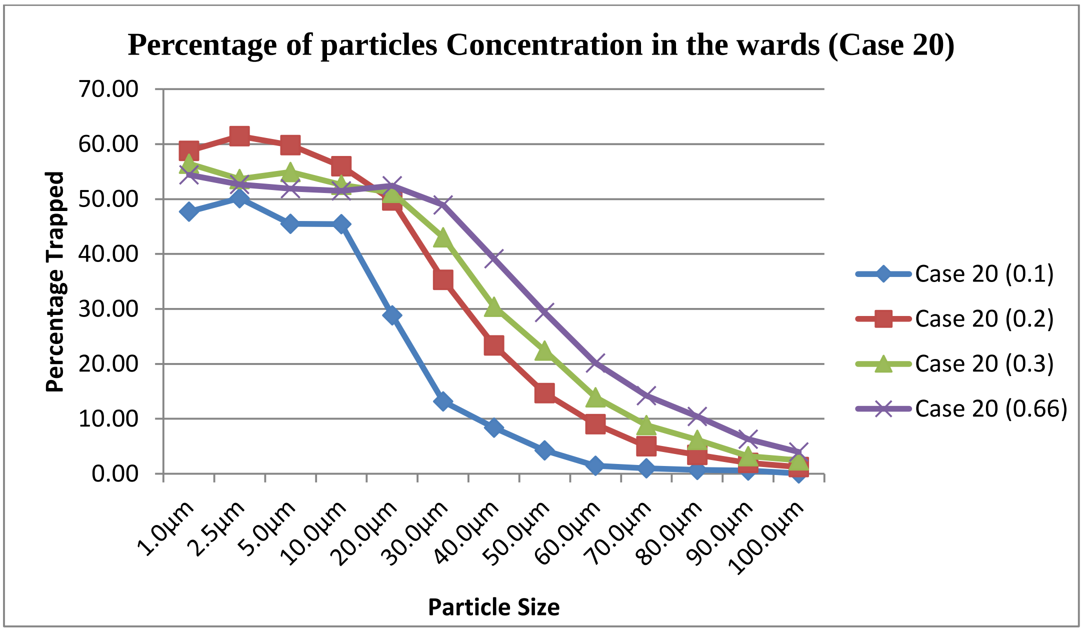


Figure 9.47: The variation in percentage of particle concentration between particles of different sizes in cases 20

The results concerning the rates of particle deposited indoors also follows similar pattern with the concentration. The deposition level for both cases 19 and 20 increases with increasing screen porosity. Cases with screen porosity of 0.3 have the highest deposition level, followed by 0.2 porosity and then 0.1 porosity with the lowest deposition rates as illustrated in figure 9.48. Moreover, with smaller particle size of between 1.0µm to 20.0µm, the deposition rates increases with growing particle size. However, with larger particle sizes of between 30.0µm to 100.0µm, dust particles deposition rates decreases with increasing particle size as illustrated in figure 9.48. With smaller particles of less than 20.0μm, the percentage of dust particles deposited on the floor surface increases with increasing particle size and with larger particle size of greater than 20.0μm, the percentage of deposition decreases with increasing particles size as illustrated in figure 9.49. The deposition percentage increases with higher screen porosity in both cases 19 and 20 as illustrated in figure 9.49. This situation is due to the influence of the particles on screen porosity and the plenums.

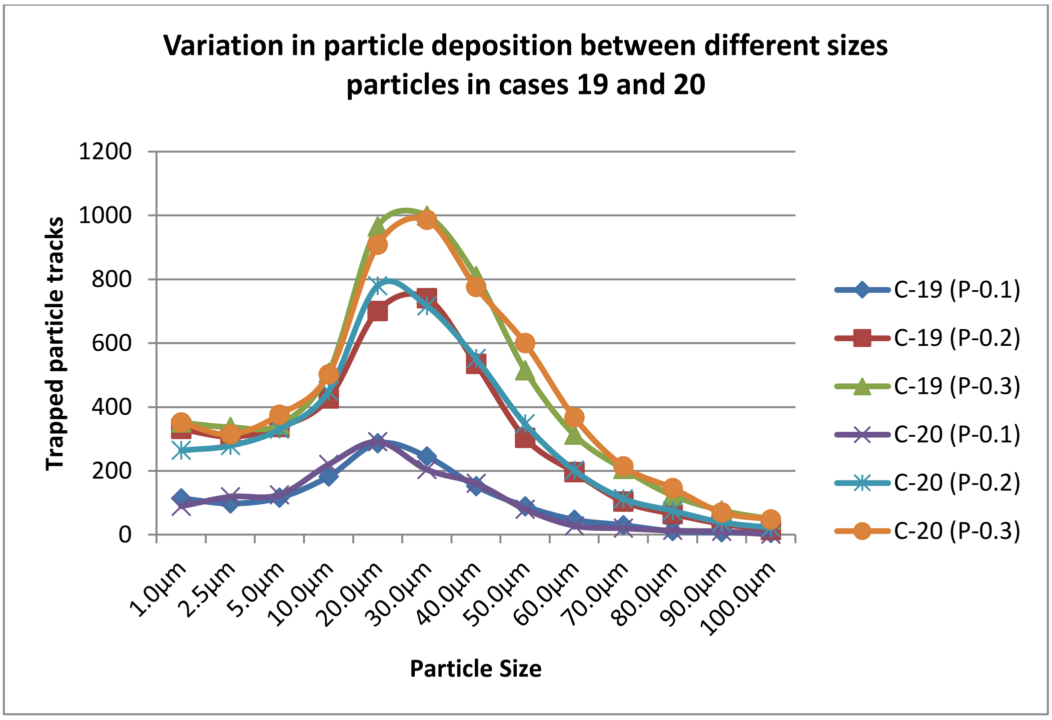


Figure 9.48: The variation in particle deposition between particles of different sizes in cases 19 and 20

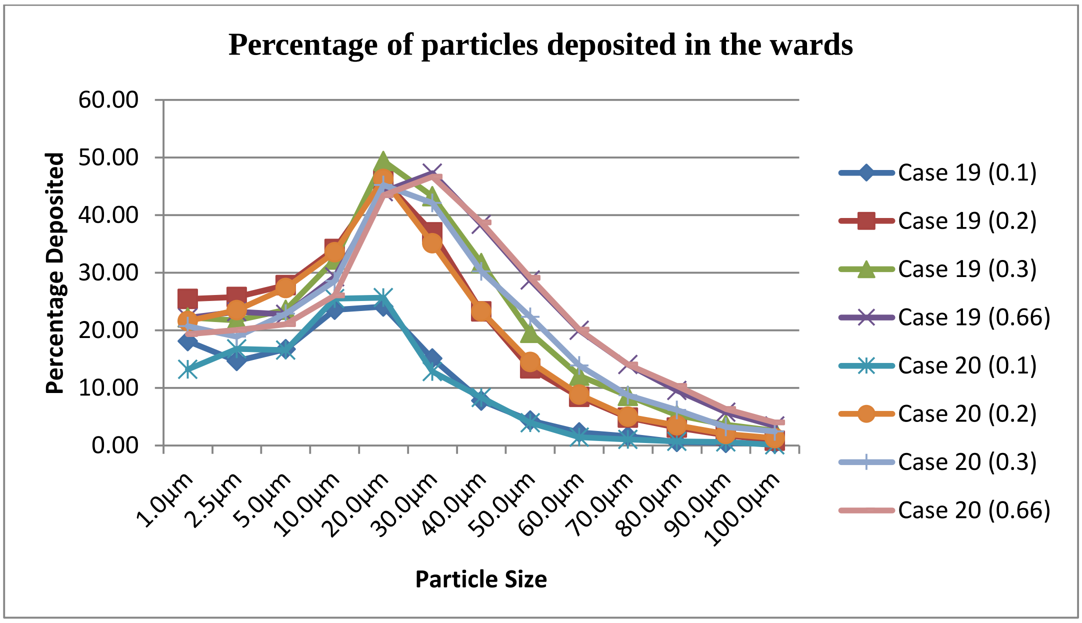


Figure 9.49: The variation in particle deposition between particles of different sizes in cases 19 and 20

The plenums with the aid of installed insect screen tend to decrease the air speed and consequently compelled the larger particles to deposit in the plenum before reaching the room/ward's indoor environment. The effect of plenum on different sizes of dust particles deposition is illustrated in figure 9.50. The deposition level is higher with larger particle size. Thus, the larger the particle size, the higher the deposition percentage as illustrated in figure 9.51.

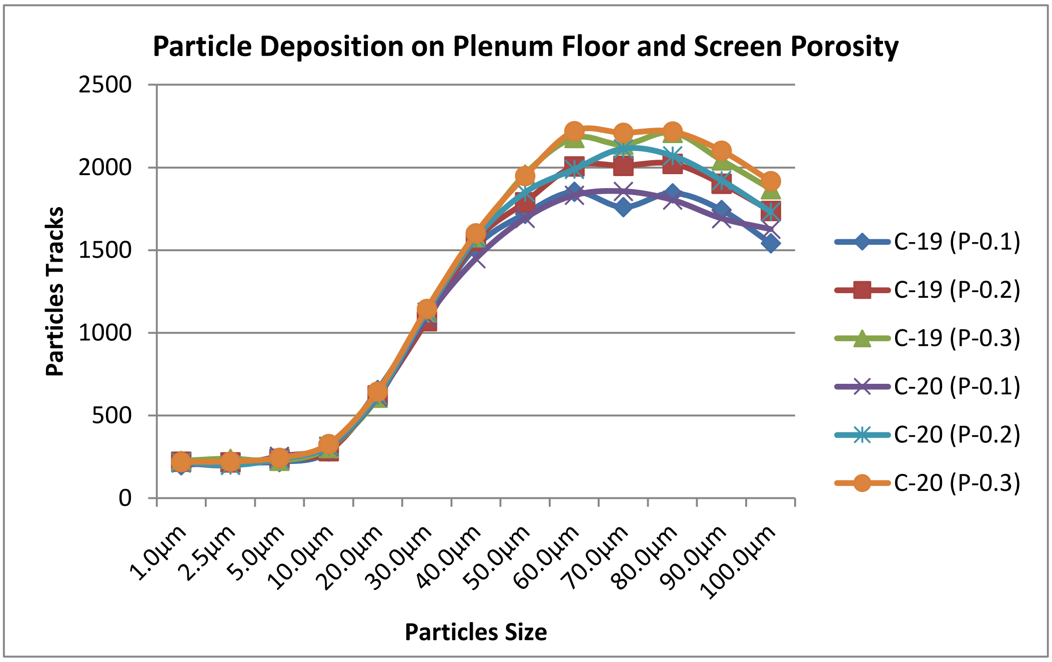


Figure 9.50: The effect of plenum on different sizes on dust particles deposition

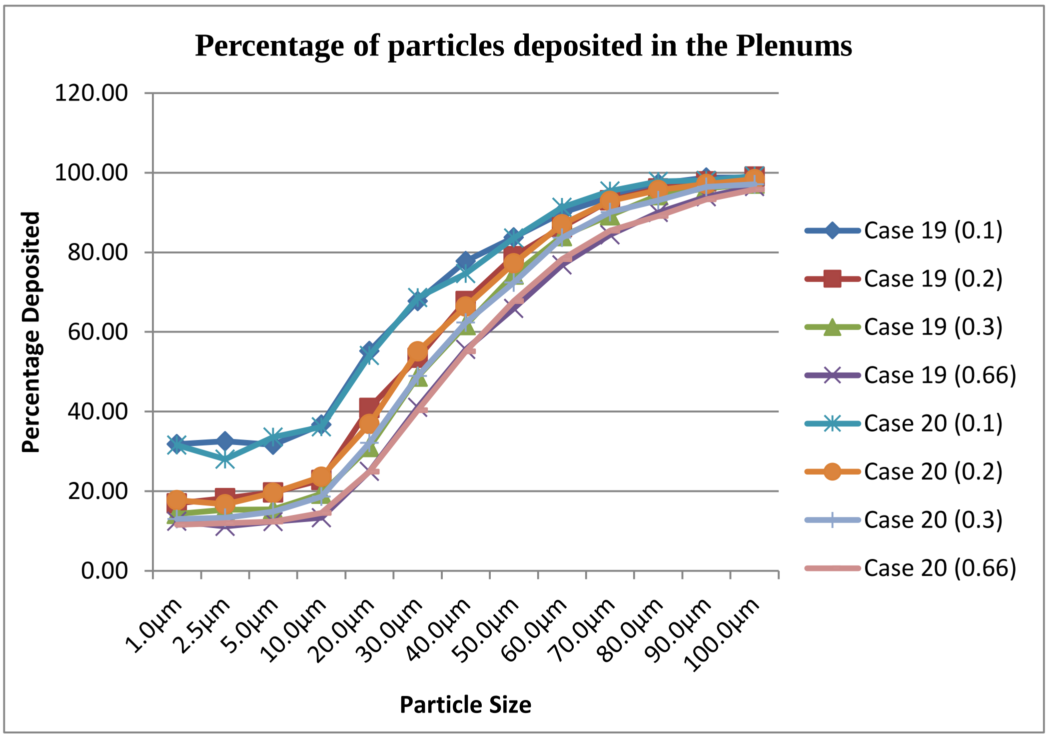


Figure 9.51: The effect of plenum on different sizes on dust particles deposition

In the present study, the influence of double plenum (cases 19 and 20) with insect screen porosities of 0.1 to 0.3 has been investigated and analysed. The result indicated that, the dust particle suspension rates increases with growing screen porosity as illustrated in figure 9.52. With smaller particle sizes of between 1.0µm to 30.0µm, the rate of suspended particles decreases with increasing particles sizes. The dust particle suspension rate is low and insignificant with larger particles of sizes between 30.0µm to 100.0µm, due to their size as illustrated in figure 9.52. With lower particle size of between 1.0µm to 30.0µm, the percentage of dust particles suspension increases with decreasing particles size and the relationship is insignificant with larger particle size of greater than 40.0µm, as illustrated in figure 9.53.

