TWO-STAGE DRYING OF WHEAT AND BARLEY

BY

AVTAR KRISHAN GUPTA
B.Sc. Engg. (Agri.)
M.Sc. Agri.Engg. (Hons.)

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TO MY MOTHER AND FATHER

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ABSTRACT

The results of a theoretical and experimental investigation into the drying of wheat and barley in two stages with an intervening rest period are presented. The reduction in drying time, excluding rest period, has been determined in comparison with the conventional continuous drying for various drying requirements. The effect of airflow rate and the temperature difference between grain and air on the reduction in moisture content and the time required to cool the grain during dryeration is also included.

The moisture diffusion equation was solved numerically assuming a spherical grain. The variable grid spacing, Crank-Nicolson approximation technique and the Gauss-Seidel iterative procedure was employed. The theoretical predictions were compared with experimental results. The drying and resting was performed on a thin layer at a temperature of 60°C. An automatic micro-computer based system was developed to record and store the experimental data.

The results indicate that the moisture redistribution during resting is well advanced after a period of two hours for wheat and one hour for barley. The extent of redistribution was measured by the increase in drying rate observed as the rest period was extended. An optimum moisture content for commencing resting is specified, which is a function of initial, final and equilibrium moisture contents. This optimum was chosen to minimise the actual drying time. There is good agreement between the theoretical and experimental predictions. It was found that the incorporation of a surface resistance into the diffusion model improves the description of the experimental results. The results enable a drying strategy to be specified that reduces the actual drying time by as much as 39%.

For dryeration experiments, the grains pre-heated to different temperatures were put into a well insulated aluminium cylinder and aerated at various airflow rates. An airflow rate of about 60-120 $m^3/hr/m^3$ of grain was found to be optimum. The moisture reduction during cooling was observed to be 0.65 to 0.78% (db) per 10°C temperature difference. It was noticed that moisture reduction also depends on initial moisture content of the grain.

The practical implications of two-stage drying are discussed.

CONTENTS

KEY TO SYMBOLS

The following symbols are commonly used with the given meaning throughout. Other symbols are defined as they occur.

Operators

ln	logarithm to base e
log	logarithm to base 10
exp ( )	exponent of
f	function of
F ( )	function of
d	differential
∂	partial differential
Δ	incremental
∇	$\frac{\delta}{\delta x^2} + \frac{\delta}{\delta y^2} + \frac{\delta}{\delta z^2}$
Σ	summation
%	percent

Lower cases

a_p	surface area of the particle
a	constant
b	constant
d_e, d_{eq}	equivalent particle diameter
d.b.	dry basis
e.m.c.	equilibrium moisture content
f	constant
g	constant or gm.
i	number of shell of the spherical kernel

j	number of time step in numerical solution
k	drying constant, min^{-1}
m.c.	moisture content
min.	minutes
m	number of shells into which spherical kernel is divided
n	iteration number in Gauss-Seidel iterative solution or number in summation of a series
p	constant
q	constant
r	correlation coefficient
r_i	radius of the spherical kernel at shell i where i varies from o to m (o for centre, m for surface)
rh	relative humidity, decimal
t	time in minutes
$t_{cont.}$	drying time with continuous drying, min.
t_d	drying time with rest period, min.
$t_{min.}$	minimum drying time with resting at the optimum point
t_r	duration of rest period, min.
t_{max}	maximum tempering or resting time
w.b.	wet basis
V_p	volume of the particle

Upper cases

A	constant
B	constant
$\bar{C}$	average or mean concentration of the kernel
C_i	concentration at shell i, i = o to m
$C_{i,j}$	concentration at shell i at time step j
$C_{i(n)}$	concentration at shell i after nth iteration

C_s	concentration at the surface of the kernel ($C_s = C_m$)
C_e	equilibrium value of concentration during drying
C_b	concentration in the beginning of drying run
C_p	specific heat of wheat/barley, k J/kg°K
DM	dry matter content of sample, g
D	diffusivity, m^2/min
Dt_r/R_p^2	dimensionless parameter
D_p	diameter of the spherical particle, metre
EMC	equilibrium moisture content
F.N.	Fourier number
I	tempering index
I_c	tempering index based on concentration
I_{RH}	tempering index based on relative humidity
K_{ii}	phenomenological coefficients, $i = 1,2,3$
K_{ij}	coupling coefficients, $i = 1,2,3$; $j = 1,2,3$; $i \neq j$
L	latent heat of vapourization, KJ/kg
MPR	maximum percent reduction in drying time
ΔM	maximum moisture removed during cooling, decimal db
M_o	initial moisture content, decimal db
M_f	final moisture content, decimal db
$M_{o,w}$	initial moisture content, % wb
$M_{f,w}$	final moisture content, % wb
$M_{r,w}$	moisture content for commencement of resting, % wb
M_e	equilibrium moisture content of drying air
M, MC	moisture content
M_w	moisture content, % wb
M_d	moisture content, % db
M_{ew}	equilibrium moisture content, % wb

M_{ed}	dynamic equilibrium moisture content, decimal db
M_{es}	static equilibrium moisture content, decimal db
M_t	moisture content at any time t, decimal db
MR_t	moisture ratio at any time t and $= \frac{M_t - M_{es}}{M_o - M_{es}}$
MR_f	final moisture ratio up to which the grains are to be dried
MR_{rest}	moisture ratio at which rest period is to commence
$\widehat{MR}_{rest}$	optimum moisture ratio for commencement of rest period
P	pressure
P_d	vapour pressure deficit
R	ratio of thicknesses of two adjacent shells of the spherical kernel
R_p	radius of the spherical particle, m
RH	relative humidity, percent
R_e	Reynold's number
S_r	skin-resistance factor
T	dry bulb temperature of air, °C
T_w	wet bulb temperature of air, °C
T_g	grain temperature, °C
T_a or T_{abs}	absolute temperature of drying air, °K
W_{1000}	weight of 1000 grains, g
X, X_o	dimensionless time and correction term

Greek Letters

α, β	functions of relative humidity and temperature in emc equations
ρ	density of the grain, kg/m^3
θ	grain temperature, °C
ϕ	skin permeability factor
π	constant (3.142857)

Chapter 1

INTRODUCTION

1.1. General

India has made dramatic agricultural progress as a result of favourable weather and the Green Revolution. It has emerged as a permanent food surplus country, which must export at least some of this surplus or let it rot in silos. Its granaries are overflowing with around 30 million tons of grain. The country is saddled with ever growing stocks of wheat in particular and literally does not know what to do with it. For four decades all agricultural and food distribution policies were geared to coping with shortages. Today these policies are completely unsuited to coping with surpluses (Schroeder, 1987; Jha, 1985). There is thus, an urgent need to improve the post-harvest processing and storage facilities.

The increased production, coupled with stable and assured prices of grains fixed by the government on yearly production cost basis, have aggravated the problem of receiving, processing, handling, marketing, transportation and storage at various levels in the country's vast food-chain. In India about 40 to 50 percent of total production is marketable surplus and the remaining is retained by farmers for food, seed and feed. The Government policy of procuring food grains at the same price throughout the year is responsible for the rush of crops for sales during the immediate post-harvest period. This in turn results in a serious glut of the produce in grain markets and has very serious implications for the smooth functioning of the whole grain handling system network (Kainth, 1982). The overall result of this is loss of food grains at various levels immediately after harvest.

The benefit of high production can be utilized only by minimizing the losses of food grains from production to consumption. The post-harvest losses as estimated by an expert committee appointed by the Government of India are presented in Table 1.1 (Tripathi, 1979). It is estimated that grains worth about £690million are lost during post harvest handling at various stages in India.

1.2 Importance of Wheat and Barley

Cereal grains, particularly wheat and rice constitute the staple food for most of the Indians. Barley is also an important crop in India. The production of wheat in India has increased from 12 to about 43 million metric tonnes over the last twenty years. Punjab is India's most progressive and productive state agriculturally. More than half the grain which goes into India's public distribution system comes from Punjab. Ninety percent of India's wheat is produced in Punjab state alone. Most of the wheat in India is milled into wheat flour and used for chapati and bread making. The area, production and yield of wheat in Ludhiana (the most important wheat producing district of Punjab), Punjab state (the wheat bowl of India) and India as a whole is presented in Table 1.2. The area, production and yield of barley is shown in Table 1.3. India has now started exporting wheat after meeting its domestic requirements.

Wheat and barley are the main crops produced in Great Britain too. Out of the total wheat production, about one-third is used for flour milling and about 50 percent is consumed as animal feed. In the case of barley, 15 to 25 percent is used for malting and distilling and about 50 percent for animal feed. The exports of wheat and barley are increasing substantially and now account for about a quarter of total production of main crops in Britain. The area, harvest and yield of wheat and barley in Britain for the last few years is presented in Table 1.4 (H.M.S.O., 1985).

Wheat and barley are thus two crops of great economic importance for both India and Britain.

1.3 Grain Handling and Marketing System in Punjab

Increased food grain productivity has recently affected the grain markets. The marketable surplus is brought by farmers soon after harvest to the grain markets which were primarily designed to handle comparatively small volumes of grains manually. The periods of grain arrivals have been shortened to 6-7 weeks in late April to early June, resulting in a complete glut of food grains during peak arrivals in the wheat markets of Punjab and several other adjoining northern states of India. Congestion and traffic jams are regular features in grain markets causing delay in marketing operations from unloading to despatch of grains to other parts of the country. To avoid this, recently the grain marketing boards have introduced "Automatic Grain Weighing, Cleaning, Stitching and Transporting Units", complete all-in-one systems, in most of the grain markets in Punjab.

Under the automatic grain handling system, when a farmer brings his produce to the market for disposal to the government agencies, a grain sample of the produce is taken out immediately on arrival. This sample is analysed for foreign matter, admixtures, damaged grain, slightly damaged and discoloured grain, broken and shrivelled grain percentage or any other examination decided by the government from time to time, and based on this analysis, the produce is graded as Grade I or Grade II. After this, the moisture content of a representative sample from the grain consignment is found and the procurement price paid to the farmer as per rate fixed by the government beforehand. If the moisture content of the sample is found to be above some prefixed percentage, the produce is either totally rejected (under extreme conditions) or there is a price cut applied for every one percent or part thereof of excess moisture present in the crop. The details of specifications for marketing of wheat and moisture deduction rates for a three year period are presented in Tables 1.5 and 1.6.