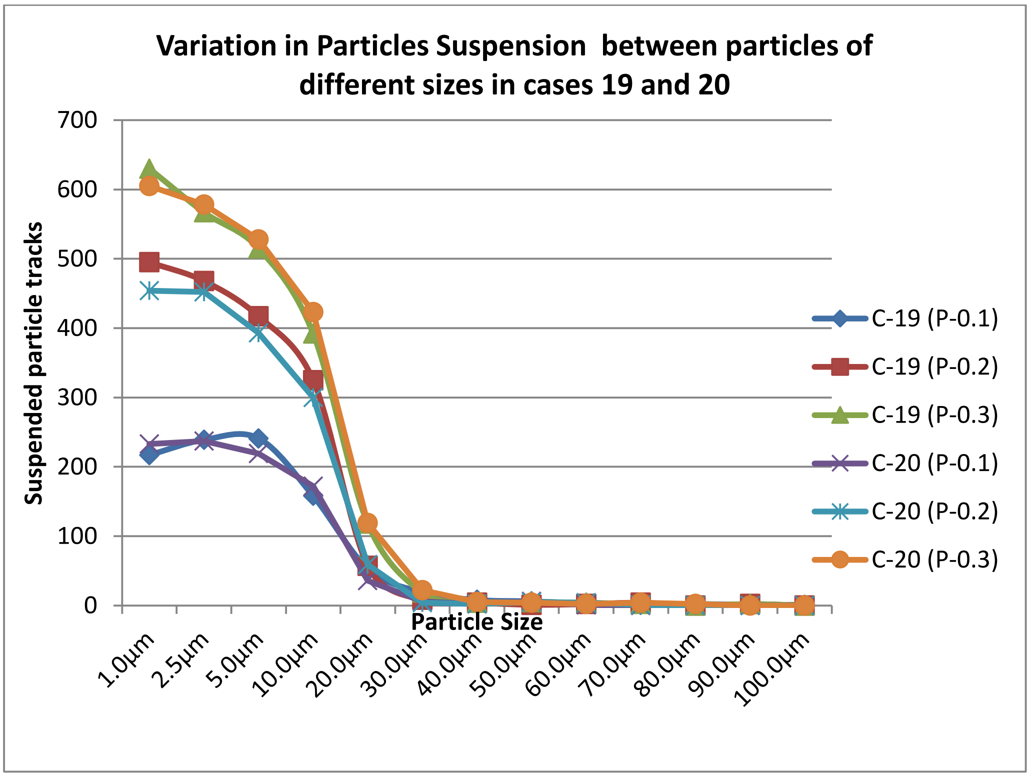


Figure 9.52: The variation in particle suspension between particles of different sizes in cases 19 and 20

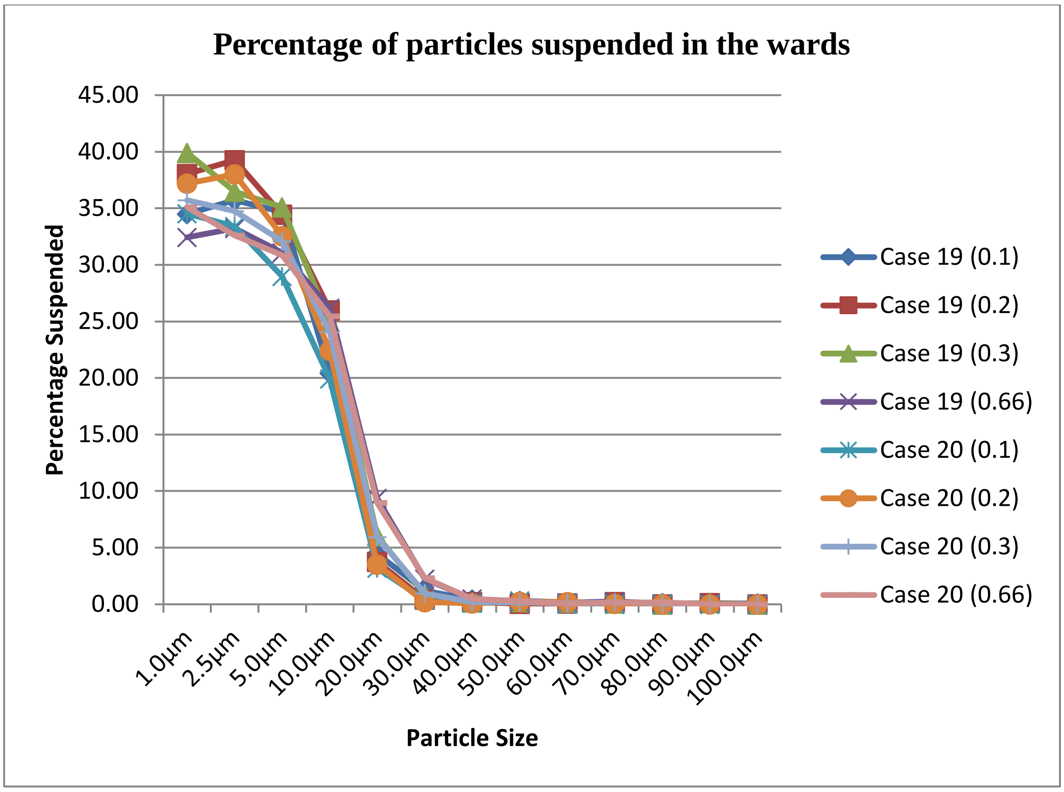


Figure 9.53: The variation in percentage of particle suspension between particles of different sizes in cases 19 and 20

Additionally, the quantity of dust particles escaped or exhausted through the outlet openings, has been investigated and analysed in the present study. The results show that, the quantity of escaped particles increases with growing screen porosity levels in both cases 19 and 20. Moreover, in terms of particle size, the particle escaped rate increases with decreasing particle size as illustrated in figure 9.54. The relationship between the percentage of particles escaped and the particle size and porosity is the same with the quantity as illustrated in figure 9.55. The tracked, escaped and trapped characteristics of different sizes dust particles for cases 19 and 20 with different insect screen porosities is presented in tables 12-33 to 12-36 of the appendices section 12.3.4.

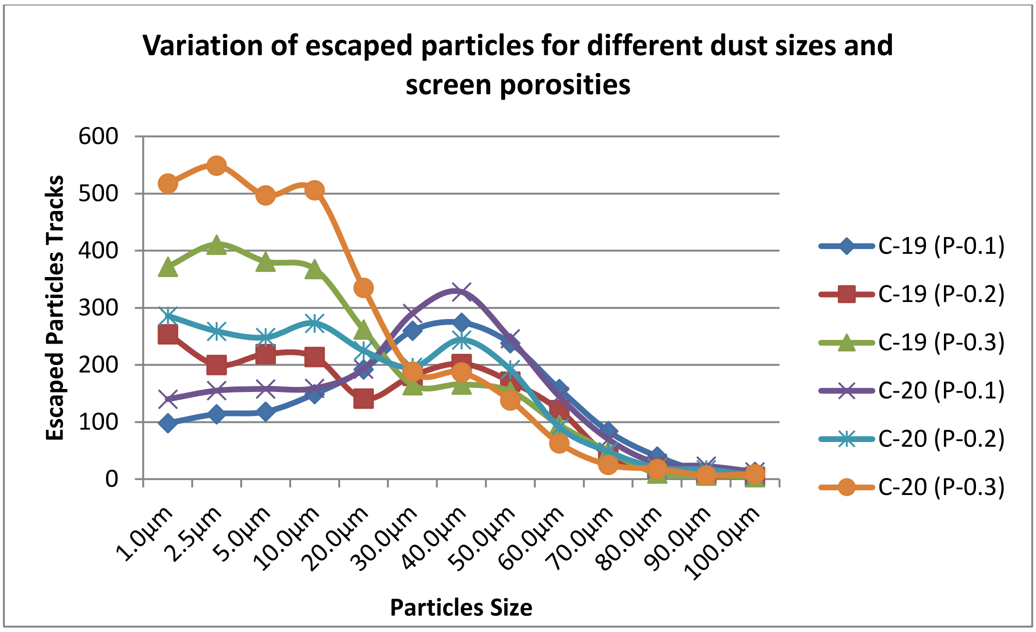


Figure 9.54: The variation in infiltration prevention (escaped) between particles of different sizes in cases 19 and 20

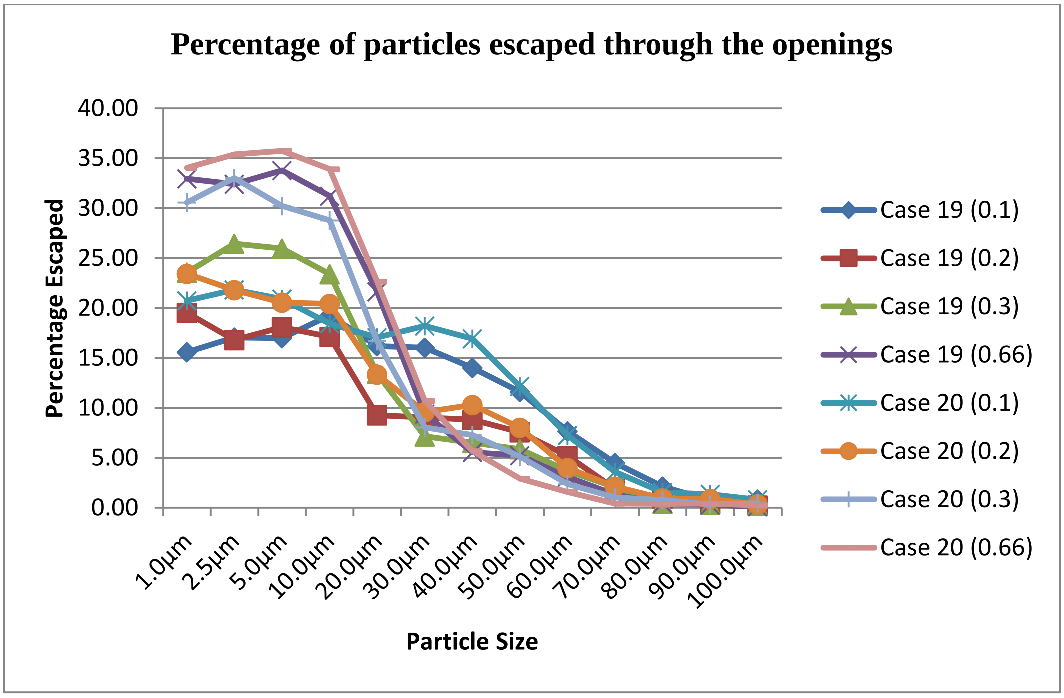


Figure 9.55: The variation in infiltration prevention (escaped) between particles of different sizes in cases 19 and 20

9.8 Chapter Conclusion

The CFD simulation and results analysis of pollutant dispersion in hospital wards of the semi-arid climate of Nigeria is presented in this chapter. The particle tracking was conducted using Lagrangian approach of the Discrete Phase Model (DPM). The simulations are conducted with insect screen installed on the wards' openings or the plenums. The effect of insect screen porosity on dust particles concentration, deposition and suspension in hospital wards has been studied. The installation of insect screen on the hospital ward openings influences pollutant dispersion in the ward, as the number of particles received indoors increases with growing screen porosity.

The influence of particle size on pollutant dispersion with different screen porosity is negligible when considering the total concentration of particles reaching the indoor space, but the influence is significant when considering particle deposition and suspension and the deposition level increases with growing particle size. Likewise, the number of suspended particles decreases with growing particle size and the level of suspension are higher with smaller size particles. The dust particles concentration indoors increases with increasing ventilation rates, except in cases with different geometrical configuration.

Likewise, the effect of outdoor prevailing wind speeds on dust particles concentration, deposition and suspension has been studied and presented. The concentration and deposition of dust particles indoors increases with increasing outdoor wind speed. The dust particles deposition indoors increases with increasing outdoor wind speed and the deposition rate is higher with larger size particles. The amount of suspended dust particles indoors increases with increasing outdoor wind speed and the suspension rate is decreasing with larger size particles.

To improve the ventilation rates in the hospital wards, while excluding mosquitoes and reducing the effect of Harmattan dust, plenums have been introduced in the windward and leeward side of the wards. The introduction of a plenum to the windward side of the ward (Case 18) resulted in 83.7% increase in air change rates, while introducing plenums to both the windward and the leeward sides of the ward (Case 19 and 20) resulted in 127.9% and 133.7% increase respectively in air change rate compared to the case without plenum (Case 16). The introduction of plenums resulted in decreased particle concentration in the interior part of the wards. With plenums incorporated, the particle deposition rates increases with growing particle size, whereas the quantity of suspended particle increases with decreasing particle size. The number of suspended particles is higher in the case without plenum (Case 16) compared to cases with plenums (Cases 18 and 19). The installation of the insect screens on the plenums with larger surface area rather than directly installing it to the ward openings will increase ventilation rates. Hence, acceptable ventilation will be achieved using screen of lower porosity that can exclude higher amount of dust compared to screens with larger porosity. The summary of different cases simulated in this chapter and their results on air change rates, average indoor air velocity, turbulent intensity and percentage of dust particle trapped indoors is illustrated in table 9-8. When the screen porosity is reduced from the default 0.66 to 0.2 the ability of stopping mosquitoes and Harmattan dust increases, while achieving the acceptable ventilation rates of 6 ach^{-1}, as could be observed from table 9-8.

Table 9-8: Indoor air characteristics of different ventilation strategies with and without plenums

Cases	**Case 16**	**Case 18**	**Case 19**	**Case 20**	**Case_20(P-0.2)**
Screen porosity	**0.66**				**0.2**
Description	Inlet centre & outlet both roof and leeward wall	Case 16 with plenum at the wind ward side	Case 16 with plenum at both windward and leeward sides	Case 19 with roof windows inside the plenum box	Case 20 with 0.2 insect screen porosity
Air change rates (ACR) ach^{-1}	13.55	24.89	30.88	31.67	15.44
% Increase in ACR on case 16	0%	83.7%	127.9%	133.7%	14.0%
Average indoor air velocity (m/s)	0.069	0.219	0.265	0.294	0.108
Average indoor turbulent intensity (%)	4.00	4.10	4.70	4.34	3.34
Percentage of dust particles trapped in the ward (1µm)	90.2%	57.7%	54.6%	54.4%	58.8%
Percentage of dust particles trapped in the ward (10µm)	91.6%	54.3%	55.4%	51.5%	56.0%
Percentage of dust particles trapped in the ward (50µm)	99.9%	23.8%	28.9%	29.4%	14.7%
Percentage of dust particles trapped in the ward (100µm)	100%	2.7%	3.4%	4.0%	1.3%

Chapter Ten

Guidance for Architects

Chapter Structure

10.1 Introduction

10.2 Site planning and orientation

10.3 Physical size of the building

10.4 Arrangement of fenestrations

10.5 Location of ventilators and baffles on the roof

10.6 The ratio of openings sizes to ward floor area

10.7 Insect screen mesh

10.8 Outdoor prevailing wind speed

10.9 Plenums integration and positions

10.10 Chapter conclusion

10 Chapter Ten: Guidance for Architects

10.1 Introduction

This chapter (chapter 10) presents guidance for architects who are responsible for hospital ward planning and designs in the semi-arid climatic zone of Nigeria (Maiduguri). This guidance will serve as feedback for the architects to feedforward for subsequent hospital ward design. The section is designed to satisfy objective number 5 of the thesis, which is *"To provide guidance for Architects"*. Section 10.2 of this chapter discusses site planning and orientation; section 10.3 presented the physical size of the building; section 10.4 presented the consideration of fenestration arrangements; section 10.5 discusses location of ventilators and provision of roof baffles; section 10.6 presented the consideration of sizes of openings to wards' floor area ration; section 10.7 described the sizes of insect screen meshes; section 10.8 presented the effects of outdoor prevailing wind speed; section 10.9 discusses the importance of integrating Plenums, their positions and size; and section 10 is the chapter conclusion.

10.2 Site Planning and orientation

The positioning of hospital wards in relation to wind flow direction is very important for effective natural ventilation. The simulation results revealed that hospital wards with oblique opening orientation in relation to outdoor prevailing wind speed provide better airflow circulation compared to those with normal orientation. In order achieve this in the study area the longer side of the hospital wards should be oriented facing North-South direction as possible, as the dominant prevailing wind direction is North-East. By doing so, the effect of solar radiation into the interior space is eliminated because the openings will be situated at the longer facades as illustrated in figure 10.1. However, based on the assessments conducted in the study area, only one (UMTH) out of the five hospital wards studies are oriented toward North-South direction.

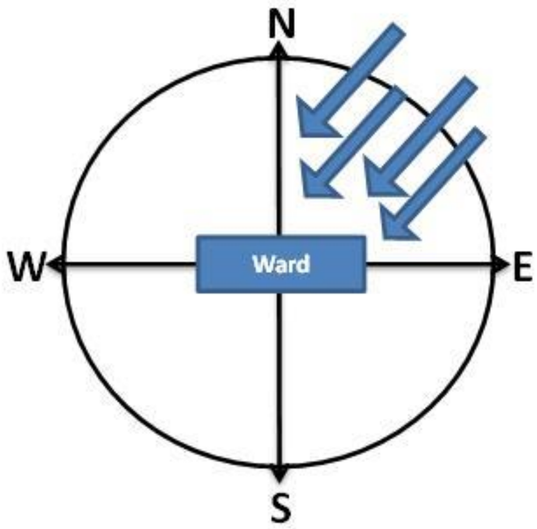


Figure 10.1: The recommended ward orientation in relation to wind direction

The nearly North-South orientation provides the opportunity to benefit from the south-westerly monsoon wind that is normally moderate and comfortable and the North-easterly trade wind that is hot and dusty but can provide enough ventilation to remove indoor air pollutants. The orientations of the five (5) existing hospital wards including USUHM, UMTH, FNPHM, NHHM and SSHM are not positioned toward the required East-West orientation except in UMTH as could be observed in figures 10.2 – 10.6. The reason for adopting these orientations might be connected to the designers' intention of orienting the inlet openings normal to the wind flow direction.

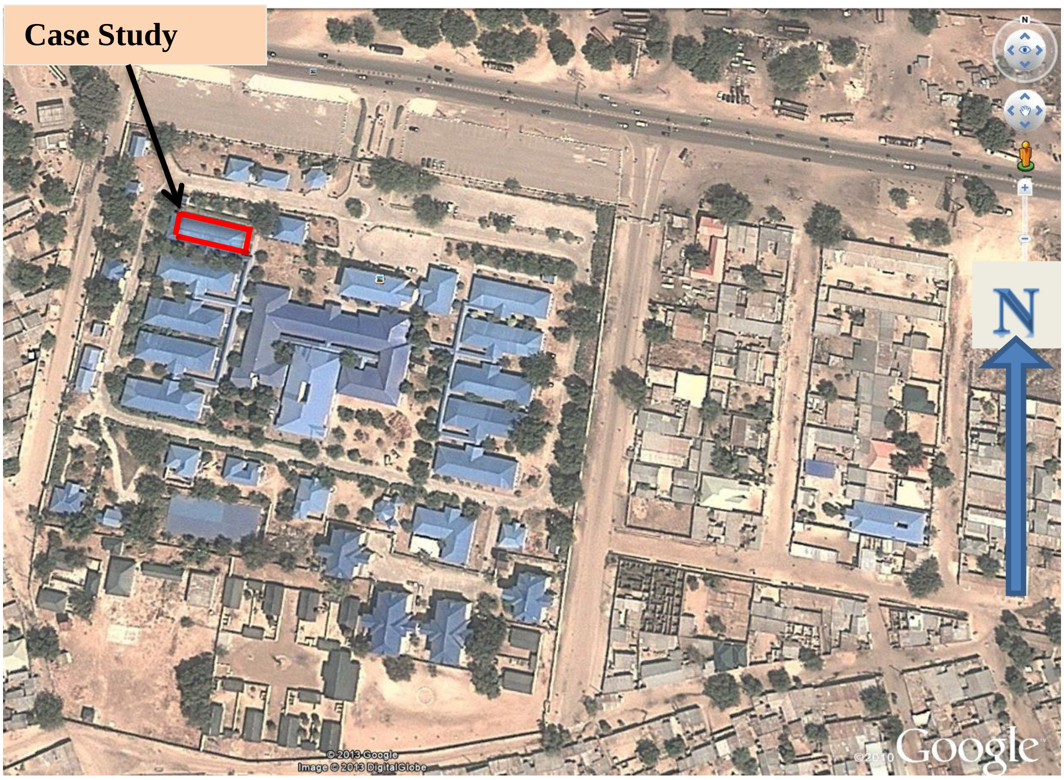


Figure 10.2: The site plan of USUHM

Figure 10.3: The site plan of UMTH

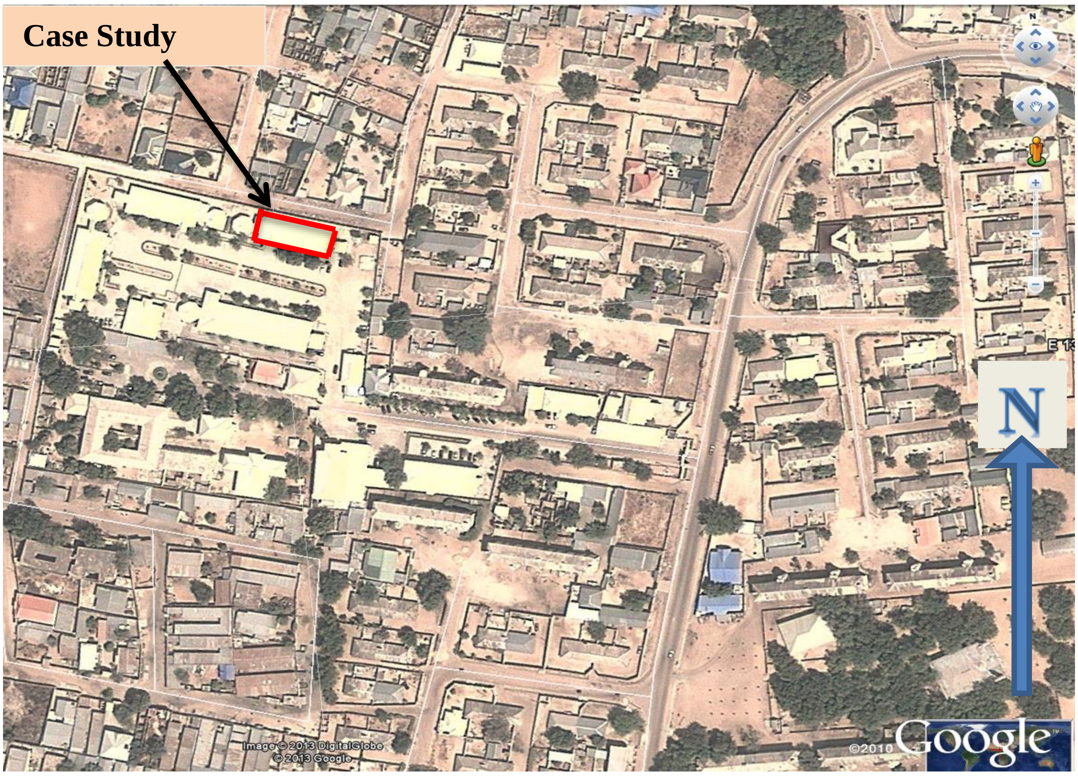


Figure 10.4: The site plan of FNPHM

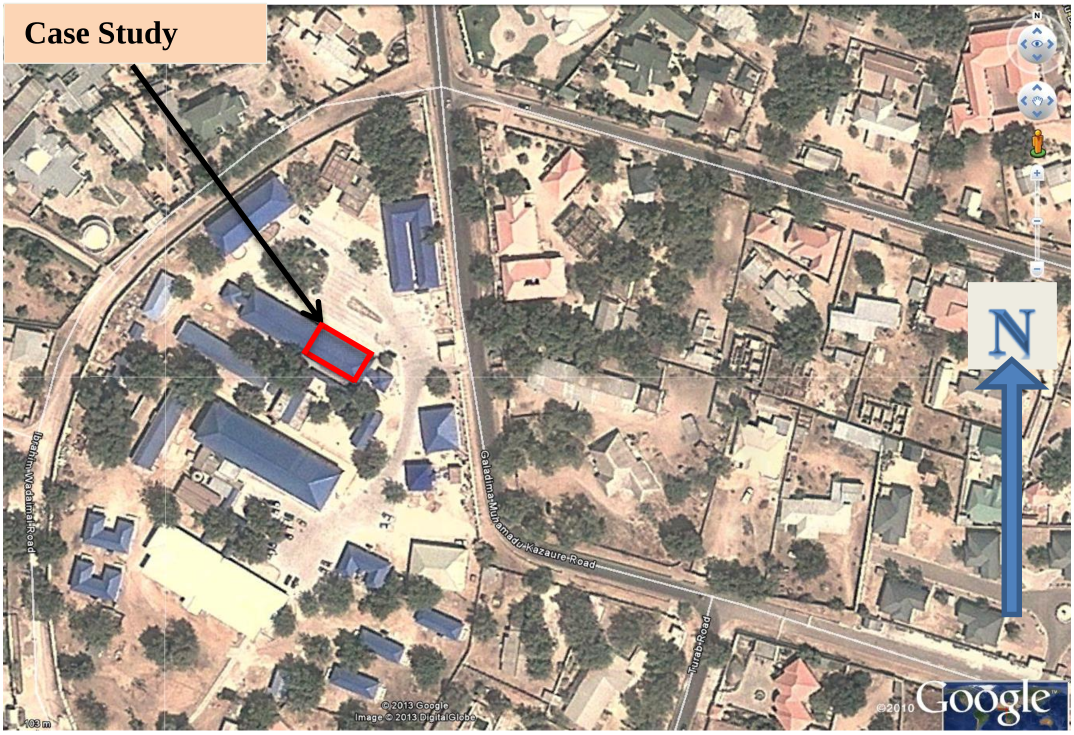


Figure 10.5: The site plan of NHHM

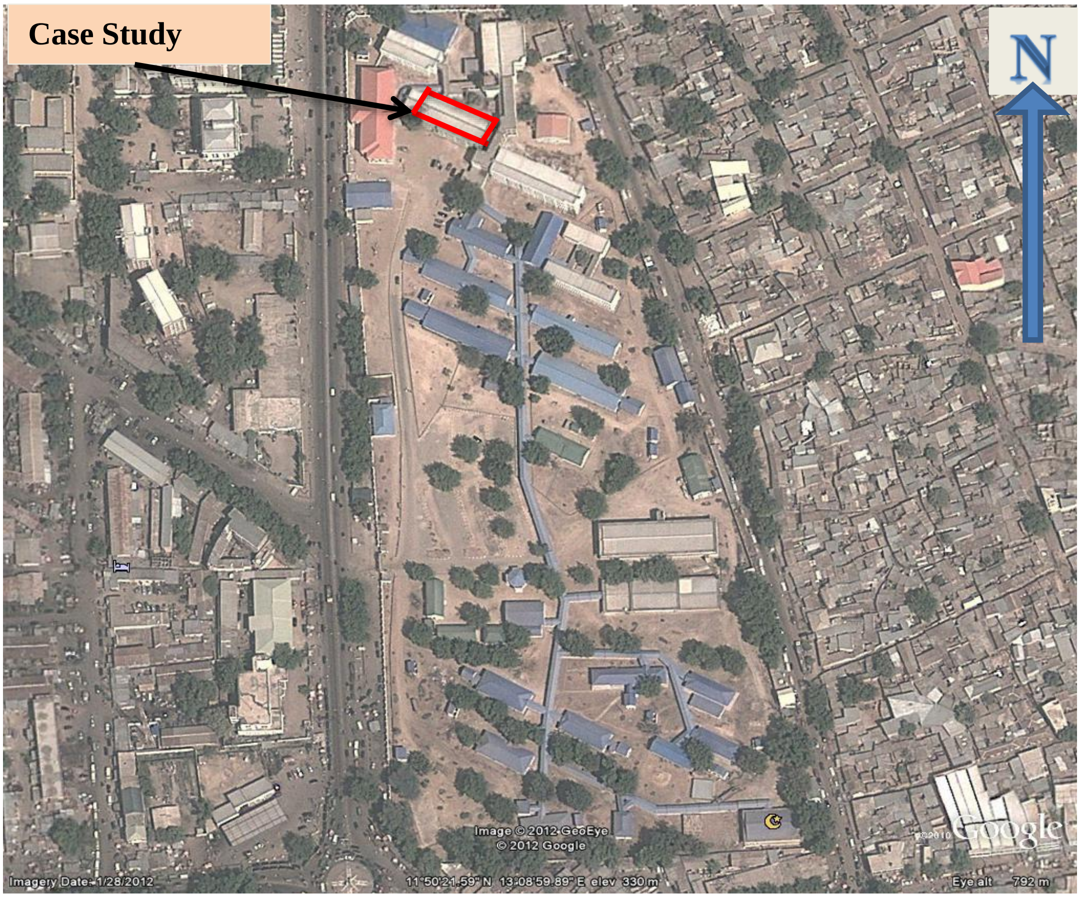


Figure 10.6: The site plan of SSHM

10.3 Physical size of the building

In this study, an existing hospital ward of size 12.5m x 11.4m x 3.2m (L x W x H), with a floor area of 142.5 m^2 has been used for the simulation of different ventilation alternatives. The hospital ward was designed to accommodate 20 patients' beds and it is a proper representative of typical hospital wards in the study area. The physical size of the wards was maintained throughout the simulation while changing the opening positions. The results indicate that, in order to achieve the required ventilation rates while eliminating or reducing the effects of mosquitoes and Harmattan dust, the physical size of the building needs to be altered by integrating plenums to both windward and leeward sides of the wards and creating the means of incorporating openings to the roof. Thus, the maximum depth of the ward is not greater than 14 m and the maximum width of the ward is not greater than 12m.