1.4 Climate and the Need for Drying

With the introduction of multiple cropping systems in India especially in Punjab, there is less time at the disposal of the farmer for cultivation of a particular crop. To have enough time for seed bed preparation and sowing of next crop, the farmer is more or less compelled to harvest the previous crop earlier and at a higher moisture content. To reduce cutter-bar losses, with the help of combine harvesting, the crop gets harvested at higher moisture content. The harvest time moisture content of wheat in Punjab varies from 8 to 28% (w.b) depending upon the time of harvest, method of harvest etc. (Singh, 1982). Added to this is the prevailing problem of "off-season" unexpected wet weather during harvesting period encountered during the last few years of wheat harvesting. The farmers have recently been stunned with the unprecedented torrential rains and hailstorms experienced either when harvesting is going on or immediately after harvest or sometimes when the fully matured crop is awaiting harvest. The Government has to pay huge sums of money every year as a compensation to the farmers in distress to keep their morale high. This year alone, Punjab Government has announced an interim relief of about Rs 1000 million (£50 million approximately) to those wheat farmers in Punjab whose crop has been totally spoiled due to heavy rains in April-May (Punjab Times, June 1987). The meteorological data for Ludhiana City, the heart of the wheat bowl of Punjab state in India is presented for recent years in Table 1.7.

The overall result of all this is that the farmer is left with black coloured sick wheat at high moisture content. Since the grain drying facilities at farm level do not exist at all, there is no alternative left for the farmer except to sell his produce at a low price thereby suffering financial loss. Since the Government is bound to purchase all crops, there are hugh stocks of wheat to be dried immediately before being put into long term storage. The instant task of procurement and handling engineers then is to get maximum output from drying plants so that grains are dried immediately at least to a moisture level at which no further deterioration will take place rather than drying them to a safe storage moisture content which is 10 percent for cereals and is a much more time consuming job.

1.5 Alternatives in Grain Drying

There are at present three approaches available to dry wet grains:

(1) Continuous drying at high or low temperature with heated air from initial high moisture content to desired final moisture content and then immediate cooling with unheated air.

(2) Continuous drying with heated air from initial high moisture content to within 1 to 2 percent of desired final moisture content, then tempering for a few hours and then slow cooling with unheated air at low air flow rates. The last 1 to 2 percent moisture gets removed during the cooling process. This process is called dryeration.

(3) Drying at high temperature for some time, then resting the grains for some period and then again drying with heated air, then resting and so on ..., a process known as cyclic drying, drying with rest periods, intermittent drying or multipass drying. Resting period is also sometimes referred to as the tempering period.

An enormous amount of research work has been done on continuous drying of corn, wheat, barley, rice and some vegetable seeds. The research work on dryeration has concentrated mainly on corn (maize) and the process seems to have been evolved to reduce stress cracks in corn due to immediate cooling after continuous high temperature drying. The research work on multipass drying has centered around paddy (rice) in most of the cases, the primary objective being to reduce the number of broken kernels thereby increasing head yield of whole grain rice from paddy during rice milling. There is not much in the literature on multistage drying of wheat and barley from an energy saving point of view. It is observed that during continuous drying, at some stage when the surface moisture has evaporated, the rate of moisture removal becomes controlled by the rate of moisture diffusion within the kernel. At this time, a significant moisture gradient has been developed and moisture will diffuse to the surface by virtue of this gradient, as described by Fick's law of diffusion. It is thus possible to allow this process to proceed without addition of heat energy for a certain time period after which heat is added again to facilitate moisture removal from the surface of the grain kernel. This process is shown diagramatically in Figure 1.1. The only work reporting energy saving by using this technique on wheat drying is by Edholm (1932). He showed that by applying hot air to the wheat grain in a series of 3 to 6 minutes with rest periods of 1 to 3 hours between each exposure to hot air, there was considerable saving in energy required to dry the grains. Beeny and Basil (1970) have reported that at times of peak deliveries of very wet grain to the grain drying complex, drying capacity could be increased by multipass drying and resting. Wet grain could be dried with the drier until it reached some manageable moisture content and then temporarily stored with little aeration for some weeks. This grain could later be dried to the desired final moisture content for storage in the same drier after the peak arrivals season is over, thus handling more wet grain safely during immediate post-harvest peak-delivery period and at the same time saving energy. The dryeration technique also appears to be an attractive alternative to continuous drying since the last few percent of moisture is most difficult to remove and time consuming. If the last 2 to 3 percent moisture is removed during a cooling period, the dryer capacity could increase substantially and there will also be a saving in the energy used for drying. There is no work reported in the literature on dryeration of wheat and barley. The intermittent drying of barley has not been investigated so far and the only work on rest period drying of wheat is as early as 1932. Although stress cracking or broken grains is not a problem in wheat and barley yet the two techniques need to be examined from the point of view of saving energy or the increased throughput of the drier.

1.6 Objectives

(1) To develop a theoretical model to predict the optimum resting stage and the duration of rest period for two stage drying of wheat and barley with an intervening rest period.

(2) To determine the effect of grain temperature and airflow rate on moisture removal during aeration with ambient air after resting.

(3) To determine the reduction in drying time by rest period drying and dryeration in comparison to continuous drying for various drying requirements of wheat and barley.

Chapter 2

REVIEW OF LITERATURE

In view of the enormous amount of literature on dryers and the drying process, it is not possible to completely cover the topic of grain drying from all aspects. Instead drying with rest periods including the technique of dryeration and the principal models and the theories which have been advanced to describe thin layer and deep bed drying will be examined. An understanding of the available literature on these topics is essential for a mathematical formulation of the two-stage drying problem and for assessing the impact of two-stage drying on continuous drying from an energy saving or a dryer throughput point of view.

2.1 Rest Period Drying

Rest period drying is also termed intermittent drying, multipass drying, multistage drying, drying with tempering periods, cyclic drying or drying with in between resting. The word 'tempering' is usually associated with grains in the field of cereal technology. In modern day language, this word has a multiplicity of meanings. In metal working, tempering may refer to the heating and cooling of steel to achieve a particular hardness. In corn (Brekke and Kwolek, 1969) and wheat (Grosh and Milner, 1959) milling, tempering refers to moistening before processing. In grain drying, the holding of the kernels between passes through a multipass drier is called tempering or resting. The length of this holding period is called the tempering time or resting time. The tempering process refers to the migration of moisture inside the kernel which serves to equalize the moisture concentration throughout the mass. High rate continuous grain drying is limited by the time taken for the moisture to travel from the centre of the grain to the surface. If the drying is performed in stages allowing the grain to stand or 'rest' after some drying, there is redistribution of moisture and an improvement in speed of drying in the subsequent stage. The tempering of grains during drying also reduces stresses in the grain and therefore milling losses.

It is believed that intermittent drying was first investigated by Edholm (1932). He has shown that, when grain is dried in a series of short drying periods with relatively long periods of rest in between, the amount of water removed per unit of drying time is much greater than when drying is continuous. This is because the limitation to drying rate, once the outer skin of the grain is dry, is the rate at which water diffuses through the grain to the skin. It was concluded that the gain is greatest when the rest periods are from one to three hours and drying times are about 3 to 6 minutes. It appeared that, if advantage is taken of this principle, considerable savings in heat and power might be made when drying is effected in the usual rapid way. This is the only work on rest period drying of wheat reported in literature.

Most of the research work on rest period drying of crops has been oriented towards rice. It has been reported that during the falling rate drying period an internal moisture gradient develops in the rice kernel like all other crops and this gradient causes cracking and subsequent breaking during milling thereby reducing the head yield of whole rice grains (Prasad et al. 1975; Schmidt and Jebe, 1959; Kunze and Choudhury, 1972). Kunze and Hall (1965, 1967) observed that brown rice fissured readily from moisture adsorption effects without the presence of a temperature gradient. They determined that a temperature difference of 16.67°C between the rice and air did not produce fissures as long as the rice was maintained at a constant moisture content. They also observed that high moisture rice kernels fissured faster than low moisture kernels when exposed to the same vapour pressure difference at a particular temperature. Kunze and Choudhury (1972) investigated the relation between moisture adsorption and tensile strength of rice. They observed that the rate of moisture adsorption and its penetration into the kernel depends on the initial condition of the kernel and the environment to which the kernel is subjected. For slow adsorption, rheological properties of a kernel are such that no fissuring occurs but at fast rates fissures occur rapidly. Arora, Henderson and Bukhardt (1973) have reported that a temperature difference larger than 43°C between the air and the rice kernel results in serious cracking. Prasad, Mannapperuma and Wratten (1975) have concluded that stresses due to moisture gradient are a major cause of cracking or checking whereas thermal stress constitutes a minimal source of damage. Kunze (1977) observed that rice fissuring after continuous drying was caused by:

(1) the grain surface readsorbing moisture from the environment; or
(2) the grain surface adsorbing moisture from centre of kernel or both.

Resting or tempering of hot rice for some time after some initial drying is one way of reducing moisture gradient in the kernel and thereby reducing fissuring or cracking. Numerous researchers have considered rice tempering and have investigated the effect of tempering time on moisture removal and milling yields in the drying of high moisture rice. Thompson _et al_. (1955) found that twelve hours were required for full tempering (complete reduction of the moisture gradient) when short grain rice was dried from 23.6 to 11.6% (wb) moisture content with 54.4°C (130°F) air and tempered at 32.2°C (90°F). Full-tempering was the time when the water vapour pressure, inside the container holding the rice, had stabilized. In summarizing the work of other researchers, Angladette (1963) found that tempering times used in multipass drying may vary from 12 hours to several days. Wasserman et al. (1964) in considering tempering times from 4 to 32 hours concluded that 1) tempering periods of 4 hours were sufficient if the tempering temperature was 40.6°C (105°F) and 2) that periods of 6 hours were satisfactory if the tempering temperature was 23.8°C (75°F), when drying rice from 20 to 13% (wb) in three phases with 43.3°C (110°F) air. The head yield of rice tempered cold (23.8°C) was 2% lower than that of the rice tempered warm (40.5°C). With warm tempering, total drying time (excluding rest period) changed but little with increased tempering time beyond 4 hours. Rice that was tempered warm required only 70% of the heated air drying time needed when rice was tempered cool.