10.4 Arrangement of Fenestrations

Different fenestration arrangements have been tested in this study. The results indicate that the positioning of inlet and outlet openings in the windward and leeward facades respectively as obtainable in the hospital wards of the study area can provide the desirable ventilation rates using the outdoor wind speed of 2.6 m /s, but cannot provide the required airflow circulation at the occupancy level in the entire ward floor area. Thus, openings were introduced on the roof toward the leeward side of the ward which resulted in the ward satisfying both the requirement of ventilation rates and airflow circulation at the occupancy level. The hospital wards should be single storey buildings with the potential to introduce outlet ventilation openings on the roof. These ventilation openings should be covered with baffle walls with cross-sectional area of 1m x 1m.

10.5 Location of Ventilators and baffles on the roof

The present study has succeeded in testing roof openings by positioning the outlet openings at different locations including leeward, centre and windward sides of the roof. The results indicate that placing the roof openings closer to the inlet openings result in airflow short-circuiting, where the incoming air would not go deep into the room, but turned back at the position of the roof outlets. This phenomenon provides higher ventilation rates but poor indoor air circulation. Therefore, it is recommended that. Architects and building service engineers should place roof outlet openings toward the leeward side of the wards away from the inlet openings.

The integration of the roof openings to the hospital wards could be achieved by providing baffle walls on both the windward and the leeward sides of the roof and seal the unused one. These openings could also be provided at both the windward and the leeward sides of the roof to be used in alternation in line with the weather condition. Since the wind flow direction in the study area is mainly North- Easterly except in the rainy season (June, July and August) when the wind flow direction changes to the South-West. The position of the ventilators and Plenums is illustrated in figure 10.7

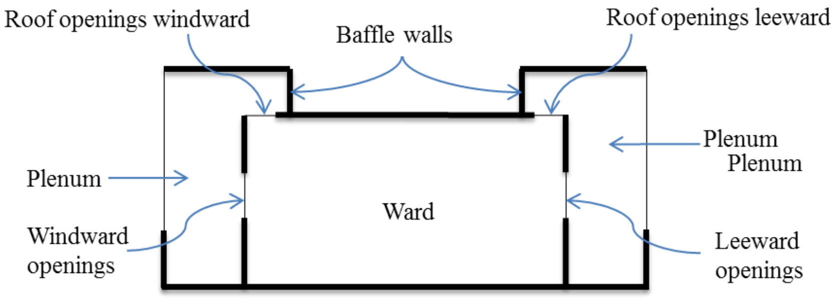


Figure 10.7: The position of the ventilators and Plenums

10.6 The ratio of opening sizes to ward floor area

The hospital wards located at USUHM was adopted as the base-case and used for the simulation. the base-case ward (Case_1) have fulfilled the International Mechanical Code requirement of operable areas should be at least 4% of the total ward floor areas as shown in Table 10-1.

Due to the pressure drop as a result of insect screen mesh, the operable areas need to be increased to account for the decrease in airflow rate. The opening area in this study was increased by opening more outlet openings on the roof surface, which facilitated the provision of the required ventilation rate and airflow circulation at the occupancy level. The sizes of openings to ward floor area in this study was not considered further because, ratio of openings size to ward floor area in the two hospital wards (Cases 16 and 20) studied have satisfied the mechanical code requirement of at least 4% and both have achieved the acceptable ventilation rates. Thus, the ratio of the opening area to the ward floor area in the improved case is 6.07% as illustrated in table 10-1.

Table 10-1: Window Area in Relation to the Hospital Ward's Floor Area

S/N	Hospital Wards	Floor Area	Opening Area	Effective ventilation area	Operable Area %
1	**Base-case (Case_1)**	12.5 x 11.4 = 142.5 m^2	1.2 x 1.2 x 8 = 11.52m^2	5.76m^2	4.05%
2	**Improved (Case 16 & 20)**	12.5 x 11.4 = 142.5 m^2	1.2 x 1.2 x 12 = 17.28m^2	8.64m^2	6.07%

10.7 Insect screen mesh

Different insect screen mesh porosities ranging from 0.9 to 0.1 have been simulated and analysed using outdoor prevailing wind speed of 2.6 m/s and using the improved case (Case16). The results indicate that, using an insect screen mesh of porosity ≥0.4 the air change rates have satisfied the ASHRAE standard requirements, while those with porosity ≤0.3 the air change rates are below the standard requirements.

However, the air change rates increases when the insect screen is installed on the Plenums rather than the ward inlet and outlet openings. With the insect screen installed on the Plenums and airflow direction normal to the inlet openings, the air change rates in all the screen sizes have satisfied the standard requirements with the exception of the case with screen porosity of 0.1. based on the simulation conducted using Case 16, the decrease in air change rate with 60^{o} and 30^{o} orientations compared to the normal (90^{o}) orientation is 10% and 47% respectively as shown in table 10-2. The position of the insect screen mesh on the Plenum is illustrated in figure 10.8.

Table 10-2: Air change rates of different ward orientations for cases 16

Orientation	ACR (Case-16)	% decrease
90 Degrees	13.5	0%
60 Degrees	12.2	10%
30 Degrees	7.2	47%

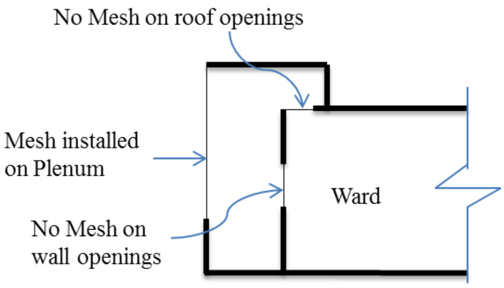


Figure 10.8: The position of insect screen mesh on the Plenum

The above percentage difference is used in interpolating and estimating the effect orientation for the case with Plenum (Case 20) with insect screen porosity of 0.2 and outdoor prevailing wind speed of 2.6 m/s. thus, the air change rate of 15.4 ach^{-1} when the outdoor prevailing wind direction is normal to the inlet openings will be 13.86 ach^{-1} and 8.16 ach^{-1} for 60^{o} and 30^{o} angle of attacks respectively.

Since the air change rates with natural ventilation strategies solely relies on the outdoor wind speed, the utilization of sliding windows with opening areas larger than the standard requirements is necessary to enable the control of the ventilation in relation to the wind flow intensity. This is to enable the hospital ward users to adjust the operable areas in line with the outdoor wind speeds.

10.8 Outdoor prevailing wind speed

Different outdoor wind speeds ranging from 1m/s to 7m/s have been simulated and analysed using insect screen porosity of 0.66 and using the improved case (Case16). The results indicate that, using outdoor prevailing wind speeds ≥ 3m/s the air change rates have satisfied the ASHRAE standard requirements, while using outdoor prevailing wind speed ≤ 2 m/s the air change rates are below the standard requirements. However, the air change rates could be increased when the insect screen is installed on the Plenums rather than directly installing it on the ward inlet and outlet openings.

10.9 Plenum integration and positions

The integration of plenum is recommended to both windward and leeward part of the ward. The leeward plenum should be incorporated to the roof openings to increase the airflow rate in the ward. In this study, the integration of plenums on both windward and leeward sides of the wards helped in reducing mosquitoes and Harmattan dust while providing the required ventilation rates. The plenums reduces the penetration of mosquitoes by permitting the employment of insect screens with lower porosity, when the insect screens are placed directly on the larger plenum openings instead of the ward openings thereby increasing the total opening area and subsequently provides acceptable ventilation rates. However, the integration of plenums also reduces the penetration of Harmattan dust particles by restricting larger particles from passing through the finer insect screens and settlement of smaller particles in the plenums before reaching the ward openings. Hence, it is recommended that, Architects and building service engineers should integrate plenums while deigning hospital wards in semi-arid climates. The typical size of the Plenum used is illustrated in figure 10.9

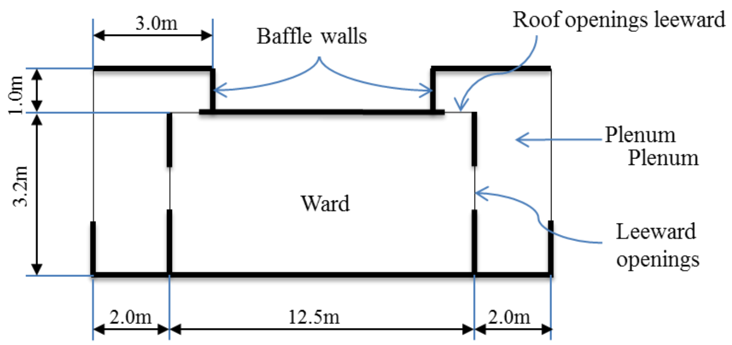


Figure 10.9: The size of the Plenum

10.10 Chapter Conclusion

This chapter discussed and presented various recommendations to be adhered to by Architects and Building Service Engineers when refurbishing or designing new hospital wards in the study area. These recommendations are deduced from the outcome of this study called ‘design guidance for Architects’ and is presented in table 10-3.

Table 10-3: Design Guidance for Architects

S/N	Parameters	Recommendations
1	Building orientation	North-South (The longer sides should be oriented toward the N-S)
2	Opening to wards’ floor area ratio	≥ 6.0 %
3	Building shape	Plenums should be incorporated to the windward and leeward facades
4	Ward size	The maximum depth of the ward is ≤14.
5	Plenum size	The Plenum height is the same with building height and the Plenum Width is 2.0m
6		The height of the baffle walls is ≥1.0m
7	Insect screen installation	Insect screen should be installed on the plenums instead of the ward openings.
8	Insect screen porosity	0.2
9	Ward openings	Ward openings should be provided with sliding windows to allow manual control of the airflow rates in line with the outdoor wind speed
10	Building height	3.2m
11	Fenestrations	Openings should be provided on the windward and leeward walls and on the roof toward the leeward side for better airflow circulation at the occupancy level.
12	Opening positions	Openings should be located at the middle of the windward and leeward walls and on the roof toward the leeward to avoid airflow short-circuiting
13	Wind speeds	When the outdoor local wind speed is ≤ 1.26 m/s (2 m/s: airport value), the ventilation should be supplemented with fan.

Chapter Eleven

Conclusions, Limitations and Recommendations

Chapter Structure

10.1 Introduction

10.2 Conclusions

10.3 Limitations

10.4 Recommendations for Future Works

10.5 Closing remarks

11 Chapter Eleven: Conclusions, Limitations and Recommendations for Future Works

11.1 Introduction

The Chapter 11 is divided into three (3) sections. It presents the conclusions, limitations and recommendations of future work in relation to ventilation and indoor air quality studies in semi-arid climates. The first section presented the conclusion of the study. The second section presented the limitations of the research and the third section presented the future research needs.

11.2 Conclusions

The major conclusion drawn from the various aspects of this study is presented in sections 11.2.1 to 11.2.6.

11.2.1 The occupants' psychosocial perception of the existing hospital wards

The questionnaire survey considered six (6) different indoor environmental conditions including indoor air quality consideration, Harmattan dust problem, Mosquitoes problem, ventilation efficiency, and the effect of indoor air quality on health.

The result shows that 84% of the respondents consider indoor air quality problem in hospital wards when discharging their duties. Moreover, owing to the poor indoor air quality in the studied hospital wards, 93% of the respondents experience odour problem with the hospital wards. In relation to Harmattan dust, 97% of the respondents experience dust problem in the wards and the problems are more severe in Harmattan season with 73% of the respondents experience dust. However, 99% of the respondents revealed that they experience mosquito problem in the wards and the problem is higher in wet season with 89% of the respondents experience mosquito problem.

In terms of thermal comfort and ventilation, 71% of the respondents are not satisfied with the thermal comfort in the hospital wards. However, in relation to ventilation, 17% of the respondents said the ventilation is good, 62% said the ventilation is fairly good and the remaining 21% are not satisfied with the ventilation in the hospital wards. Finally, 43% of the respondents have experienced the deterioration of patients' health due to indoor air quality problem while the remaining 53% did not experience. Thus, the above conclusions confirmed the existence of ventilation and indoor air quality problems in the hospital wards of semi-arid climates.

11.2.2 The measurement of ventilation rates in the existing hospital wards

The results of the full-scale measurements conducted in the months of November and December indicate that the air change rates in four hospital wards have not met the ASHRAE standard of 6 ach^{-1} in patient rooms, as presented in chapter 6. Out of the nine (9) measurements conducted in the four selected hospital wards, only one have made the ASHRAE requirements, because of high wind speed at the time of the measurement. These results affirm the outcome of the psychosocial perception. Thus, ventilation system in the hospital wards of the study area needs to be optimized to achieve the standard requirement.

11.2.3 The opening position and ventilation rates in hospital wards

In the present study, the influence of natural ventilation strategies with various opening positions on the ventilation rates and indoor air speed and distribution has been investigated using seventeen (17) different cases as presented in chapter 8. These opening positions are alternated between higher, middle and lower levels of the windward façade, leeward façade and side façade and roof top of the hospital wards. The result shows that, the case 16 with inlet openings at the middle of the windward façade, and the outlet openings at both the middle of the leeward façade and the leeward end of the roof provided the highest air change rates and the best in terms of airflow circulation and distribution at the occupancy level.

11.2.4 The influence of building orientation, wind speed and Insect screen porosity on ventilation rates

The highest indoor air velocities at the windward sides of the ward, near and opposite the inlet openings are 20% and 12% of the external incident wind velocity for heights 1.0 m and 0.6 m above floor level respectively. The indoor air speeds in the remaining positions at the centre and toward the outlet openings are less than or equal to 2% of the external incident wind velocity.