Beeny and Basil (1970) conducted one of the most comprehensive studies on multipass drying of very wet paddy (rice) at 24 percent moisture with tempering or resting periods between passes of 10 min, 5 hours and 10 hours duration and under air flow rates through grain bed of 70 $ft^3/min/ft^2$ and 140 $ft^3/min/ft^2$. The air temperature was held at 54.4°C and the grain temperature was kept below 47.8°C. The results of their study can be summarized as follows:

(1) The head yield increases with an increase in the number of passes through drier.

(2) The drying time is greatly reduced as the number of passes is increased.

(3) The head yield increases with prolongation of tempering period but only slightly after 5 hours.

(4) The fuel consumption is reduced as the length of tempering is increased.

(5) The drier capacity increases with increased air flow.

(6) The head yields are lowered with increased air flow.

Yan (1972) conducted experiments to investigate the effects of tempering on the drying rate of rice using two different intermittent drying time ratios, half hour drying to half hour tempering (1:1) and half hour drying to one hour tempering (1:2). The drying temperatures used were 37.8°C (100°F), 48.8°C (120°F) and 60°C (140°F). Results showed that tempering does increase the rate of drying in subsequent stages, but this increase in rate lasted only for about 10 minutes. After this, the rate was almost the same as the continuous drying. No significant difference was observed between the two intermittent drying ratios. Itoh et al. (1974) and Itoh and Terao (1974) also concluded that the rate of drying paddy increased with longer tempering times and that rice qualities such as cracking and germination were closely related to the length of the tempering periods. It was also observed that the amount of moisture transfer between hull and kernel of rice increased with increase of difference in initial moisture contents of hull and kernel at the beginning of tempering. Nishiyama and Kumamoto (1973) computed grain drying characteristics from drying air psychrometry while studying rice drying with a multipass tempering drier. It was recognised that humidity ratio increment curves which also represent the drying rate, have the tendency to begin at a high value in the 2nd pass and do not continue from the 1st pass. The 3rd pass curve has the same tendency as the 2nd but lower in value. This in other words means higher drying rate after rest period.

Steffe, Singh and Bakshi (1978) studied the effect of tempering time on moisture removal and milling yield in the drying of high moisture rice (at about 31%). Drying air temperatures of 38°C and 50°C, drying periods of 20 min. and 35 min., and tempering times from 0 to 24 hours were considered. After drying, rice was put into a pre-heated one litre moisture proof jar and placed in an oven maintained at 37.5°C. The jars were kept in the oven for the desired tempering time. The following conclusions were drawn:

(1) Tempering high moisture rice between drier passes aids in removing moisture and maintaining head rice yield but does not appear to affect total rice yield.

(2) Cooling high moisture rice immediately after a drying pass may reduce the total and head yield of the grain.

(3) In reducing the water in high moisture rice (at 31%) by 3 to 4.5% per pass when using 38°C air and 20 min. drying periods, a 35 minute tempering period is sufficient.

(4) In using 35 min. drying period (at 38°C air) or 20 min. drying period at 50°C air temperature, tempering times of 3 hrs. are satisfactory and shorter times may be adequate. These times should apply for drying medium grain rice when the ambient air is at about 26°C and 31% rh.

The authors also conducted statistical tests on the milling yield data. The following conclusions were reached when considering Bartlett's test and one way analysis of variance:

(1) Under all drying conditions considered, tempering had no effect on the total rice yield.

(2) In all test groups, the head yield was lowest when no tempering was allowed between drying passes.

In other words, it was concluded that tempering reduces breakage of rice.

Walker and Bakker-Arkema (1981) while studying energy efficiency in three stage concurrent flow rice drying with two tempering phases concluded that tempering does not significantly improve the drying rate of rice in a concurrent flow dryer. Tempering times of 0, 0.67, 1.37 and 2 hours were studied at drying air temperatures of 65.6°C and 121.1°C. It was however observed that rice could be dried in a concurrent flow drier at air temperatures as high as 121.1°C provided that the air flow is 0.04 m^3/sec, and the grain flow is 158.7 kg/hr. A three stage drier, however, provided the operator with more flexibility in selecting drying air temperature, depending upon initial moisture content, and better quality control than a one and two stage dryer.

Steffe and Singh (1980) developed a theoretical model to simulate the drying and tempering of rough rice. The model was based on liquid diffusion theory and assumes the grain to consist of a spherical core (starchy endosperm) surrounded by two concentric shells (bran and hull respectively). During tempering, measured changes in relative humidity in the void volume of a mass of rough rice were compared to predicted changes in surface liquid concentration of a rough rice kernel. The results of modelling are presented in terms of the following equations which predict tempering time:

$$t_{1.0} = 24.145 - 5.344 \ln(T) + 0.253 \ln(\Delta M_d) - 0.287 (rh) + 1.096 (M_o) \qquad 2.1$$

$$t_{1.0} = 21.5373 - 4.899 \ln(T) + 0.131 \ln(\Delta t) - 0.491 (rh) + 2.132 (M_o) \qquad 2.2$$

$$t_{0.95} = 11.194 - 2.365 \ln(T) + 0.259 \ln(\Delta M_d) - 0.223 (rh) + 1.146 (M_o) \qquad 2.3$$

$$t_{0.95} = 8.509 - 1.905 \ln(T) + 0.135 \ln(\Delta t) - 0.012 (rh) - 0.083 (M_o) \qquad 2.4$$

where $t_{1.0}$ = time required for complete tempering

$t_{0.95}$ = time required for 95 percent tempering

ΔM_d = moisture reduction during one drying pass (decimal d.b.)

Δt = time elapsed during one drying pass, hours.

It was concluded that for a temperature of 35°C and other typical drying conditions, tempering was 95% complete in less than two hours and *fully complete in less than five hours. Higher temperatures will* shorten required tempering times.

Rest period drying of corn (maize) has also been analysed and experimentally verified. Allen (1959) showed that by intermittent drying, the time of drying maize to the desired final moisture content was shorter. Brook (1977) concluded that tempering times beyond 1.25 hours had a negligible effect on the final moisture content and temperature of corn in a concurrent flow dryer. He attributes this to the uniformities of the average m.c. and temperature between kernels after drying in a concurrent flow dryer. Brook (1977) also noted that higher inlet temperatures resulted in a decrease in tempering time. Brook and Bakker-Arkema (1978) developed a simulation model for concurrent flow drying based on diffusion within spherical products. Multistage concurrent flow dryers with intermediate tempering and a counterflow cooler were simulated. It was concluded that the multistage concurrent flow dryer could be expected to produce a better quality dried product at a reduced energy cost over a crossflow dryer. Brook and Bakker-Arkema (1980) used a dynamic programming optimization scheme for finding the optimum operational parameters and dimensions of a multistage concurrent flow corn dryer. The objective function was based on costs for energy consumed during drying and fixed and variable capital costs. It was concluded that although the two or three-stage dryers had a higher investment than a single-stage dryer, yet on a per square meter of column area basis, the single stage concurrent flow dryer was more expensive to operate than a two or three-stage concurrent flow dryer due to the decreased grain flow rate of the single stage units. Since the increase in breakage can be related to moisture removal rate, a multistage concurrent flow dryer with tempering was again preferable to a single-stage dryer.

Harnoy and Radajewski (1982) while performing the experiments on corn have concluded that by introducing rest periods, the thermal efficiency of drying improved thus allowing a greater mass of grain to be dried per unit time for the same energy input. An attempt has been made to give the basic relationship between the "blowing ratio" i.e. the ratio of the total cycle time to the actual drying time, and the efficiency of drying for various temperatures and air velocities. It has been established than an intermittent drying system operating at its optimum blowing ratio was more economical than the conventional system for the continuous drying of grain.

In addition to wheat, rice and corn, experiments on rest period drying of other crops like peanut, coffee and cocksfoot seed have also been conducted. Kunze _et al_. (1968) studied the continuous and intermittent drying of peanuts under vacuum. Various combinations of drying and tempering periods ranging from ½ hour to 4 hours were tried and it was concluded that a short drying period and long tempering period were most effective for drying per hour of vacuum pump operation. This result is mentioned to be reasonable by the authors since more moisture could migrate to the kernel surface in 4 hours than in one hour. Troeger and Butler (1980) dried peanuts at different initial moisture content by periodically interrupting air flow as a means of conserving energy. The tests carried included 15 min. on and 45 min. off, 30 min. on and 30 min. off, 45 min. on and 15 min. off, 3 hours on and 1 hour off, and continuous drying. Two air flow rates, 12.5 and 25 $m^3/min/m^3$ of peanuts were used and drying was carried out at a temperature of about 10°C above ambient. Results indicated that interruptions of 15 min. per hour at low rate of air flow did not significantly affect the total drying time (drying + resting) and reduced heat energy consumption by only about 10 per cent. Longer periods of interruptions further decreased heat energy use but total time required to complete drying process gets increased which is a little inconvenient.

Cordeiro et al. (1985) evaluated the effects of temperature and resting time on the quality, moisture distribution and energy consumption during coffee drying in a fixed bed drier. Coffee grains of the "Catuai" variety were dried at temperatures of 50, 60 and 70°C for periods of 9.7 and 4 hours respectively at air flow rate of 15 $m^3/min/m^2$. Aeration was achieved by means of an electric fan that functioned under the same drying conditions, with off times of 0, 6 and 12 hours. It was observed that the resting period facilitated the renewal of the moisture resulting in a reduction of the moisture gradient across the bed and reduced energy consumption.

Improved energy utilisation during drying of cocksfoot seed at 43.5°C with varying rest periods has been demonstrated by Woodforde and Lawton (1965). The continuous drying of the seed was compared with three types of intermittent drying: 1 hour on and ½ hour off ...; 1 hour on and 1 hour off ...; 3 hours on, 2 hours off and 2 hours on. The one hour on and one hour off combination was found to present best choice for drying from 29.1% to 8.2 % moisture content. A maximum reduction of 28.57% in drying time, from 5 hr 36 min. to 4 hours, was observed and four passes were required to complete drying.

The research work reported so far relates to rest period drying in which no air whether heated or unheated was applied to grains during resting or tempering. Ezeike and Otten (1981) performed theoretical analysis of the tempering phase of a cyclic drying process considering tempering with and without airflow based on thermodynamic consideration of heat, work and mass distribution within the kernel. It was shown that during the tempering period only thermal effects apply; that is, heat is exchanged between the kernels and the air and the change in temperature is proportional to the enthalpy change following redistribution of moisture in the kernels. The temperature change for tempering with air flow was shown to be greater than without air flow. Furthermore it was shown that when unheated air was passed through the grain during the tempering period, a higher level of energy was required to sustain the drying process in subsequent stages. It was concluded that there is thus a distinct advantage in allowing the grain to rest in quasi-stationary air.

Cyclic drying or multipass drying of grain without involving any real rest period has also been reported in literature. Kelly (1941) used alternate exposure of grain to heating and cooling in drying wheat. Wheat kernels were heated by passing them through a heated rotating drum and cooled with ambient air upon discharging. Multiple passes were required to dry the grain completely. Cofer (1963) used a cyclic hot and cold temperature drying system to reduce stress cracks in tests. He found that little moisture was removed during cooling period but the advantage was that drying air temperatures as high as 120 to 230°C could be used without any cracking of grains. Kenyon and Shove (1969) utilised alternate periods of heated and cooled air to remove moisture from all depths of a column of wet corn.

It was observed that the moisture gradient in the column could be minimized by controlling input air temperature and relative humidity and by manipulating the direction of air flow. The technique employed the increased temperature generated by the heating periods as a source of energy for moisture removal from grains during subsequent cooling. Air flow during cooling was 1/10th of the air flow during heating whereas temperatures during heating and cooling were 135°F and 50°F respectively. Browning _et al_. (1971) have demonstrated that overdrying can be reduced by alternate use of heated and unheated air in a batch-in-bin system. Shove (1973) has found that temperature cycling enhances deep bed drying. It was shown that creating temperature differences in deep beds of grain by the application of a fluctuating air temperature enhances drying by reducing the moisture content of the grain above the drying zone. The temperature cycling time should, of course, coincide as closely as possible with the time required to change the grain temperature which depends on the air flow.

Combination drying is another alternative technique to continuous drying without any rest period in real terms. It is a system in which high temperature, high-speed drying is followed by in-bin low-temperature drying and cooling which may take 2 days to 2 months. Kalchik _et al_. (1979) found that combination drying systems produced improved corn quality. Morey _et al_. (1978, 1981) concluded that combination drying results in a reduction in energy requirements compared to conventional high temperature drying with in-dryer cooling.

Sokhansanj _et al_. (1983) determined the minimum tempering time to ensure uniform moisture distribution throughout the artificially wetted grain kernel in the case of wheat, barley, rapeseed and corn as 32, 48, 1 and 96 hours at 21°C and 46, 48, 4 and 122 hours at 2°C.

2.2 Dryeration

The term DRYERATION is a compound of the English words DRY and (A)ERATION. This is a process which was developed in the United States to prevent stress cracking, first in maize and subsequently in rice but which was found to give an important bonus of substantial energy savings (Thompson and Foster, 1967). It is a system in which the grain is dried with hot air to within 2 or 3% of the desired final moisture content and then transferred hot to a steeping bin in which it is allowed to sweat, temper or rest for several hours before being finally dried by evaporative cooling with relatively low volumes of unheated air.

Thompson and Foster (1967) investigated the effect of tempering on the rate of moisture removal and on the final quality of maize while drying corn from 25 to 14% moisture content. Corn heated to 60°C (140°F) in the dryer and allowed to temper lost about 2% moisture during aeration cooling. A combination of 8 hour tempering and aeration at 0.5 cfm per bushel (24 $m^3/hr/m^3$) provided the highest moisture removal. It was observed that dryeration could reduce the breakage of corn attributed to immediate cooling after continuous drying by up to 80%. It was also observed that two-stage drying with a tempering period after each stage added little either to the dryer capacity or the corn quality obtained with dryeration.

Sabbah _et al_. (1972) performed some experiments to study the effect of tempering after drying on cooling shelled corn. The test procedure involved three stages. First the corn was dried, then it was rested and finally it was cooled with air. The equipment included a dryer, a cooler and a tempering cabinet. After drying, the grain was removed from the dryer, the test section along with grain almost sealed with styrofoam lids at the top and bottom, weighed and put in the tempering cabinet. The drying air temperature was about 74°C (165 ± 5°F) and temperature in the tempering cabinet was adjusted and controlled at about 63°C (145 ± 2°F) (the average temperature of corn after drying was completed). After tempering, the test section was taken out of the cabinet, weighed and lids removed and cooled with air flow rate of 5, 20 and 75 cfm per bushel (240, 960 and 3600 $m^3/hr/m^3$). Tempering periods of 0, 1, 2 and 4 hours were considered along with complete tempering. The time to complete the tempering process, t_{max}, was defined as the time required for the moisture concentration at the surface to reach a maximum, determined as

$$t_{max} = \frac{R_p^2}{6D} \qquad 2.5$$

where R_p = radius (ft.) and D is the mass diffusivity of the kernel in sq. ft. per hr.

The actual time for complete tempering based on research data was found to be 0.8 t_{max}. A tempering index, I, was formulated to predict the effect of partial tempering on rate of moisture removal during cooling. This index is a function of actual tempering time t_r, the mass diffusivity D, and the equivalent radius of the spherical kernel Rp.

$$I = \frac{1}{A^{3/2}} \exp \frac{3}{2} (1 - \frac{1}{A}) \qquad 2.6$$

$$\text{where } A = (\frac{6\ t_r\ D}{Rp^2} + 0.2)$$

In order to estimate the moisture removed during the cooling process, a drying equation was necessary which applies during the process of cooling grain that has been completely tempered. Such an equation was, however, not developed but most of the results are presented in graphical form. The tempering index, applied graphically, gave a reasonable prediction of the actual drying curve for partially tempered grain.

Lasseran (1977) conducted some experiments on drying of maize in France from 36% to 16% (wb) and concluded that dryeration increased drier output by between 29 and 60.5% and reduced energy consumption by between 14.6 and 37.2%. Reduction in grain fragility after drying was also observed. Gustafson et al. (1983) studied the effect of short term (0-60 min) tempering of corn before cooling on the breakage susceptibility and moisture removal during cooling using both thin layer and deep bed drying processes. The two models developed were:

$$\ln (BRK) = 4.957 - 12.86\ M_f - 0.04138\ t_r + 0.000436\ t_r^2 \qquad 2.7$$

$$100\ (\Delta M) = 2.10 + 7.65\ M_f + 0.01069\ T + 0.1149\sqrt{t_r} \qquad 2.8$$

where BRK = breakage susceptibility (%)

McKenzie et al. (1969) carried out extensive tests on dryeration of maize and rice on a commercial scale and have made useful practical recommendations on this technique of grain drying. It has been concluded that air flow rates for dryeration cooling should be between ½ and 1 cfm per bushel (24 to 48 $m^3/hr/m^3$) so that corn will cool in at least 6 to 12 hours. Increasing air flow will speed the cooling process, but will force the heated air out of the maize before it has had time to pick up a full moisture load. Faster cooling at high air flow rates will also increase stress crack formation thereby serving no purpose as an alternate to continuous drying. Their tests also showed that the moisture condensation problem associated with dryeration is reduced by insulating the bins. The downward air flow used in an insulated bin proved satisfactory for cooling and storing maize in the same bin without moving. Calderwood and Hutchison (1969) developed a system of dryeration for multipass drying of rice which reduces the number of dryer passes needed to complete drying. Instead of allowing the rice to temper in its own heat between passes, power fans were used to force low rates of air through rice in the tempering bin, cooling it to nearly the outside temperature before it is returned through the drier. This cooling, accomplished slowly, lowers moisture content leaving less for the dryer to do. In a series of tests, an average of 1.16% moisture was removed by aeration during the holding period compared to no moisture removed when rice was tempered at high temperatures between dryer passes. It was observed that the heat absorbed by the rice during the dryer pass was used more efficiently for drying when it was dissipated by slow aeration than when it was retained for pre-heating of rice for the next dryer pass. The dryerated rice in general required 20% fewer passes and there was about 14% saving in energy or it could be said that one less dryer pass is required than normal.

Calderwood and Webb (1971) conducted tests to evaluate the effect of retention time per pass of rice in the dryer, duration of tempering time, aeration cooling during tempering, drying air temperature and air flow rate on moisture removal per pass during multipass drying of rice in addition to its milling and cooking quality. Rice was cooled by aeration during the tempering period between dryer passes. It has been concluded that in multipass drying of rice when each pass consisted of drying + tempering with aeration cooling, tempering rice for periods up to 12 hours at high temperature following dryer passes did not significantly change the amount of moisture removed during the subsequent cooling cycle. Duration of the tempering period appeared to have no effect on the milling yield. Drying tretments during which rice attained maximum temperatures up to 50°C (122°F), appeared to have no adverse effects on cooking quality. Shorter retention time per pass, higher drying air temperature and a relatively greater number of passes resulted in less dryer operation time for the same amount of drying.

Nellist (1984) modelled drying of cereal grains from 36 and 20% (w.b.) moisture content to 15% and has compared normal drier with cooling and dryeration. His conclusions about dryeration are:

(1) It could greatly increase the throughput of a continuous flow drier.

(2) The system is more efficient overall than normal drying with rapid cooling in the drier.

(3) Provided tempering times and temperatures can be kept below eight hours and 44°C respectively there may be very little damage to germination and hence to the quality of milling wheat. This needs checking by experiment and as yet the process should not be used for other than feed grain.

(4) The system requires a higher level of management expertise than conventional heated air drying and cooling.