The simulation results further show that, the higher the indoor air speed, the lower the turbulent intensity inside the ward. Moreover, the highest draught risk estimated at 1.0 m occupancy level for case 1(base-case) and case 16 (best-case) is 10.2% and 16.8% respectively. However, the highest draught risk estimated at 0.6 m occupancy level for case 1(base-case) and case 16 (best-case) is 6.6% and 10.7% respectively. These risks are important in temperate climates, but in hot climates and especially in naturally ventilated buildings their effect is insignificant. This is because building occupants in hot climates can tolerate higher air speeds.

Moreover, in relation to the effect of building orientation on ventilation efficiency, the volumetric airflow rates and the air change rates are higher in cases with external wind incidents normal to the inlet openings (90^o), and then followed by angles 60^o, 30^o and 0^o respectively. In the best-case (case 16), the air change rates in wards with outdoor wind incidents angles of 90^o, 60^o and 30^o have satisfied the ASHREA standard of 6 ach^{-1} in hospital wards while angle 0^o did not. Furthermore, the study confirms that, the average indoor air speeds for wind flow with oblique angle of attack to the openings (30^o and 60^o) are higher compared to the cases with normal (90^o) angle of attack. Thus, the oblique orientations provide better airflow distributions compared to the cases with outdoor wind flow orientation normal to the inlet openings, which channel the airflow directly from the inlet to the outlet.

The volumetric flow rates and the air change rates decreases, with decreasing insect screen porosity. In the best-case (case 16) the air change rates of openings with screen porosities ranging from 0.4 to 0.9 have satisfied the ASHREA standard of 6 ach^{-1} in hospital wards, while the remaining openings with porosities 0.1 to 0.3 did not fulfilled the requirement. Likewise, the higher the outdoor air velocity, the higher the volumetric flow rates and air change rates and vice versa. In the best-case (case 16), the air change rates for simulation with outdoor air velocity ranging from 3 m/s to 7 m/s (airport values, which are being converted to local wind speed in the city centre) have satisfied the ASHREA standard of 6 ach^{-1} in patients room, when the ward's opening orientation is normal to the wind flow direction. However, cases simulated with outdoor wind velocities less than 3 m/s did not fulfil the ASHRAE requirement.

11.2.5 The influence of monthly average weather condition on ventilation rates, indoor air velocity and temperature

The monthly ventilation rates in hospital wards of the study area have been simulated using Case16 (best case). The results indicated that, the highest air change rates of 17.33 ach^{-1} (Case 1) and 25.21 ach^{-1} (Case 16) are experienced in the months of March and June, while the lowest air change rates of 11.33 ach^{-1} (Case 1) and 16.07 ach^{-1} (Case 16) are experienced in the month of September. But the air change rates in all the 12 months simulation for both Cases 1 and 16 have satisfied the ASHRAE standards of 6 ach^{-1} in hospital wards. The average indoor air temperatures in 9 out of the 12 months in a year have satisfied the adaptive comfort (24.2 ^{o}C – 29.2 ^{o}C) requirements except the months of April, May and June, in which the temperatures are slightly higher than the adaptive comfort level. The highest indoor air temperatures of 32.2 ^{o}C (Case 1) and 32.3 ^{o}C (Case 16) are experienced in the month of May, while the lowest indoor air temperatures of 22.0 ^{o}C (Case 1) and 22.1^{o}C (Case 16) are experienced in the month of January.

11.2.6 The influence of insect screen, wind speed, and plenum on dust particle concentration indoors

The influence of insect screen, outdoor wind speed and integration of plenums on dust particles concentration, deposition and suspension in hospital wards was investigated using the best case (case 16), as presented in chapter 9. In this study, screen porosities ranging from 0.1 to 0.9 and dust particle sizes ranging from 0.1μm to 100μm have been used in the simulation. The installation of insect screen on the hospital ward openings influences pollutant dispersion in the ward, as the number particles received indoors increases with growing screen porosity. However, the influence of particle size in pollutant dispersion with different screen porosity is negligible with particle sizes of less than 10μm, but it is significant with larger particles sizes of greater than 10μm when considering the total concentration of particles reaching the indoor space. The influence is significant with both particle deposition and suspension. However, the dust particles concentration indoors increases with increasing ventilation rates, except in cases with installed plenums.

The introduction of a plenum to the windward side of the ward (Case 18) resulted in 83.7% increase in air change rates, while introducing plenums to both the windward and the leeward sides of the ward (Case 19) resulted in 127.9% increase in air change rate, and including the roof openings inside plenums in case 19 (case 20) resulted in 133.7% increase in air change rates compared to the case without plenum (Case 16). The introduction of plenums resulted in decreased particle concentration in the interior part of the wards. The plenum usually reduces the speed of air before the air reaches the inlet openings and by doing so leads to deposition of dust particles. The plenums improve the ventilation rates as a result of installing the insect screen on the larger plenum opening rather than the smaller room inlet and outlet windows. As a result of high ventilation rate recorded by case 20, the screen porosity in this case was reduced from 0.66 to 0.2 which resulted in 51.25% reduction in air change rates, which subsequently lead to considerable reduction in indoor dust particle concentration.

11.3 Limitations

The list of important limitations used in this study is as follows:

a) The semi-arid climates in this study refers to Nigerian part of the semi-arid, precisely, Maiduguri.

b) Hospitals vary widely depending on their functions, but this study is limited to hospital multi-bed wards only.

c) The study did not consider furniture and other indoor geometries.

d) Due the wide range of issues covered by indoor air quality, this study is limited to those consequences that are cause by inefficiency of natural ventilation designs, specifically of Mosquito and Harmattan dust.

e) The measurement of ventilation rates using tracer gas decay techniques is only valid for the period of the measurement.

f) In the process of the questionnaire survey, responses from patients were not collected, because their health condition might influence their environmental perception.

g) In this study, the ventilation effectiveness was assessed based on the visualisation of contours of airflow circulation pattern in the hospital wards and quantitative calculation was not conducted.

h) Relative humidity is not considered in the simulation, owing to the limitation of CFD fluent 13.0 in setting relative humidity. However, due to the low humidity level in the study area (semi-arid climate), its effect is insignificant

i) The study does not consider dust particles with indoor sources.

j) It is generally accepted that, negative pressure is required for airborne precaution and natural ventilation cannot control the airflow direction through the doorway. The pressure difference between the ward and other adjacent spaces is not considered.

k) This study did not consider heat gains from patients and other internal objects in the wards.

l) In order to simplify the simulation process and further reduce computational power effectively, the following assumptions which are also limitations are used for particle dispersion

   i. Heat and mass transfer between air and particles are neglected;
   ii. No particle rebounds on solid surfaces, such as walls, floors and ceilings;
   iii. No particle coagulation in the particle deposition process;
   iv. All particles are in spherical solid shape.

m) It is difficult to control thermal comfort when using natural ventilation, especially when the outdoor air exceeds comfort temperatures, detailed thermal comfort study was not conducted because it is beyond the scope of the research.

11.4 Recommendations for Future Works

Owing to the constraints of computational power when using CFD simulation tools and practical issues when conducting full-scale measurements, many simplification and assumptions have been made. Thus, the study is not perfect and therefore the following recommendations are hereby suggested.

11.4.1 Full-scale measurement

Owing to the complexity of airflow movement and circulation within a building, it is important to consider all factors affecting building interaction with air in the surrounding environment. Most of the hospital wards investigated in this study are part of larger buildings and the ventilation assessments were conducted only in the location of interest (hospital wards). Therefore, these measurements did not consider the interaction of these hospital wards with the other adjoining rooms. Thus it is recommended in future to conduct the full-scale measurement for the entire building rather than the location of interest alone. This will provide the required information considering the complexity of airflow in and around buildings.

However, the measurements were only made for ventilation rates, temperature and relative humidity, without considering indoor air speed. Thus it is recommended that, the indoor air speed should be measured together with the other parameters because of its influence on indoor air quality and ventilation in buildings' indoor environment

11.4.2 CFD simulation

The reliability of any CFD simulation depends largely on how the existing building characteristics are replicated within the virtual CFD environment. In the present study, indoor parameters such as the indoor dwarf walls, furniture and the building occupants are not considered. These indoor parameters may likely influence the outcome of the study. Therefore, it is recommended that, furniture and other objects obtainable in the interior part of the building should be considered when performing simulation for natural ventilation. However, more accurate methods such as Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) should also be explored and employed in the studies of natural ventilation, provided that the required computational power is available.

11.4.3 Natural ventilation

Due to its lower or zero energy requirements, natural ventilation is one of the most sustainable strategies that could provide acceptable indoor air quality, especially in developing countries that are facing energy shortages. In the present study, the possibility of natural ventilation strategies in providing acceptable indoor air quality in hospital wards has been studied. Natural ventilation was selected due to the protracted energy shortage in the study area, Nigeria. Therefore, it is recommended for architects and other building designers to consider natural ventilation from the design stage. In the present hospital wards investigated, it is difficult to incorporate openings to the roof because of the roofing type. Thus, it is suggested that building should be design in such a way that, it can be easily modified for natural ventilation and openings can be easily incorporated to the roofing systems. However, designers should consider the effect of insect screens in reducing ventilation rates from the design stage by accounting for the pressure drop through increasing the opening size or numbers.

11.4.4 Indoor air quality

The two major outdoor sources of indoor air pollutants in the study area are mosquitoes and Harmattan dust. The severity of these factors in the hospital wards of the study area was evaluated through psychosocial perception only. Even though, it is difficult to ascertain the amount of mosquitoes in an indoor environment, but the measurement of dust concentration indoors is feasible. In the present study, the data related to dust is obtained from measured outdoor data. Therefore, it is recommended to ascertain the effect of Harmattan dust on indoor air quality in the building indoor environment using scientific method.

11.4.5 Thermal Comfort

The focus of this study is about ventilation and indoor air quality in hospital wards. However, thermal comfort is one of the major parameters of consideration in building indoor environment studies. Owing to scope and data constraint, the present study did not include thermal comfort study. Thus, it is recommended to conduct a detailed thermal comfort analysis of the cases studied in this research especially the best case.

11.5 Closing remarks

Numerous researches have been conducted studying the ventilation and indoor air quality of hospital wards. But most of these studies are conducted in the context of temperate climates rather than tropics (semi-arid climates). These studies did not consider tropical issues such as mosquitoes and Harmattan dust. Moreover, the solutions to these factors requires installation of protective measures on the ventilation openings and these measures result in pressure drop across the opening, which subsequently reduced the ventilation rates in the building. The decrease in ventilation rates implies higher pollutant concentration indoors. Thus this study was intended to reduce the existing knowledge gap between the temperate and the tropics, by providing sustainable ventilation with consideration to factors such as mosquitoes and Harmattan dust.

To achieve the objectives of this study, various research methods has been employed including psychosocial perception, full-scale measurement and CFD simulations. The identification of research problems though literature review only is not enough. Thus, the psychosocial perception and the full-scale measurement were used to identify and confirm the pressing ventilation and indoor air quality problems in the study area. However, owing to the flexibility of the Computational Fluid Dynamics (CFD), it was used in simulating various natural ventilation strategies and predicted the best strategy for the study area.

The outcome of this study is significant for architects, building system designers as a feed forward to new designs and existing buildings refurbishments. In this study, a methodology for measuring buildings adaptability to natural ventilation design has been developed. This methodology will be applied in ascertaining the level of compliance of a building to accommodate the proposed natural ventilation strategies.

Appendices

12 Appendices

12.1 Appendix 1: Questionnaire Survey

Questionnaire Survey

Natural Ventilation: A Case for Improving Indoor Air Quality in HealthCare Facilities of Semi-Arid Climates

Dear Sir/Madam,

Mr. ***Mohammed Alhaji Mohammed*** is a PhD research student in the School of Architecture, Planning and Landscape, Newcastle University. He is currently collecting data for his PhD research titled *"Natural Ventilation: A Case for Improving Indoor Air Quality in HealthCare Facilities of Semi-Arid Climates"*. He is required to conduct a questionnaire survey to seek opinions from the immediate users of healthcare facilities (Multi-Bed Wards) in the study area on various issues related to Indoor Air Quality and Ventilation. The survey is conducted by interacting with the concerned persons including Medical Doctors, Nurses and other Healthcare workers.

I hope that you will extend any help you can to make his research successful. We always value your participation and appreciate your active contribution in this phase of the study.

Thanks in advance for your positive cooperation.

Yours Sincerely

Dr Steve Dudek

Ph.D. Supervisor

Questionnaire Survey

"Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals of Semi-Arid Climates"."

[DOCTORS, NURSES AND HEALTHCARE WORKERS]

Mr. ***Mohammed Alhaji Mohammed*** is a PhD research student in the School of Architecture, Planning and Landscape, Newcastle University. He is currently collecting data for his PhD research titled *"Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals of Semi-Arid Climates"*. He is required to conduct a questionnaire survey to seek opinions from the immediate users of healthcare facilities on various issues related to the study. The survey will be conducted by interacting with the concerned persons including Medical Doctors, Nurses and other healthcare workers.

Thank you in advance for providing any assistance required to make his research successful.

Your positive participation and active contribution are valued and very much appreciated.

Section I: Respondent's General Information

Name (Optional)		***Rank:***	
Organization Name		***Department/Section:***	
Mailing Address :		***E-mail :***	
		Experience:	
Tel :		***Ward***	

Section II: Indoor Air Quality

Air Quality	
1. Have you ever considered Indoor Air Quality as a Problem In the wards?	*Yes* ☐ *No* ☐
How?	1.
	2.
	3.
2. Do you usually experience some smell or odour in the wards?	*Yes* ☐ *No* ☐
How?	1.
	2.
	3.
3. Do you recognize some indoor air contaminants sources within/around the wards?	*Yes* ☐ *No* ☐
Where?	1.
	2.
	3.
4. What are your general views about indoor air quality in the wards?	
Comments (Why):	***Suggestions***
	1.

	2.
	3.
	4.
	5.
Harmattan Dust	6.
5. Do you normally experience dust problem in the wards?	*Yes* ☐ *No* ☐
6. What are the possible sources of these dusts?	***Suggestions***
	1.
Comments (Why):	2.
	3.
	4.
	5.
	6.
7. Are their noticeable dust particles on the floor, furniture etc.	*Yes* ☐ *No* ☐
8. Is the dust problem worst in certain season?	*Yes* ☐ *No* ☐
9. If yes which season	*Dry* ☐ *wet* ☐ *Harmattan* ☐ *other* ☐
Comments (Why):	***Suggestions***
	1.
	2.
	3.
	4.
Mosquito	5.
10. Do you usually experience Mosquito problem in the wards?	*Yes* ☐ *No* ☐
11. What are the possible sources of entrance of these mosquitoes?	***Suggestions***
Comments (Why):	1.
	2.
	3.
	5.
	5.
	6.
12. Is the mosquito problem worst in certain season?	*Yes* ☐ *No* ☐
13. If yes which season	*Dry* ☐ *wet* ☐ *other* ☐
Comments (Why):	***Suggestions***
	1.
	2.
	3.
	4.
	5.
Thermal Comfort	6.
14. Are you satisfied with thermal comfort (Temperature and Humidity) in the ward?	*Yes* ☐ *No* ☐
Temperature/Humidity	***Suggestions***
Comments (Why):	1.
	2.
	3.
	4.
	5.
15. Is the ward draught	*Yes* ☐ *No* ☐
16. Is the ward humid	*Yes* ☐ *No* ☐
Ventilation	
17. What is the nature of the airflow in the ward space?	Good ☐ *Fairly Good* ☐ *Not so Good* ☐

	Suggestions
Ventilation	1.
Comments (Why):	2.
	3.
	4.
	5.
	6.
18. Have you experienced any cases of deterioration in patient health due to indoor air quality problems in the wards?	*Yes* ☐ *No* ☐
Comments (Why):	***Suggestions***
	1.
	2.
	3.
	4.
General Comments (if any)	1.
	2.
	3.
	4.
	5.

Thank you for completing this survey

12.2 Appendix 2: Walkthrough Evaluation Checklist

S/N	Performance Indicators	Evaluation Terms	Comments
Name of Hospital/Ward			
Building Parameters			
01	Building age		
02	Number of storeys		
03	Availability of Balcony		
04	Surrounding vegetation		
05	Building Density Nearby		
06	Existing type of ventilation		
Multi-Bed Ward Parameters			
01	Investigated Ward Size		
02	Investigated Ward Floor Area		
03	Investigated Ward Shape and Form		
04	Isolated or space within building		
05	Investigated Ward Level		
06	Investigated Ward Height		
07	Ward Orientation		
08	Internal partitions		
09	Stair case inside the ward		
10	Nurses area		
11	Doctors room		
12	Utility rooms		
13	Conveniences		
14	Treatment area		
15	No of access and entrance Lobby		
16	Investigated Ward Occupancy		
Multi-Bed Ward Openings			
01	Number of windows		
02	Type of Windows		
03	Size of Windows		
04	Forms and Materials of Windows		
05	High level windows		
06	Number of Doors		
07	Type of Doors		
08	Size of Doors		
09	Forms and Materials of Doors		
10	Types and Materials of Curtains		
11	Types and Materials of Netting		
12	Window orientation		
Multi-Bed Ward Furniture			
01	Furniture Types		
02	Number of Beds		
03	Material and type of waiting chairs		
Multi-Bed Ward Ceiling			
01	Type ceiling		
02	Ceiling colour		
03	Ceiling shape/form		
04	Ceiling skirting		
Multi-Bed Ward Floor			
01	Types of floor finishing		
02	Type of floor tiles		
03	Tiles shape and form		

04	Tiles colour		
05	Type and shape of floor Skirting		
Multi-Bed Ward Wall			
01	Wall type		
02	Walling Material		
03	Wall shape and form		
04	Type and colour of paint		
Multi-Bed Ward Ventilation System			
01	Mechanical Ventilation		
02	Natural Ventilation		
03	Hybrid Ventilation		
04	Ceiling Fans		

12.3 Appendix 3: Particle tracking data

12.3.1 Insect Screen Porosity and Dust Particles Concentration

Table 12-1: Tracked, escaped and trapped characteristics of 1µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (1.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18635	149	27	63	50	1	5	3	14	2	0
0.2	18800	18469	325	92	126	71	2	15	19	4	2	0
0.3	18800	18247	545	172	232	87	4	25	25	5	3	0
0.4	18800	17969	815	304	308	99	18	40	46	7	9	0
0.5	18800	17703	1052	445	377	88	19	59	64	16	29	0
0.6	18800	17484	1223	519	419	72	39	83	91	43	50	0
0.7	18800	17199	1459	675	524	59	63	64	74	65	77	0
0.8	18800	17039	1521	658	593	55	59	81	75	127	113	0
0.9	18800	16822	1669	698	643	68	95	83	82	149	160	0
1.0	18800	16058	2373	846	804	143	245	167	168	162	207	0

Table 12-2: Tracked, escaped and trapped characteristics of 2.5µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (2.5µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18627	153	27	64	49	1	6	6	14	6	0
0.2	18800	18452	337	90	140	71	2	18	16	11	0	0
0.3	18800	18238	550	180	208	94	2	28	38	8	4	0
0.4	18800	17921	853	318	331	101	9	48	46	13	13	0
0.5	18800	17667	1074	458	393	76	17	65	65	32	27	0
0.6	18800	17464	1235	543	459	65	32	65	71	50	51	0
0.7	18800	17197	1430	633	529	54	43	85	86	93	80	0
0.8	18800	16989	1561	675	580	69	66	78	93	128	122	0
0.9	18800	16844	1636	675	638	69	84	85	85	162	158	0
1.0	18800	16057	2369	922	792	122	255	145	133	179	195	0

Table 12-3: Tracked, escaped and trapped characteristics of 5.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (5.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18619	159	25	53	68	2	6	5	20	2	0
0.2	18800	18430	356	90	146	94	0	14	14	12	0	0
0.3	18800	18233	556	187	207	106	7	26	23	9	2	0
0.4	18800	17924	845	358	274	99	7	52	55	20	11	0
0.5	18800	17673	1073	460	378	88	19	72	56	29	25	0
0.6	18800	17421	1290	619	415	62	38	77	79	48	41	0
0.7	18800	17226	1421	689	469	53	56	72	82	76	77	0
0.8	18800	16964	1576	728	545	49	77	91	86	121	139	0
0.9	18800	16839	1663	761	576	60	94	93	88	137	161	0
1.0	18800	16068	2414	975	740	166	214	148	171	142	176	0

Table 12-4: Tracked, escaped and trapped characteristics of 10.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (10.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18605	173	58	41	58	1	6	9	15	7	0
0.2	18800	18442	341	140	91	90	1	12	7	16	1	0
0.3	18800	18219	571	277	134	96	10	27	27	8	2	0
0.4	18800	17980	800	456	164	89	9	46	36	15	5	0
0.5	18800	17651	1106	686	230	59	18	59	54	21	22	0
0.6	18800	17477	1247	759	260	47	31	71	79	44	32	0
0.7	18800	17118	1539	957	333	46	58	75	70	81	62	0
0.8	18800	16954	1638	976	364	39	69	100	90	118	90	0
0.9	18800	16777	1744	1053	396	48	93	70	85	131	148	0
1.0	18800	16122	2381	1260	480	119	225	159	138	145	152	0

Table 12-5: Tracked, escaped and trapped characteristics of 20.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (20.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18602	169	104	5	58	0	2	0	24	5	0
0.2	18800	18453	332	240	1	78	0	7	6	14	1	0
0.3	18800	18229	562	479	3	71	0	5	4	8	1	0
0.4	18800	17937	857	776	15	39	4	12	11	5	1	0
0.5	18800	17677	1107	1017	13	25	5	29	18	12	4	0
0.6	18800	17460	1328	1222	28	10	7	28	33	7	5	0
0.7	18800	17257	1499	1371	27	8	23	31	39	30	14	0
0.8	18800	16937	1780	1628	36	8	37	36	35	49	34	0
0.9	18800	16853	1835	1643	50	6	37	51	48	63	49	0
1.0	18800	15833	2835	2263	88	65	166	137	116	67	65	0

Table 12-6: Tracked, escaped and trapped characteristics of 30.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (30.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18584	165	123	0	32	9	1	0	35	16	0
0.2	18800	18424	345	297	0	47	1	0	0	23	8	0
0.3	18800	18234	557	526	0	30	0	0	1	9	0	0
0.4	18800	17881	913	897	0	12	0	2	2	6	0	0
0.5	18800	17680	1117	1104	0	9	0	2	2	3	0	0
0.6	18800	17477	1320	1299	1	7	0	5	8	2	1	0
0.7	18800	17242	1555	1537	0	7	2	4	5	3	0	0
0.8	18800	16970	1823	1800	2	8	0	7	6	4	3	0
0.9	18800	16779	2010	1980	1	9	7	10	3	9	2	0
1.0	18800	15448	3350	3142	7	14	55	64	68	2	0	0

Table 12-7: Tracked, escaped and trapped characteristics of 40.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (40.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18552	176	142	0	28	6	0	0	44	28	0
0.2	18800	18437	311	268	0	31	12	0	0	36	16	0
0.3	18800	18238	540	513	0	25	1	1	0	17	5	0
0.4	18800	18012	772	753	0	18	0	0	1	14	2	0
0.5	18800	17709	1083	1063	0	20	0	0	0	8	0	0
0.6	18800	17468	1328	1318	0	10	0	0	0	4	0	0
0.7	18800	17195	1601	1590	0	10	0	1	0	4	0	0
0.8	18800	16988	1812	1798	0	11	0	2	1	0	0	0
0.9	18800	16837	1963	1954	0	8	0	0	1	0	0	0
1.0	18800	15302	3497	3424	0	10	4	31	28	1	0	0

Table 12-8: Tracked, escaped and trapped characteristics of 50.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (50.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18609	130	111	0	15	4	0	0	50	11	0
0.2	18800	18464	289	261	0	20	8	0	0	31	16	0
0.3	18800	18281	488	463	0	22	3	0	0	24	7	0
0.4	18800	18044	734	713	0	17	4	0	0	17	5	0
0.5	18800	17868	923	914	0	9	0	0	0	9	0	0
0.6	18800	17525	1271	1256	0	15	0	0	0	4	0	0
0.7	18800	17347	1452	1439	0	13	0	0	0	1	0	0
0.8	18800	17111	1689	1670	0	19	0	0	0	0	0	0
0.9	18800	17046	1753	1745	0	8	0	0	0	1	0	0
1.0	18800	15490	3309	3288	0	2	0	13	6	1	0	0

Table 12-9: Tracked, escaped and trapped characteristics of 60.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (60.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18630	136	120	0	13	3	0	0	24	10	0
0.2	18800	18519	248	222	0	24	2	0	0	23	10	0
0.3	18800	18347	434	417	0	16	1	0	0	16	3	0
0.4	18800	18135	651	640	0	9	2	0	0	10	4	0
0.5	18800	17880	912	895	0	17	0	0	0	7	1	0
0.6	18800	17693	1105	1099	0	6	0	0	0	2	0	0
0.7	18800	17524	1275	1258	0	17	0	0	0	1	0	0
0.8	18800	17269	1530	1515	0	15	0	0	0	1	0	0
0.9	18800	17119	1680	1671	0	9	0	0	0	1	0	0
1.0	18800	15691	3108	3098	0	8	0	0	2	1	0	0

Table 12-10: Tracked, escaped and trapped characteristics of 70.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (70.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18675	99	84	0	10	5	0	0	23	3	0
0.2	18800	18559	223	216	0	7	0	0	0	13	5	0
0.3	18800	18407	383	365	0	17	1	0	0	5	5	0
0.4	18800	18193	602	590	0	12	0	0	0	2	3	0
0.5	18800	18066	732	725	0	7	0	0	0	1	1	0
0.6	18800	17815	982	975	0	7	0	0	0	2	1	0
0.7	18800	17650	1149	1143	0	6	0	0	0	0	1	0
0.8	18800	17427	1373	1363	0	10	0	0	0	0	0	0
0.9	18800	17294	1506	1499	0	7	0	0	0	0	0	0
1.0	18800	15967	2833	2829	0	4	0	0	0	0	0	0

Table 12-11: Tracked, escaped and trapped characteristics of 80.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (80.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18700	87	81	0	4	2	0	0	9	4	0
0.2	18800	18618	173	166	0	6	1	0	0	8	1	0
0.3	18800	18440	357	348	0	8	1	0	0	1	2	0
0.4	18800	18324	489	484	0	4	1	0	0	3	4	0
0.5	18800	18135	665	663	0	2	0	0	0	0	0	0
0.6	18800	17976	824	823	0	1	0	0	0	0	0	0
0.7	18800	17749	1051	1047	0	4	0	0	0	0	0	0
0.8	18800	17621	1179	1177	0	2	0	0	0	0	0	0
0.9	18800	17445	1355	1352	0	3	0	0	0	0	0	0
1.0	18800	16320	2480	2474	0	6	0	0	0	0	0	0

Table 12-12: Tracked, escaped and trapped characteristics of 90.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (90.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18716	77	72	0	2	3	0	0	2	5	**0**
0.2	18800	18630	170	166	0	4	0	0	0	0	0	0
0.3	18800	18531	266	263	0	2	1	0	0	0	3	0
0.4	18800	18415	383	379	0	2	2	0	0	0	2	0
0.5	18800	18210	587	585	0	2	0	0	0	1	2	0
0.6	18800	18116	682	681	0	0	1	0	0	2	0	0
0.7	18800	17954	846	846	0	0	0	0	0	0	0	0
0.8	18800	17816	984	984	0	0	0	0	0	0	0	0
0.9	18800	17713	1087	1086	0	1	0	0	0	0	0	0
1.0	18800	16657	2143	2143	0	0	0	0	0	0	0	0

Table 12-13: Tracked, escaped and trapped characteristics of 100.0µm dust particles for different insect screen porosities

Porosity	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (100.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
0.1	18800	18720	74	71	0	2	1	0	0	0	6	0
0.2	18800	18666	130	126	0	3	1	0	0	1	3	0
0.3	18800	18573	227	225	0	2	0	0	0	0	0	0
0.4	18800	18464	336	336	0	0	0	0	0	0	0	0
0.5	18800	18334	465	464	0	1	0	0	0	1	0	0
0.6	18800	18269	531	531	0	0	0	0	0	0	0	0
0.7	18800	18068	732	732	0	0	0	0	0	0	0	0
0.8	18800	17970	830	830	0	0	0	0	0	0	0	0
0.9	18800	17879	921	921	0	0	0	0	0	0	0	0
1.0	18800	17105	1695	1695	0	0	0	0	0	0	0	0

12.3.2 Outdoor Prevailing Wind Speeds and Dust Particles Concentration Indoors

Table 12-14: Tracked, escaped and trapped characteristics of 1µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (1.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18353	438	72	304	30	11	9	12	7	2	0
2.0 m/s	18800	17918	850	178	511	64	26	40	31	22	10	0
3.0 m/s	18800	17503	1226	486	480	78	23	78	81	36	35	0
4.0 m/s	18800	17277	1409	621	501	71	47	88	81	54	60	0
5.0 m/s	18800	17159	1480	634	543	67	49	97	90	63	98	0
6.0 m/s	18800	16913	1664	729	616	65	79	97	78	103	120	0
7.0 m/s	18800	16757	1730	750	651	61	81	103	84	150	163	0