Not much work has been done on mathematical modelling of dryeration process. Sutherland et al. (1971, 1983) have studied heat and mass transfer during aeration of deep grain beds to predict times and front shapes for equilibrium without including the effects of finite transfer and diffusion coefficients and have presented graphs which allow the rapid determination of temperature and moisture front speeds for a wide variety of aeration conditions. The practical effects of importance of these fronts in preserving grain quality due to moisture equalisation by aeration have been considered but there appears to be little emphasis on moisture removal during aeration and its relevance to reduction in drying time over continuous drying.

No work appears to have been done on rest period drying of barley and dryeration of wheat and barley.

2.3 Internal Diffusion Models

In some biological products the moisture content is high enough to maintain a free water surface. The drying process under this condition is governed by heat and mass transfer between the water surface and the drying medium and is independent of the material (Allen, 1960). Drying under these conditions proceeds at a constant rate until the surface moisture is removed. This period is followed by a falling rate period, during which drying is controlled largely by the product and involves the (1) movement of moisture within the material to the surface by diffusion, and (2) removal of moisture from the surface. The rate of removal of moisture from the surface of the kernel is greater than the moisture movement within the kernel which results in a decreasing rate of moisture removal. The cereal grains usually dry solely during the falling rate period (Brooker *et al*. 1974).

Essential to any grain drying simulation is a single kernel or thin layer drying equation that predicts moisture removal rate as a function of the drying variables. A substantial portion of the grain drying literature is devoted to the development of thin layer or single kernel drying equations.

Two general approaches to the study of thin layer drying of cereal grains are:

(1) the development of theoretical equations

(2) the development of empirical or semi-empirical equations.

The theoretical approach concerns either the diffusion equation or the simultaneous heat and mass transfer equations. The empirical thin layer equations are derived from experimental data on continuous drying. The main justification for the empirical equation is a satisfactory fit to all experimental data and subsequent benefit in describing deep bed drying of grains. These constitute a lumped parameter representation of the drying process, and ignore the contributions of spatial variation in the kernel. Empirical equations are accurate and dependable as long as the analysis is conducted within the range of experimental observations. The semi-empirical approach concerns approximated theoretical solutions. The reasons for using theoretical equations are to give some physical explanation and understanding of the transfer process. The approximated equations are simpler and take less computing time in comparison to the theoretical equations and still provide some understanding of the transfer process.

A review of thin layer drying equations based on internal diffusion is presented here and a discussion of various empirical and semi-empirical models developed for drying of grains is given in Appendix 2.1.

Based on the differential equation for diffusion and making certain approximations, Lewis (1921) derived the following expression for drying under constant air temperature and relative rumidity

$$\ln\left(\frac{M - M_e}{M_o - M_e}\right) = -kt \qquad 2.9$$

Hukill (1947) observed that the rate of moisture loss is approximately proportional to the difference between the moisture content of the grain and the equilibrium moisture content for corn and sorghum. Several investigators (Simmonds, Ward and McEwen, 1953; O'Callaghan, 1954; Henderson and Perry, 1955; Hall and Rodriguez-Aris, 1958; Allen, 1960; Boyce, 1966; Kachru, Ojha and Kurup, 1971; and Watson and Bhargava, 1974) have proposed the above equation for wheat, rice, barley and shelled corn. This equation was based on the assumption that all resistance to drying is at the outer layer of the kernel. For wheat grains McEwen et al. (1954) interpreted this layer as the aleurone layer between the outer skin (pericarp) and the endosperm mass of the grain kernel. It has, however, been demonstrated (Babbitt, 1949) that the much thicker endosperm mass is of greater importance in limiting diffusion. Equation 2.9 is often referred to as the exponential (or logarithmic) law or model. The constant k is determined by the physical characteristics of the product. This equation is the basis for many thin layer drying equations. It is simple to evaluate and lends itself well to digital computation.

In order to solve the diffusion equation,

$$\frac{\partial M}{\partial t} = D \nabla^2 M \qquad 2.10$$

an appropriate geometric shape must first be assumed for the approximate representation of the individual grain kernel e.g. a sphere, cylinder or slab. The diffusion equation is then written in terms of the appropriate coordinates e.g. spherical, cylindrical or cartesian. In some of these cases, series solutions, such as those given by Crank (1979), may be used to provide estimates of the average moisture ratio. The value of the diffusion coefficient is obtained from an analysis of the drying curves and depends on the assumed shape of the particle. For example, Pabis and Henderson (1961) found that if shelled corn particles were taken to be brick shaped, the diffusion coefficient derived was 2.4 times that found under the assumption of spherical geometry.

Babbit (1949) appears to be the first to apply the diffusion equation to data for agricultural crops. Chu and Hustrulid (1968) developed numerical solutions of the diffusion equation for a spherical solid, when the diffusion coefficient is concentration dependent, and applied these numerical solutions to the analysis of the experimental data for shelled corn. They demonstrated that the drying can be predicted with good accuracy for known air temperature, relative humidity and known initial moisture content. Pabis and Henderson (1961) have shown that a three dimensional equation of internal diffusion with diffusion coefficient variable with time describes the drying curve very well for shelled yellow maize dried in a single kernel layer. They found that the equation of internal diffusion for a sphere gives better results than the brick shape.

Husain et al. (1972) presented a simultaneous heat and mass transfer model allowing variable mass diffusivity, for the single kernel drying of rough rice, the shape of which they represented by an infinite cylinder. Solving their equations numerically, using an explicit alternating direction method, they concluded that the thermal diffusion effect could be neglected. Nellist (1976) fitted four alternative equations to the experimental data for ryegrass seeds. These equations are the single exponential equation, diffusion equation for a sphere, the equation of diffusion through an infinite plate and a two term exponential equation. The two term exponential gave the best fit but acceptable results were given by the series equation of diffusion through an infinite plate. The two term exponential equation gave the best fit, because this equation has a more flexible shape and more degrees of freedom than that of the series equation for either the infinite plate or sphere.

Chinnan and Young (1977) considered peanut pods as two concentric shells, kernel and hull. They applied the mathematics of diffusion considering liquid, vapour and both liquid and vapour diffusion. The liquid diffusion model was found to give a better fit to the experimental data for thin layer drying than the vapour diffusion model. They observed that the vapour-liquid diffusion model gives a better fit to experimental data than either the liquid diffusion or vapour diffusion models. Ingram (1976) applied a liquid diffusion model to moisture transfer in grains and developed a series method of finite difference solution of the diffusion equation. This method is a more accurate representation of the solution than would be possible with the finite difference method, and also facilitates their incorporation into the system of deep bed drying equations. Steffe and Singh (1980) have applied the mathematics of diffusion to rough rice. They considered rough rice as three concentric shells - endosperm, bran and hull. Good agreement was found with experimental observations.

Bruce (1985) fitted a simple exponential model, Page equation and a numerical solution to Fick's law of diffusion for a sphere with moisture dependent diffusivity, to exposed layer barley drying up to 150°C. He found that the simple exponential model described the effect of air temperature on drying rate, but did not predict well the shape of the drying curves. The Page model gave a much better prediction of the observed drying curve, but was still poor at describing initial drying behaviour. It was concluded that although the simpler models are expected to be useful where economy of computation is paramount, yet the diffusion model with concentration dependent diffusivity is more accurate and allows intra-kernel moisture movement to be modelled.

Liquid diffusion models have also been presented for wheat (Becker and Sallans, 1957), soybeans (Haghighi and Segerlind, 1978) and peanuts (Young and Whitaker, 1971). Nishiyama (1975) solved the spherical diffusion equation for rice using a constant surface moisture content. He obtained the following solution

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2 X} \qquad 2.11$$

where $X = kt + X_o$ = dimensionless time

X_o = correction term

The correction term was chosen to correct for the discrepancies between the experimental and theoretical drying curves due to the assumption of a constant surface moisture content. Nishiyama's approach has some of the same drawbacks that are encountered with empirical thin layer equations, the main being that the moisture distribution inside of the kernel is not evaluated.

Moisture content at any time can be predicted by any of the grain drying models if the drying parameters such as either drying constant or diffusion coefficient and equilibrium moisture content (emc) are known. The drying constant and emc are inputs to most of the empirical and semi-empirical models whereas the main inputs to the diffusion model are the diffusion coefficient and the surface boundary condition. The surface moisture content during drying in most of the diffusion models is taken to be equal to emc of the drying air and hence emc is an important parameter affecting drying.

The drying parameters are related to the drying air condition and depend also on the grain being dried. Various investigators have expressed this relationship in different ways. A brief review of literature on drying constant is given in Appendix 2.2 and available expressions for different crops are summarized in Table 2.1 The work of different investigators on diffusion coefficient and emc is reviewed in Appendices 2.3 and 2.4 and mathematical relationships of these two parameters with drying air condition and crop variables are summarized in Tables 2.2 and 2.3 respectively.

Chapter 3

THEORY

The physical mechanism of drying in capillary porous products such as cereal grains is quite complicated and is not yet well understood. It is generally agreed that the moisture within a grain kernel moves in the form of a liquid and/or vapour. A number of physical mechanisms have been proposed to describe the transfer of moisture in cereal grains (Brooker et al. 1974).

(1) liquid movement due to surface forces (capillary flow)

(2) liquid movement due to moisture concentration differences (liquid diffusion)

(3) liquid movement due to diffusion of moisture on the pore surfaces (surface diffusion)

(4) vapour movement due to moisture concentration differences (vapour diffusion)

(5) vapour movement due to temperature differences (thermal diffusion)

(6) water and vapour movement due to total pressure differences (hydrodynamic flow).

Luikov (1966, 1980) developed the following equations for describing the drying of capillary porous products based on the physical mechanisms mentioned above.