Table 12-15: Tracked, escaped and trapped characteristics of 2.5µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (2.5µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18311	474	71	315	55	16	7	10	12	3	0
2.0 m/s	18800	17958	806	197	446	63	25	30	45	22	14	0
3.0 m/s	18800	17569	1167	456	454	83	33	77	64	35	29	0
4.0 m/s	18800	17298	1381	612	503	67	33	85	81	62	59	0
5.0 m/s	18800	17103	1543	681	571	71	55	88	77	68	86	0
6.0 m/s	18800	16947	1614	699	592	68	79	85	91	105	134	0
7.0 m/s	18800	16818	1700	741	623	64	97	91	84	122	160	0

Table 12-16: Tracked, escaped and trapped characteristics of 5.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 (5.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18360	432	108	239	51	9	14	11	7	1	0
2.0 m/s	18800	17920	846	257	415	60	29	48	37	23	11	0
3.0 m/s	18800	17562	1188	528	399	79	30	90	62	23	27	0
4.0 m/s	18800	17307	1392	648	445	73	57	87	82	46	55	0
5.0 m/s	18800	17115	1514	725	486	51	60	103	89	80	91	0
6.0 m/s	18800	16865	1686	788	565	67	71	95	100	121	128	0
7.0 m/s	18800	16840	1675	747	547	77	98	101	105	136	149	0

Table 12-17: Tracked, escaped and trapped characteristics of 10.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((10.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18319	469	280	97	67	4	10	11	11	1	0
2.0 m/s	18800	17863	910	563	215	53	19	29	31	20	7	0
3.0 m/s	18800	17599	1157	741	230	55	21	61	49	21	23	0
4.0 m/s	18800	17314	1385	884	271	59	30	71	70	50	51	0
5.0 m/s	18800	17082	1568	909	363	56	58	98	84	78	72	0
6.0 m/s	18800	16948	1641	883	433	50	76	101	98	105	106	0
7.0 m/s	18800	16835	1704	994	439	53	80	81	107	120	141	0

Table 12-18: Tracked, escaped and trapped characteristics of 20.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((20.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18318	450	385	3	54	5	3	0	18	14	0
2.0 m/s	18800	17915	871	837	0	24	0	5	5	14	0	0
3.0 m/s	18800	17562	1229	1169	11	10	2	17	20	7	2	0
4.0 m/s	18800	17269	1506	1382	26	24	10	37	27	12	13	0
5.0 m/s	18800	17122	1618	1372	78	19	31	61	57	34	26	0
6.0 m/s	18800	16973	1704	1401	115	21	39	62	66	59	64	0
7.0 m/s	18800	16758	1856	1463	160	29	55	79	70	82	104	0

Table 12-19: Tracked, escaped and trapped characteristics of 30.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((30.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18495	292	238	0	53	1	0	0	9	4	0
2.0 m/s	18800	18027	759	747	0	12	0	0	0	13	1	0
3.0 m/s	18800	17609	1189	1181	0	7	0	1	0	2	0	0
4.0 m/s	18800	17285	1513	1488	0	13	0	6	6	2	0	0
5.0 m/s	18800	17068	1720	1673	3	17	10	11	6	10	2	0
6.0 m/s	18800	16958	1813	1742	8	4	16	22	21	17	12	0
7.0 m/s	18800	16743	1996	1894	11	11	28	25	27	36	25	0

Table 12-20: Tracked, escaped and trapped characteristics of 40.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((40.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18601	199	167	0	32	0	0	0	0	0	0
2.0 m/s	18800	18094	699	681	0	17	1	0	0	6	1	0
3.0 m/s	18800	17686	1108	1094	0	14	0	0	0	6	0	0
4.0 m/s	18800	17366	1428	1414	0	12	0	1	1	6	0	0
5.0 m/s	18800	17119	1680	1658	0	16	0	4	2	1	0	0
6.0 m/s	18800	16946	1851	1830	0	12	1	4	4	2	1	0
7.0 m/s	18800	16788	2006	1972	2	9	2	9	12	4	2	0

Table 12-21: Tracked, escaped and trapped characteristics of 50.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((50.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18706	94	80	0	14	0	0	0	0	0	0
2.0 m/s	18800	18266	532	519	0	12	1	0	0	2	0	0
3.0 m/s	18800	17786	1012	1000	0	11	1	0	0	1	1	0
4.0 m/s	18800	17524	1272	1265	0	7	0	0	0	4	0	0
5.0 m/s	18800	17220	1575	1558	0	17	0	0	0	5	0	0
6.0 m/s	18800	17057	1742	1727	0	15	0	0	0	1	0	0
7.0 m/s	18800	16902	1898	1879	0	18	0	0	1	0	0	0

Table 12-22: Tracked, escaped and trapped characteristics of 60.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((60.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18741	59	51	0	8	0	0	0	0	0	0
2.0 m/s	18800	18445	355	352	0	3	0	0	0	0	0	0
3.0 m/s	18800	17918	876	865	0	11	0	0	0	4	2	0
4.0 m/s	18800	17573	1224	1209	0	15	0	0	0	2	1	0
5.0 m/s	18800	17343	1454	1441	0	13	0	0	0	2	1	0
6.0 m/s	18800	17158	1640	1631	0	9	0	0	0	2	0	0
7.0 m/s	18800	16925	1875	1866	0	9	0	0	0	0	0	0

Table 12-23: Tracked, escaped and trapped characteristics of 70.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((70.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18775	25	21	0	4	0	0	0	0	0	0
2.0 m/s	18800	18523	277	271	0	6	0	0	0	0	0	0
3.0 m/s	18800	18097	703	694	0	9	0	0	0	0	0	0
4.0 m/s	18800	17765	1032	1023	0	9	0	0	0	3	0	0
5.0 m/s	18800	17443	1355	1346	0	9	0	0	0	2	0	0
6.0 m/s	18800	17181	1617	1608	0	9	0	0	0	2	0	0
7.0 m/s	18800	17033	1765	1757	0	8	0	0	0	2	0	0

Table 12-24: Tracked, escaped and trapped characteristics of 80.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((80.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18788	12	9	0	3	0	0	0	0	0	0
2.0 m/s	18800	18618	182	181	0	1	0	0	0	0	0	0
3.0 m/s	18800	18241	559	558	0	1	0	0	0	0	0	0
4.0 m/s	18800	17875	924	922	0	2	0	0	0	0	1	0
5.0 m/s	18800	17657	1143	1139	0	4	0	0	0	0	0	0
6.0 m/s	18800	17360	1440	1436	0	4	0	0	0	0	0	0
7.0 m/s	18800	17244	1556	1554	0	2	0	0	0	0	0	0

Table 12-25: Tracked, escaped and trapped characteristics of 90.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((90.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	18795	5	5	0	0	0	0	0	0	0	0
2.0 m/s	18800	18660	140	139	0	1	0	0	0	0	0	0
3.0 m/s	18800	18347	453	452	0	1	0	0	0	0	0	0
4.0 m/s	18800	18048	752	752	0	0	0	0	0	0	0	0
5.0 m/s	18800	17731	1068	1066	0	1	1	0	0	0	1	0
6.0 m/s	18800	17527	1273	1271	0	2	0	0	0	0	0	0
7.0 m/s	18800	17342	1457	1455	0	2	0	0	0	1	0	0

Table 12-26: Tracked, escaped and trapped characteristics of 100.0µm dust particles for different outdoor wind speeds

Velocity m/s	Tracked	Escaped Before entering the room	Trapped	Trapped Surfaces_Case_16 ((100.0µm)						Escaped via openings		Incomplete
				Floor surface	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	Wall outlets	Roof outlets	
1.0 m/s	18800	19799	1	1	0	0	0	0	0	0	0	0
2.0 m/s	18800	18704	96	96	0	0	0	0	0	0	0	0
3.0 m/s	18800	18459	341	341	0	0	0	0	0	0	0	0
4.0 m/s	18800	18186	614	614	0	0	0	0	0	0	0	0
5.0 m/s	18800	17859	940	940	0	0	0	0	0	0	1	0
6.0 m/s	18800	17638	1161	1161	0	0	0	0	0	1	0	0
7.0 m/s	18800	17491	1309	1309	0	0	0	0	0	0	0	0

12.3.3 Effect of Plenums on Dust Particles Concentration Indoors

Table 12-27: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 16

Particle size	Tracked	Escaped Before entering the room	Trapped	% Trapped	Trapped Surfaces_Case_16								Escaped via openings		% Escaped	Incomplete
					Floor surface	% Deposited on floor	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended	Wall outlets	Roof outlets		
1.0µm	18800	17256	1393	90.22	627	40.61	498	44	53	79	92	49.61	69	82	9.78	0
2.5µm	18800	17300	1362	90.80	605	40.33	498	61	49	72	77	50.47	69	69	9.20	0
5.0µm	18800	17258	1405	91.16	683	44.29	450	42	52	101	77	46.82	63	74	8.88	0
10.0µm	18800	17261	1410	91.62	850	55.23	293	52	43	89	83	36.39	66	63	8.38	0
20.0µm	18800	17233	1529	97.57	1413	90.17	30	19	12	30	25	7.40	24	14	2.43	0
30.0µm	18800	17295	1503	99.87	1486	98.74	0	9	0	6	2	1.13	2	0	0.13	0
40.0µm	18800	17331	1466	99.80	1452	98.84	0	14	0	0	0	0.95	3	0	0.20	0
50.0µm	18800	17433	1365	99.85	1353	98.98	0	12	0	0	0	0.88	2	0	0.15	0
60.0µm	18800	17556	1243	99.92	1236	99.36	0	7	0	0	0	0.56	1	0	0.08	0
70.0µm	18800	17688	1111	99.91	1100	98.92	0	11	0	0	0	0.99	1	0	0.09	0
80.0µm	18800	17888	911	99.89	910	99.78	0	0	1	0	0	0.11	0	1	0.11	0
90.0µm	18800	17965	833	99.76	830	99.40	0	1	2	0	0	0.36	0	2	0.24	0
100.0µm	18800	18075	725	100.0	723	99.72	0	2	0	0	0	0.28	0	0	0.00	0

Table 12-28: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 18

Particle size	Tracke d	Escaped Before entering the room	Trapped Ward surfaces	% trapped ward surfaces	Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_18 (Case 16 with Plenum)								Escaped via openings		% Escape d	Incomplete
							Floor surface	% Deposited on floor	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspend ed	Wall outlets	Roof outlets		
1.0µm	18800	17103	991	57.72	240	13.98	354	20.62	371	31	150	39	46	37.10	234	252	28.31	0
2.5µm	18800	17158	926	55.72	247	14.86	351	21.12	332	36	136	36	35	34.60	234	255	29.42	0
5.0µm	18800	17120	962	56.59	253	14.88	387	22.76	335	23	145	36	36	33.82	248	237	28.53	0
10.0µm	18800	17024	976	54.34	349	19.43	499	27.78	225	37	140	35	40	26.56	213	258	26.22	0
20.0µm	18800	16787	1134	55.78	602	29.61	978	48.11	16	20	93	18	9	7.67	153	144	14.61	0
30.0µm	18800	16560	1097	48.54	1090	48.23	1057	46.77	0	6	28	2	4	1.77	50	23	3.23	0
40.0µm	18800	16359	881	35.80	1574	63.96	875	35.55	0	2	4	0	0	0.24	6	0	0.24	0
50.0µm	18800	16271	606	23.77	1943	76.23	600	23.54	0	6	0	0	0	0.24	0	0	0	0
60.0µm	18800	16254	418	16.29	2148	83.71	415	16.17	0	3	0	0	0	0.12	0	0	0	0
70.0µm	18800	16389	284	11.68	2147	88.32	281	11.56	0	3	0	0	0	0.12	0	0	0	0
80.0µm	18800	16408	159	6.59	2253	93.41	157	6.51	0	2	0	0	0	0.08	0	0	0	0
90.0µm	18800	16624	90	4.10	2106	95.90	90	4.10	0	0	0	0	0	0.00	0	0	0	0
100.0µm	18800	16786	55	2.70	1979	97.30	55	2.70	0	0	0	0	0	0.00	0	0	0	0

Table 12-29: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 19

Particle size	Tracked	Escaped Before entering the room	Trapped Ward surfaces	% trapped ward surfaces	Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_19 (Case 16 with Double Plenum)								Escaped via openings		% Escaped	Incomplete
							Floor surface	% Deposited on floor	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended	Wall outlets plenum	Roof outlets		
1.0µm	18800	16715	1138	54.58	260	12.47	462	22.16	391	45	158	43	39	32.42	473	214	32.95	0
2.5µm	18800	16747	1159	56.45	229	11.15	477	23.23	396	59	153	38	36	33.22	451	214	32.39	0
5.0µm	18800	16641	1163	53.87	267	12.37	492	22.79	346	47	187	40	51	31.08	520	209	33.77	0
10.0µm	18800	16576	1233	55.44	297	13.35	651	29.27	277	56	139	57	53	26.17	461	233	31.21	0
20.0µm	18800	16414	1274	53.39	596	24.98	1051	44.05	40	13	134	20	16	9.35	409	107	21.63	0
30.0µm	18800	16031	1371	49.51	1138	41.10	1309	47.27	1	2	52	2	5	2.24	222	38	9.39	0
40.0µm	18800	15798	1166	38.84	1670	55.63	1152	38.37	0	5	9	0	0	0.47	161	5	5.53	0
50.0µm	18800	15926	830	28.88	1894	65.90	825	28.71	0	5	0	0	0	0.17	150	0	5.22	0
60.0µm	18800	15898	584	20.12	2229	76.81	580	19.99	0	4	0	0	0	0.14	89	0	3.07	0
70.0µm	18800	16079	389	14.30	2296	84.38	382	14.04	0	7	0	0	0	0.26	36	0	1.32	0
80.0µm	18800	16294	240	9.58	2255	89.98	239	9.54	0	1	0	0	0	0.04	11	0	0.44	0
90.0µm	18800	16401	139	5.79	2253	93.91	138	5.75	0	1	0	0	0	0.04	7	0	0.29	0
100.0µm	18800	16648	72	3.35	2078	96.56	72	3.35	0	0	0	0	0	0.00	2	0	0.09	0

Table 12-30: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 20

Particle size	Tracked	Escaped Before entering the room	Trapped	% trapped ward surfaces	Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_20 (Case 19 with roof opening inclusive in the plenum)								Outlets plenum opening	% Escaped	Incomplete
							Floor surface	% Deposited on floor	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended			
1.0µm	18800	16706	1139	54.39	242	11.56	404	19.29	397	58	163	60	57	35.10	713	34.05	0
2.5µm	18800	16672	1121	52.68	254	11.94	427	20.07	385	55	162	45	47	32.61	753	35.39	0
5.0µm	18800	16671	1105	51.90	263	12.35	448	21.04	344	56	156	49	52	30.86	761	35.74	0
10.0µm	18800	16577	1145	51.51	324	14.57	579	26.05	224	54	195	52	41	25.46	754	33.92	0
20.0µm	18800	16382	1267	52.40	603	24.94	1050	43.42	28	22	117	27	23	8.97	548	22.66	0
30.0µm	18800	16101	1321	48.94	1089	40.35	1259	46.65	1	3	55	3	0	2.30	289	10.71	0
40.0µm	18800	15754	1193	39.17	1680	55.15	1179	38.71	0	6	8	0	0	0.46	173	5.68	0
50.0µm	18800	15844	868	29.36	2002	67.73	860	29.09	0	7	1	0	0	0.27	86	2.91	0
60.0µm	18800	16021	560	20.15	2175	78.27	559	20.12	0	1	0	0	0	0.04	44	1.58	0
70.0µm	18800	16034	393	14.21	2362	85.39	389	14.06	0	4	0	0	0	0.14	11	0.40	0
80.0µm	18800	16246	267	10.45	2277	89.15	263	10.30	0	4	0	0	0	0.16	10	0.39	0
90.0µm	18800	16415	150	6.29	2225	93.29	150	6.29	0	0	0	0	0	0.00	10	0.42	0
100.0µm	18800	16644	86	3.99	2065	95.78	86	3.99	0	0	0	0	0	0.00	5	0.23	0

12.3.4 Effect of Plenums and Screen Porosity on Dust Particles Concentration Indoors

Table 12-31: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 19 with insect screen porosity of P-0.1

Particle size	Tracked	Escaped Before entering the room	Trapped	% trapped ward surfaces	Trapped Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_19 (P-0.1)								Escaped via openings			Incom-plete
							Floor surface	% Deposited	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended	Wall outlets plenum	Roof outlets	% Escaped	
1.0µm	18800	18171	331	52.62	200	31.80	114	18.12	142	32	6	17	20	34.50	97	1	15.58	0
2.5µm	18800	18131	337	50.37	218	32.59	98	14.65	147	51	6	21	14	35.72	113	1	17.04	0
5.0µm	18800	18105	357	51.37	220	31.65	116	16.69	150	66	2	11	12	34.68	117	1	16.98	0
10.0µm	18800	18027	340	43.98	284	36.74	182	23.54	81	46	3	15	13	20.44	149	0	19.28	0
20.0µm	18800	17614	339	28.58	655	55.23	286	24.11	3	41	3	4	2	4.47	190	2	16.19	0
30.0µm	18800	17176	264	16.26	1100	67.73	245	15.09	0	14	5	0	0	1.17	253	7	16.01	0
40.0µm	18800	16845	160	8.18	1521	77.80	152	7.77	0	6	2	0	0	0.41	267	7	14.02	0
50.0µm	18800	16747	95	4.63	1720	83.78	89	4.34	0	4	2	0	0	0.29	233	5	11.59	0
60.0µm	18800	16739	50	2.43	1853	89.91	47	2.28	0	1	2	0	0	0.15	155	3	7.67	0
70.0µm	18800	16925	31	1.65	1760	93.87	30	1.60	0	1	0	0	0	0.05	81	3	4.48	0
80.0µm	18800	16902	13	0.68	1845	97.21	11	0.58	0	1	1	0	0	0.11	34	6	2.11	0
90.0µm	18800	17036	8	0.45	1743	98.81	7	0.40	0	0	1	0	0	0.06	12	1	0.74	0
100.0µm	18800	17239	6	0.38	1542	98.78	5	0.32	0	0	1	0	0	0.06	10	3	0.83	0

Table 12-32: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 19 with insect screen porosity of P-0.2

Particle size	Tracked	Escaped Before entering the room	Trapped	% trapped ward surfaces	Trapped Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_19 (P-0.2)								Escaped via openings			Incomplete
							Floor surface	% Deposited	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended	Wall outlets plenum	Roof outlets	% Escaped	
1.0µm	18800	17499	826	63.49	221	16.99	331	25.44	339	32	58	30	36	38.05	224	30	19.52	0
2.5µm	18800	17608	775	65.02	217	18.20	307	25.76	332	20	56	28	32	39.26	186	14	16.78	0
5.0µm	18800	17589	754	62.26	238	19.65	337	27.83	303	20	43	23	28	34.43	197	22	18.08	0
10.0µm	18800	17549	752	60.11	285	22.78	427	34.13	211	22	44	21	27	25.98	192	22	17.11	0
20.0µm	18800	17279	758	49.84	622	40.89	701	46.09	19	5	13	6	14	3.75	139	2	9.27	0
30.0µm	18800	16798	749	37.41	1072	53.55	741	37.01	0	3	1	3	1	0.40	181	0	9.04	0
40.0µm	18800	16503	539	23.47	1556	67.74	535	23.29	0	1	3	0	0	0.17	200	2	8.79	0
50.0µm	18800	16535	304	13.42	1790	79.03	303	13.38	0	1	0	0	0	0.04	170	1	7.55	0
60.0µm	18800	16474	198	8.51	2007	86.29	196	8.43	0	0	2	0	0	0.09	117	4	5.20	0
70.0µm	18800	16640	108	5.00	2011	93.10	104	4.81	0	2	2	0	0	0.19	41	0	1.90	0
80.0µm	18800	16693	65	3.08	2023	96.01	65	3.08	0	0	0	0	0	0.00	19	0	0.90	0
90.0µm	18800	16855	36	1.85	1902	97.79	34	1.75	0	1	1	0	0	0.10	3	4	0.36	0
100.0µm	18800	17044	14	0.80	1738	98.97	14	0.80	0	0	0	0	0	0.00	4	0	0.23	0

Table 12-33: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 19 with insect screen porosity of P-0.3

Particle size	Tracked	Escaped Before entering the room	Trapped	% trapped ward surfaces	Trapped Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_19 (P-0.3)								Escaped via openings			Incomplete
							Floor surface	% Deposited	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended	Wall outlets plenum	Roof outlets	% Escaped	
1.0µm	18800	17221	981	62.13	226	14.31	351	22.23	385	26	114	54	51	39.90	315	57	23.56	0
2.5µm	18800	17246	904	58.17	239	15.38	337	21.69	369	38	92	39	29	36.49	361	50	26.45	0
5.0µm	18800	17333	860	58.62	226	15.41	345	23.52	318	24	96	36	41	35.11	317	64	25.97	0
10.0µm	18800	17228	899	57.19	305	19.40	507	32.25	213	26	103	24	26	24.94	311	57	23.41	0
20.0µm	18800	16847	1083	55.45	608	31.13	965	49.41	32	8	52	9	17	6.04	248	14	13.42	0
30.0µm	18800	16491	1018	44.09	1126	48.77	999	43.27	0	3	11	4	1	0.82	163	2	7.15	0
40.0µm	18800	16241	814	31.81	1579	61.70	810	31.65	0	3	1	0	0	0.16	166	0	6.49	0
50.0µm	18800	16167	520	19.75	1959	74.40	515	19.56	0	5	0	0	0	0.19	154	0	5.85	0
60.0µm	18800	16209	317	12.23	2179	84.10	313	12.08	0	4	0	0	0	0.15	92	3	3.67	0
70.0µm	18800	16405	208	8.68	2138	89.27	206	8.60	0	2	0	0	0	0.08	48	1	2.05	0
80.0µm	18800	16456	123	5.25	2211	94.33	123	5.25	0	0	0	0	0	0.00	10	0	0.43	0
90.0µm	18800	16671	78	3.66	2044	96.01	76	3.57	0	0	2	0	0	0.09	7	0	0.33	0
100.0µm	18800	16877	49	2.55	1870	97.24	49	2.55	0	0	0	0	0	0.00	3	1	0.21	0

Table 12-34: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 20 with insect screen porosity of P-0.1

Particle size	Tracked	Escaped Before entering the room	Trapped	% trapped ward surfaces	Trapped Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_20 (P-0.1)								Outlet Plenum	% Escaped	Incomplete
							Floor surface	% Deposited	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended			
1.0µm	18800	18125	322	47.70	213	31.56	89	13.19	170	36	2	9	16	34.52	140	20.74	0
2.5µm	18800	18090	356	50.14	199	28.03	119	16.76	164	43	3	16	11	33.38	155	21.83	0
5.0µm	18800	18044	344	45.50	254	33.60	125	16.53	147	32	7	21	12	28.97	158	20.90	0
10.0µm	18800	17937	392	45.42	312	36.15	220	25.49	93	40	5	15	19	19.93	159	18.42	0
20.0µm	18800	17667	327	28.86	613	54.10	291	25.68	5	25	0	2	4	3.18	193	17.03	0
30.0µm	18800	17207	210	13.18	1093	68.61	204	12.81	0	6	0	0	0	0.38	290	18.20	0
40.0µm	18800	16860	163	8.40	1449	74.69	161	8.30	0	2	0	0	0	0.10	328	16.91	0
50.0µm	18800	16775	86	4.25	1693	83.60	80	3.95	0	6	0	0	0	0.30	246	12.15	0
60.0µm	18800	16794	29	1.45	1832	91.33	28	1.40	0	1	0	0	0	0.05	145	7.23	0
70.0µm	18800	16854	20	1.03	1856	95.38	20	1.03	0	0	0	0	0	0.00	70	3.60	0
80.0µm	18800	16955	13	0.70	1804	97.78	13	0.70	0	0	0	0	0	0.00	28	1.52	0
90.0µm	18800	17075	10	0.58	1692	98.09	10	0.58	0	0	0	0	0	0.00	23	1.33	0
100.0µm	18800	17159	1	0.06	1627	99.15	1	0.06	0	0	0	0	0	0.00	13	0.79	0

Table 12-35: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 20 with insect screen porosity of P-0.2

Particle size	Tracked	Escaped Before entering the room	Trapped	% trapped ward surfaces	Trapped Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_20 (P-0.2)								Outlet Plenum	% Escaped	Incomplete
							Floor surface	% Deposited	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended			
1.0µm	18800	17579	718	58.80	217	17.77	264	21.62	300	29	70	36	19	37.18	286	23.42	0
2.5µm	18800	17611	731	61.48	199	16.74	279	23.47	328	29	52	24	19	38.02	259	21.78	0
5.0µm	18800	17592	723	59.85	237	19.62	330	27.32	254	25	64	22	28	32.53	248	20.53	0
10.0µm	18800	17462	749	55.98	316	23.62	449	33.56	167	14	65	26	28	22.42	273	20.40	0
20.0µm	18800	17114	839	49.76	622	36.89	780	46.26	15	5	23	7	9	3.50	225	13.35	0
30.0µm	18800	16757	721	35.29	1126	55.12	717	35.10	0	2	1	1	0	0.20	196	9.59	0
40.0µm	18800	16429	554	23.37	1573	66.34	552	23.28	0	2	0	0	0	0.08	244	10.29	0
50.0µm	18800	16407	352	14.71	1849	77.27	347	14.50	0	5	0	0	0	0.21	192	8.02	0
60.0µm	18800	16514	206	9.01	1989	87.01	202	8.84	0	4	0	0	0	0.17	91	3.98	0
70.0µm	18800	16524	114	5.01	2114	92.88	113	4.96	0	1	0	0	0	0.04	48	2.11	0
80.0µm	18800	16634	75	3.46	2071	95.61	75	3.46	0	0	0	0	0	0.00	20	0.92	0
90.0µm	18800	16822	39	1.97	1922	97.17	39	1.97	0	0	0	0	0	0.00	17	0.86	0
100.0µm	18800	17040	22	1.25	1732	98.41	22	1.25	0	0	0	0	0	0.00	6	0.34	0

Table 12-36: Tracked, escaped and trapped characteristics of different sizes dust particles for Case 20 with insect screen porosity of P-0.3

Particle size	Tracked	Escaped Before entering the room	Trapped	% trapped ward surfaces	Trapped Floor Plenum windward	% trapped plenum floor	Trapped Surfaces_Case_20 (P-0.3)								Plenum outlet	% Escaped	Incomplete
							Floor surface	% Deposited	Ceiling surface	Wall Windward	Wall Leeward	Wall Right	Wall Left	% Suspended			
1.0µm	18800	17106	956	56.43	220	12.99	351	20.72	342	42	128	45	48	35.71	518	30.58	0
2.5µm	18800	17137	892	53.64	222	13.35	314	18.88	328	41	131	36	42	34.76	549	33.01	0
5.0µm	18800	17155	904	54.95	244	14.83	376	22.86	288	39	133	37	31	32.10	497	30.21	0
10.0µm	18800	17041	925	52.59	328	18.65	502	28.54	194	31	112	42	44	24.05	506	28.77	0
20.0µm	18800	16792	1027	51.15	646	32.17	908	45.22	24	10	60	15	10	5.93	335	16.68	0
30.0µm	18800	16459	1008	43.06	1145	48.91	986	42.12	0	5	17	0	0	0.94	188	8.03	0
40.0µm	18800	16230	781	30.39	1602	62.33	776	30.19	0	4	1	0	0	0.19	187	7.28	0
50.0µm	18800	16110	604	22.45	1948	72.42	600	22.30	0	4	0	0	0	0.15	138	5.13	0
60.0µm	18800	16147	370	13.95	2220	83.68	368	13.87	0	2	0	0	0	0.08	63	2.37	0
70.0µm	18800	16347	218	8.89	2210	90.09	214	8.72	0	4	0	0	0	0.16	25	1.02	0
80.0µm	18800	16417	148	6.21	2217	93.03	146	6.13	0	2	0	0	0	0.08	18	0.76	0
90.0µm	18800	16622	70	3.21	2101	96.46	70	3.21	0	0	0	0	0	0.00	7	0.32	0
100.0µm	18800	16826	48	2.43	1917	97.11	48	2.43	0	0	0	0	0	0.00	9	0.46	0

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