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} T_g + \nabla^2 K_{13} P \qquad 3.1$$

$$\frac{\partial T_g}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T_g + \nabla^2 K_{23} P \qquad 3.2$$

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31} M + \nabla^2 K_{32} T_g + \nabla^2 K_{33} P \qquad 3.3$$

where K_{11}, K_{22}, and K_{33} are the phenomenological coefficients, while the other K-values represent the coupling coefficients. The coupling results from the combined effects of the moisture, temperature, and total pressure gradients on the moisture, energy, and total mass transfer. Few of the phenomenological transfer coefficients for cereal grains are known at the present time. Therefore, Luikov's system of equations has not yet been applied to grain. The moisture flow due to a total pressure gradient is not significant in the temperture ranges employed in cereal grain drying. When there is no gradient of total pressure, the system of differential moisture transfer equations will take the form

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} T_g \qquad 3.4$$

$$\frac{\partial T_g}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T_g \qquad 3.5$$

The system of equations 3.4 and 3.5 is the most general system of equations. It is valid not only for drying processes but also for any type of moisture transfer. The above two equations have been applied to a number of products including corn (Husain et al. 1972). It was concluded that consideration of the coupling effects of temperature and moisture in the analysis of cereal grain drying is required in very limited cases e.g. conduction drying. So equations 3.4 and 3.5 become

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M \qquad 3.6$$

$$\frac{\partial T_g}{\partial t} = \nabla^2 K_{22} T_g \qquad 3.7$$

where K_{11} is called moisture diffusivity and K_{22} is thermal diffusivity.

It has not been conclusively proven so far whether the moisture moves in the liquid or vapour state although it is recognised that mechanism of moisture movement is diffusion as stated by Fick's law (Crank, 1979; Henderson, 1974). Drying may be a combination of liquid and vapour diffusion with one or the other dominating certain phases of drying.

The model on drying proposed in this study assumes that diffusivity is not a function of moisture content. This is a very common assumption and it has been made in most of the diffusion models for grain drying. In studying wheat drying, Becker (1959) found that the diffusion coefficient was independent of moisture content in the range from 13 to 25 percent (db). Steffe (1979) tested the assumption, that diffusivity is independent of moisture concentration, in the drying of white rice and found it to be valid.

Heat transfer equations have been neglected in the model because the resistance to heat flow in grain drying is very small compared to the resistance to mass flow. The temperature and concentration profiles can be compared by considering the Lewis number (Parker et al. 1974) which is the thermal diffusivity divided by the mass diffusivity. The two profiles are very similar when the Lewis number is equal to one i.e. both the diffusivities are equal. Young (1969) developed a modified form of the Lewis number from the vapour diffusion and heat transfer equations. He concluded that heat transfer could be neglected if the number was greater than 60. Husain et al. (1973) showed that the solutions to the isothermal and non-isothermal liquid diffusion equations are very close for biological materials because these have high Lewis number. The Lewis number for rough rice was calculated as 7446 from available data on diffusivities. The value of this number for wheat and barley is around 2000 and hence the exclusion of the heat transfer equations is justified. Sabbah (1971) reached a similar conclusion in the analysis of corn drying.

A grain kernel is not defined by a common geometric shape. However, to simplify the mathematical analysis, it is necessary to assume a simple configuration. This practice has been successful in characterizing the drying behaviour of numerous biological products. Hustrulid and Flikke (1959) used a spherical geometry to describe the drying curve for shelled corn. Pabis and Henderson (1961) were able to successfully simulate the thin layer drying of corn considering it to be brick-shaped. Researchers working with long grain rice varieties have generally used a cylinderical shape to describe drying (Husain et al. 1972; Walker and Bakker-Arkema, 1981; Arora et al. 1973; Kunze and Choudhury, 1972). In considering the drying characteristics of a single grain of rough rice, Hosokawa and Motohashi (1973) found that the shape of the kernel could be assumed to be spherical. For the purpose of theoretical analysis here, wheat and barley both have been assumed to be spherical in shape.

The purpose of this theoretical analysis is mainly to study the redistribution of moisture in the grain kernel during the rest period and analytic solutions tend to be more difficult to apply under such conditions. Hence, numerical approximation techniques have been used to predict the moisture distribution at various points within the spherical kernel and also the mean moisture content of the grain with time during drying, resting and redrying phases of two stage drying.

3.1 Numerical Analysis

The diffusion of moisture within a spherical kernel under constant diffusivity conditions is described by the following equation.

$$\frac{\partial C}{\partial t} = D \left[\frac{\partial^2 C}{\partial r^2} + \frac{2}{r} \frac{\partial C}{\partial r} \right] \qquad 3.8$$

where C is the concentration at any distance r from the centre of the kernel. One possible set of surface boundary conditions used in the solution of this diffusion equation are

$$\left. \begin{array}{l} C_s = C_b , \; t < 0 \\ C_s = C_e , \; t \geqslant 0 \end{array} \right\} \qquad 3.9$$

where C_b is the concentration in the beginning, before the start of the drying process. The abrupt change in C_s at t = o produces a discontinuity in $\overline{C}$ because C_s is used in the calculation for mean moisture content of the kernel. If the spherical kernel is divided into ten equal thickness shells, for example, this discontinuity becomes serious because the outermost shell will contain some 27% of the moisture in the sphere and this will result in an instant drop in mean moisture content of the kernel at time t = 0 of the order of 2 to 3% which produces unjustifiable errors in grain drying analysis. The concentration can be considered to be directly proportional to the moisture content provided the dry matter density is assumed to be constant. The abrupt change in calculated $\overline{C}$ could be reduced by using a large number of shells which adds greatly to the computation required and hence does not seem to be justified either. Table 3.1 shows the effect of number of shells on instant drop in moisture content of the kernel and the relative time required for computation when the above equation was solved numerically using the Crank-Nicolson approximation employing the Gauss-Seidel iterative techniques. This technique of approximation was selected because the analysis becomes independent of Fourier number [F.N. = (D.Δt)/ (Δr)^2] which involves thickness of shell (Δr) and duration of time step (Δt) whereas the easier Schmidt method is applicable only for Fourier Number of 0.5 (Smith, 1974). The details are provided in later section.

To overcome the discontinuity problem and to reduce the number of shells to keep down the computation time, variable grid spacing was employed (Woods, 1976). The shell thickness was constantly reduced by a factor with innermost shell having maximum thickness and the surface shell, the least possible.

3.1.1 Formulation of the Equations

If the sphere is divided into a number of shells of varying radial width and the time dimension is similarly divided into discrete time steps Δt, a grid may be visualised in the r, t plane as shown in Fig. 3.1. In terms of the Crank-Nicolson approximation,

$$\frac{\partial c}{\partial t} = \frac{C_{i,j+1} - C_{i,j}}{\Delta t} \qquad 3.10$$

$$\frac{\partial c}{\partial r} = \frac{1}{2}\left[\frac{C_{i+1,j+1} - C_{i-1,j+1}}{(\Delta r_1 + \Delta r_2)} + \frac{C_{i+1,j} - C_{i-1,j}}{(\Delta r_1 + \Delta r_2)}\right] \qquad 3.11$$

$$\frac{\partial^2 c}{\partial r^2} = \frac{1}{2}\left[\frac{\Delta r_1(C_{i+1,j}-C_{i,j})-\Delta r_2(C_{i,j}-C_{i-1,j})}{0.5\ \Delta r_1\ \Delta r_2\ (\Delta r_1 + \Delta r_2)} + \frac{\Delta r_1(C_{i+1,j+1}-C_{i,j+1})-\Delta r_2(C_{i,j+1}-C_{i-1,j+1})}{0.5\ \Delta r_1 \Delta r_2\ (\Delta r_1 + \Delta r_2)}\right]$$

3.12

$$\left.\begin{aligned} \Delta r_1 &= r_i - r_{i-1} \\ \Delta r_2 &= r_{i+1} - r_i \end{aligned}\right] \qquad 3.13$$

Substituting 3.13 in 3.11 and 3.12 and then replacing various parts of equation 3.8 by their corresponding numerical approximations and simplifying we get

$$C_{i,j+1} = \frac{1}{P}\left[B(i) + Q\, C_{i-1,j+1} + S\, C_{i+1,j+1}\right] \qquad 3.14$$

where $P = \frac{1}{D(\Delta t)} + \frac{1}{X} + \frac{1}{Y}$

$$Q = \frac{1}{X} - \frac{1}{Z}$$

$$S = \frac{1}{Y} + \frac{1}{Z}$$

$$X = [r_i - r_{i-1}]\ [r_{i+1} - r_{i-1}]$$

$$Y = [r_{i+1} - r_{i-1}]\ [r_{i+1} - r_i]$$

$$Z = r_i\ [r_{i+1} - r_{i-1}]$$

and $B(i) = \frac{C_{i,j+1}}{D(\Delta t)} + \frac{C_{i,j+1}}{X} - \frac{C_{i-1,j+1}}{X} - \frac{C_{i+1,j+1}}{Y} + \frac{C_{i,j+1}}{Y} + \frac{C_{i-1,j+1}}{Z} - \frac{C_{i+1,j+1}}{Z}$

Equation 3.14 can be used to calculate concentration at any point in the spherical kernel at the next time step.

At the centre of the kernel, r = 0 so the term $\frac{2}{r}\frac{\partial C}{\partial r}$ in equation 3.8 becomes indeterminate i.e.

as $r \rightarrow 0$, $\frac{2\frac{\partial C}{\partial r}}{r} \rightarrow \frac{0}{0}$

By applying L'Hospital's rule, 3.8 reduces to

$$\frac{\partial C}{\partial t} = 3D\,\frac{\partial^2 C}{\partial r^2} \qquad 3.15$$

Substituting 3.10 and 3.12 in 3.15 and simplifying

$$C_{0,j+1} = \frac{B}{(1+3F)} + \frac{3F}{(1+3F)} \quad C_{1,j} \qquad 3.16$$

where $F = \dfrac{D\ \Delta t}{r_1^2}$

and $B = \left[\ 1-3F\right] C_{o,j} + 3F\ C_{1,j}$

The mean concentration of the spherical shell at any time j is given by equation 3.17. The variation in concentration between two respective grids was assumed to be curvilinear and expressed as a quadratic equation. A separate equation was used for the outermost and the innermost shell but for all other shells numerical integration was carried out to calculate the mean concentration.

$$C = \frac{r_1^3 \left[\dfrac{3C_1+2C_o}{15}\right] + \sum_{i=1}^{m-2}\left[\dfrac{a_i}{5}\left[r_{i+1}^5 - r_i^5\right] + \dfrac{b_i}{4}\left[r_{i+1}^4 - r_i^4\right] + \dfrac{d_i}{3}\left[r_{i+1}^3 - r_i^3\right]\right] + \dfrac{1}{3}\left[r_m^3 - r_{m-1}^3\right]\left[\dfrac{C_m + C_{m-1}}{2}\right]}{(r_m^3/3)}$$

3.17

where $a_i = \dfrac{\left\{C_{i+1}\ r_i\ (r_{i-1} - r_i)\right\} + \left\{C_{i-1}\ r_i\ (r_i - r_{i+1})\right\} + C_i\left\{r_{i-1}\ (r_{i+1} - r_i) + (r_i - r_{i-1})\ r_{i+1}\right\}}{(r_i - r_{i-1})\ (r_{i+1} - r_i)\ r_i\ r_{i-1} - (r_i - r_{i+1})\ (r_{i-1} - r_i)\ r_i\ r_{i+1}}$

$$d_i = \frac{(C_i\ r_{i-1} - C_{i-1}\ r_i) - a_i\ (r_i - r_{i-1})\ r_i\ r_{i-1}}{(r_{i-1} - r_i)}$$

$$b_i = \frac{(C_i - d_i)}{r_i} - a_i\ r_i$$

$$r_i = \frac{r_m\ (1 - R^i)}{(1 - R^m)} \quad \text{and} \quad R = \frac{(r_{i+1} - r_i)}{(r_i - r_{i-1})}$$

Here R is the ratio of the thickness of any two adjacent shells. The total radiu of the kernel, R_p, was divided into m shells and described as the sum of a geometric series and $r_m = R_p$.

3.1.2 Rest Period Boundary Condition

During the rest period, the mean concentration of the kernel remains constant and only the redistribution of moisture within the kernel takes place. The surface moisture content during the rest period is not equal to the equilibrium moisture content of drying air since the grains are not being exposed to hot air. A quadratic equation was used to express the surface moisture content during resting in terms of concentrations in the next two shells. The surface concentration during resting is given by

$$C_s = \frac{C_{m-1}\,(r_m - r_{m-2})^2 - C_{m-2}\,(r_m - r_{m-1})^2}{(r_m - r_{m-2})^2 - (r_m - r_{m-1})^2} \qquad 3.18$$

It can be seen that as the thickness of the outermost shell becomes smaller and smaller, the surface concentration approaches the concentration at the last but one shell, i.e.

As $(r_m - r_{m-1}) \longrightarrow 0 \quad , \quad C_S \longrightarrow C_{m-1}$

It was observed that with variable grid spacing, after fixing the grid size (discussed in Section 3.1.4), the surface moisture concentration during rest period calculated by the integral method, involving the total weighted concentration of whole kernel, the weighted concentration of all but the last shell and the volume of the last shell, started oscillating. This could be due to the limited accuracy of the microcomputer used in analysis and crude tolerance limit for convergence of iterations combined with extremely small volume of the last shell because the surface shell contained just about 1% of the total volume of the spherical kernel. This method was hence found to be unsatisfactory. The quadratic equation approach (equation 3.18) however worked well and was used in subsequent analysis.

The complete derivations of equations 3.12, 3.17 and 3.18 are given in Appendix 3.1.

3.1.3 Solution Procedure

In terms of the Gauss-Seidel iteration (Smith, 1974), the formulated equations could be written as

for i = 0 i.e. centre of kernel, $C_{o(n+1)} = \frac{B}{(1+3F)} + \frac{3F}{(1+3F)} C_{1(n)}$ 3.19

For i = 1 to the (m-1)th shell, $C_{i(n+1)} = \frac{Q}{P} C_{i-1(n+1)} + \frac{S}{P} C_{i+1(n)} + \frac{B(i)}{P}$ 3.20

where n denotes the number of the iteration. The concentration at the surface of the kernel is calculated from 3.18 or known from 3.9 when all other concentrations from centre of the kernel to the (m-1)th shell are known. The Gauss-Seidel iterations are performed starting from the centre of the kernel and proceeding towards the surface. The concentrations at individual shells are updated immediately after computations. This solution procedure was adapted because it provides faster rate of convergence of the iterations as compared to Jacobi's method (Smith, 1974). The iterations are continued until the difference between the updated concentrations and the previously stored concentrations at all shells of the kernel becomes less than a predefined tolerance limit. This procedure is repeated for all time steps. The concentrations at individual shells are used to calculate the mean moisture content of the kernel from equation 3.17 at a particular time. The computations are continued until the mean moisture content of the kernel becomes less than a predefined final moisture content. The iterations are started by defining the initial concentration at all shells, which is equal to the initial moisture content of the grain to be dried and the equilibrium moisture content of the drying air at the surface. The Gauss-Seidel iterations updating is illustrated in Fig. 3.2. The flow chart showing the systematic calculation procedure for numerical calculation of concentrations at all shells of the kernel in a two-stage drying process is presented in Appendix 3.2.

A computer program in BASIC was developed based on this flow-chart.

3.1.4 Fixing Grid Size

It was observed that the tolerance limit for convergence of Gauss-Seidel iterations, length of time step and introduction of over-relaxation and under-relaxation has no effect on initial drop in concentration immediately at the onset of drying. However the number of shells into which the kernel is divided (m) and the ratio in which shell thickness is reduced (R) had a profound effect on initial drop. The effect of m and R on predicted concentration of the kernel in the beginning is presented in Table 3.2. A grid of 10 shells with R = .61 was selected keeping in view the computation time and taking an initial drop in concentration of 0.1% to be reasonable. At lesser values of R, the numerical solution tended to be unsatisfactory.

It was observed that when the boundary conditions changed suddenly e.g. from drying to resting and again from resting to re-drying, the solution created some fluctuations in mean concentration of the kernel if the time step was too great. The solution required some settling time to cope with the abrupt change in boundary conditions.

The time steps were hence adjusted at various stages of the two stage drying process. The drying stage started with a low time step (0.1 min.) and was then subjected to higher time steps (1 min.) to reduce computation time. The time step was reduced to 0.1 min. when the drying stage was about to end and resting was to start. The numerical solution was subjected to low time steps (.02 to .05 min.) during the whole of the resting stage to keep the change in mean concentration to a bare minimum and at the same time completing the computations within manageable time. The time step was increased again to 1 min. after the start of the redrying stage. The varying time step at different stages provided a maximum instant drop of 0.1 percent in mean concentration during the start of the drying and redrying stages and during the resting period.

The grid size for a numerical solution was hence completely defined by fixing m (number of shells), R (ratio in which shell thickness changes) and Δt (time step at various stages).

3.1.5 Final Computer Program

The final computer program based on analysis presented in previous sections is given in Appendix 3.3. It incorporates a fixed grid of varying shell thickness and variable time steps. The inputs to the program are:

(1) Initial concentration or moisture content of grain (percent wet basis) - MO

(2) Final moisture content to which the grain is to be dried (percent wetbasis) - MF

(3) Equilibrium moisture content of drying air (percent wet basis) - EM

(4) Diameter of the spherical kernel (metres) - DP

(5) Mass diffusivity of grain (sq. metre/min) - D

(6) Initial drying time after which resting starts (min) - SR

(7) Time from beginning of drying after which rest period ends (min) - ER

The moisture contents taken on wet basis are converted to dry basis in the program and all subsequent calculations and analysis is carried out on dry basis. The program stops execution when final moisture content is reached. If the duration of rest period is infinite, it is assumed that after resting, moisture content at all shells of the kernel is the same as the mean moisture content of the kernel at the end of the drying stage and to predict the redrying stage, this mean moisture content is then taken as the initial moisture content to run the program.

3.1.6 Comparison of Analytic and Numerical Solution

The solution of the diffusion equation 3.8 in spherical coordinates is given by Crank (1979) as

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(- \frac{n^2 D \pi^2}{R_p^2} t\right) \qquad 3.21$$

The moisture concentration calculated at various times from this equation by summation of a different number of terms of the infinite series is compared with the numerically developed solution of the diffusion equation for a typical drying run in Table 3.3. It is observed that the numerical solution compares well with high accuracy analytic solution obtained by summation of as much as 100 or more terms of the infinite series.

The analytic solution with 100 terms of the infinite series is compared graphically with the numerical solution in Fig. 3.3.

3.2 Theoretical Results

The computer program developed in the previous sections was used to study the effect of duration of rest period and the stage at which resting is done, on a two stage drying process. The reduction in drying time excluding rest period, was evaluated relative to continuous single stage drying. The value of diffusivity used in the theoretical analysis was calculated from equation proposed by Smith et al. (1982) for barley and the diameter of the spherical kernel was taken as the geometric mean of three dimensions of a barley grain at axis perpendicular to one another. The results were expressed in the form of a dimensionless parameter (Dt_{λ}/R_p^2) so that the analysis becomes independent of the variation in the values of diffusivity and radius of the particle.

The moisture redistribution during the rest period in a typical two-stage drying run is presented in Figure 3.4. It can be seen that after 12 minutes of drying, there is a considerable moisture gradient which has developed inside the kernel. The inner half of the spherical kernel is still at the starting moisture content and moisture has just started diffusing outwards from the centre. It can be further observed that if the grain is rested after this much initial drying, then the gradient starts to diminish. This moisture starts equalizing as the resting progresses. The surface moisture content starts increasing as the rest period passes and the moisture at the centre of the kernel starts decreasing. It needs a rest period of infinite duration to completely equalize the moisture within the kernel. After an infinite rest time, the moisture content is uniform and equal to the mean moisture content, which is constant throughout resting. If the grain surface attains the maximum attainable value of surface moisture content, the redrying will be at the fastest rate and there will be maximum benefit of introducing a rest period. However, the concept of infinite resting is just a hypothetical one and is not possible from a practical point of view.

The rate at which the surface moisture content increases during the rest period is shown in Figure 3.5 for the same two-stage drying run. It can be seen that the surface moisture content rises abruptly during the first few minutes of the rest period. In the particular case shown, the kernel attained 67.7% of the maximum attainable value of surface moisture content after 10 minutes of resting and 83.3% of the maximum value in just 30 minutes of rest period. It can be observed that in two hours, it has reached almost the maximum possible value of surface moisture content. Sabbah (1971) defined a parameter called the tempering index to define the rise in surface moisture content with the passage of rest period.

$$I_c = \frac{C_{s\,(t)} - C_{s\,(t=o)}}{C_{s\,(t=\infty)} - C_{s\,(t=o)}} \qquad 3.22$$

where C_s refers to the surface moisture content of the kernel and t is the duration of the rest period. This index can be used to indicate the extent to which resting has advanced the equalisation of moisture in the grain. The tempering index based on this analysis for this drying run is shown along with the rise in surface moisture content. It can be seen that the grain attained the tempering index of .91 after 1 hour of resting and .96 after two hours of resting. In other words, it could be said that tempering or resting was 96 percent complete in about two hours and 91 percent in just one hour. The duration of rest period will be further examined in detail in the following sections.

3.2.1 Optimum Resting Stage

Some of the redrying curves in a typical two-stage drying situation when resting is done at different stages but for fixed duration, are presented in Fig. 3.6. These curves were analysed for different drying requirements and results are presented graphically in Fig. 3.7. The drying requirement is shown as MR_f (final required moisture ratio) for the sake of simplicity rather than indicating it as the difference of initial and final moisture content to which the grains are to be dried. Similarly, the stage at which resting has been done is defined by MR_{rest} so that it also becomes independent of initial and equilibrium moisture content under a particular drying situation. It can be seen clearly from Fig. 3.7 that for each drying requirement, there is a particular MR_{rest} at which the reduction in drying time over continuous drying is the maximum. It means for each drying situation, there is a particular stage at which resting should be done in order to extract the maximum benefit of introducing two-stage drying. This stage of resting is referred to as the optimum resting point and is denoted by $\widehat{MR}_{rest}$ in subsequent discussions. If the grain is rested too early in a continuous drying process, it might not have developed enough moisture gradient within the kernel so as to derive the maximum benefit from a rest period. Similarly, if resting is done too late, the kernel might already have dried to such an extent that there is no potential left in the grain to redistribute its moisture and hence no (or little) benefit of resting. It means physically therefore that resting has to be done at an appropriate level of initial drying in order to keep the total drying time to a minimum in a two-stage drying process. It can be further concluded from Figure 3.7 that as MR_f decreases, $\widehat{MR}_{rest}$ also decreases which in other words means that the more is the drying requirement, the later is the resting point. It could also be mentioned in another way that the more is the drying requirement, the more is the time of initial drying after which the rest period is to start. The drying requirement actually indicates the difference in the initial and the final moisture content of the grain during drying or the reduction in grain moisture content required during drying.

3.2.2 Duration of Rest Period

The effect of duration of rest period for two different stages of resting (i.e. MR_{rest}) is presented in Fig. 3.8 and Fig. 3.9. The detailed analysis of Fig. 3.9 is shown in Figs. 3.10 and 3.11. The Figures 3.8 and 3.9 appear to be similar in characteristics. It can be clearly seen from Fig. 3.10 that as the duration of rest period increases, the reduction in drying time over continuous drying also increases for all values of MR_f i.e. under all conditions of drying requirement. It can be concluded further that as MR_f increases, the reduction in drying time also increases, i.e. if drying requirement is less, the benefit of introducing rest period is relatively more. The analysis of Fig. 3.11 reveals that the bulk of the benefit of resting is obtained during the first one hour of rest period if drying requirement is less i.e. if MR_f is more e.g. for $MR_f = .667$, reduction in drying time is 43% with one hour of resting whereas for infinite resting it is about 46%. At this drying requirement, therefore, there seems to be little justification for a rest period duration of more than an hour. However, if MR_f is equal to .401, i.e. if the drying requirement is more, then one hour of rest reduces drying time by 25% and infinite resting by 33%. It could be concluded from this that the greater is the required reduction in moisture content during drying, relatively more should be the duration of rest period.

Another aspect of two-stage drying is illustrated in Fig. 3.12. It can be seen that for a particular drying requirement, the optimum stage of resting varies a little with the duration of rest period. As the duration of rest period is increased, $\hat{MR}_{rest}$ also increases which in other words means that the longer is the duration of rest period, the earlier is the optimum point of resting i.e. the less is the initial drying time for a particular drying requirement.

3.2.3 Discussion

The theoretical results of two-stage drying with an intervening rest period are summarized in Figures 3.13 and 3.14. It can be clearly seen from these two figures that:

1. For each drying requirement defined by MR_f, there is an optimum stage of resting defined by $\hat{MR}_{rest}$. This resting stage is affected by the duration of rest period but the effect does not seem to be significant from the point of view of overall reduction in drying time. As MR_f increases, $\hat{MR}_{rest}$ also increases i.e. if less moisture is to be removed from the grain during drying then resting has to be done at an earlier stage and vice versa.

2. If the rest period is provided at the optimum point of resting, there could be a reduction in drying time of as much as 46 percent depending upon the duration of rest period and the requirement of moisture reduction during drying.

3. As MR_f increases, the reduction in drying time also increases. This means that if the requirement of moisture reduction during drying is less, then there is comparatively more benefit of introducing a single rest period in a two-stage drying process.

4. If the duration of rest period is increased, the benefit of resting in terms of reduction in drying time also gets increased. The relative effect of increasing the duration of rest period is more at low values of MR_f. Suffice is to say that the more is the moisture reduction required during drying, the longer should be the duration of rest period.

5. At higher values of MR_f, the value of the dimensionless parameter (Dt_r/R_p^2), beyond a certain range, seems to have a little effect on reduction in drying time, e.g. if $MR_f = .667$, increasing the value of this parameter from .047 to infinity, gives a further reduction in drying time of only about 2%. It means that if the required reduction in moisture content during drying is less, then the type and variety of crop (which affects diffusivity), the size of the grain and a longer duration of rest period have a limited effect on reduction in drying time in a two-stage drying process.

6. The rest period of about 1 to 2 hours duration appears to be enough for most of the commonly encountered drying situations in practice.

There is, thus, a distinct advantage of introducing a rest period in a drying process. The reduction in drying time by as much as 46% could increase the throughput of a continuous dryer by up to 85% if all other factors affecting the dryer output like initial moisture content of the crop, the final moisture content, drying air temperature, type of the dryer and ambient air conditions are the same. The resting stage can be introduced easily in a batch drying process. In a continuous drying situation, resting could be achieved by providing a tempering zone without any supply of hot air. The location of this tempering or resting zone across the length of the continuous dryer could be worked out from the dryer design parameters. Once the incoming moisture content of the grain and the target moisture content are known, the optimum point of resting could be found from the analysis presented above. From this optimum resting stage, the initial drying time can be determined if the performance characteristics of the dryer are known. The theoretical analysis, hence, indicates that the two-stage drying process with an intervening rest period at an optimum point is an adaptable proposition in commercial grain drying.

Chapter 4

THIN LAYER DRYING EXPERIMENTS

4.1 Thin Layer Drying Apparatus

Thin layer drying should be conducted under controlled conditions of air temperature, relative humidity and air flow rate. An apparatus was therefore needed for the purpose of providing these required conditions.

The schematic diagram of the thin layer drying apparatus is shown in Figure 4.1. To dry wheat and barley under controlled conditions of air temperature and relative humidity, atmospheric air was supplied by a backward curved centrifugal fan, A, through a pipe fitted with an orifice plate, B, to the bottom of a glass tower packed with plastic rings, C. At the top of the tower water was sprayed at the required dew point temperature of the air. At the exit, the air passing through the packed tower was approximately saturated and was then heated to the required temperature by electric heaters, D. The tape heaters, T, were also provided in the upper portion of the moisturising column and in the pipe preceding the electric heaters to avoid condensation of moisture from saturated air before it gets heated. The hot air was then passed through the tray, G, containing a thin layer of about one grain thickness of wheat or barley via gauge, E, and honeycomb flow straightener, F. The tray was supported on a frame, U, suspended from an electronic balance, H, capable of transferring continuous weights to a micro-computer. The apparatus is shown in Figures 4.2 to 4.4 and further details are provided under various sections.

4.1.1 Moisturing Column

The moisturising column, C, as shown in Figure 4.1, consists of a vertical glass tower packed with plastic rings used as saturation media. The desired air condition may be defined by dew point temperature and dry bulb temperature. The atmospheric air was passed through the packed cooling tower from the bottom and water was allowed to pass down the tower in the opposite direction to the air so that air got humidified. The desired dew point temperature of the air was obtained by controlling the temperature of water being circulated from tank, J, with the help of a water pump, P. The water temperature was maintained to within ± 0.1°C by a temperature controller, M. The water in the tank, J, could be heated with water heaters, I, or cooled by circulation through an ice-bank cooler, S, which was run with refrigeration unit, R. The circulation of water between ice bank cooler and water tank could be controlled with valve, V, depending upon the required dew point temperature below ambient. The rate of circulation of water through moisturising column could be varied with valve, Z, and measured with rotameter, L.

4.1.2 Drying Chamber

The schematic diagram of the drying chamber is shown in Figure 4.5. It consists of drying tray, G, tray support system, B, suspension frame, U, and the outer enclosure, D. The drying tray was made of 200 mm square nylon wire mesh fixed on an aluminium frame. The grain sample was spread on the nylon mesh and air could easily pass through it. The drying tray is supported on a 265 mm square aluminium frame which can be attached to the suspension system. The outer enclosure is firmly fixed with the main frame, F, of the whole structure through spacers, S, and is provided with a cover plate, C, with a hole in the centre for passing the tray suspension frame. The outer metallic enclosure, D, along with its cover causes the hot air leaving the grain to flow down through the duct formed around the inner drying chamber, N, with the help of polythene sheet, P, fixed to the enclosure. This arrangement ensures minimum heat loss from the drying chamber and a portion of the upstream piping and reduces the thermal gradient in the system. The inner drying chamber, N, is fixed on a base plate, M, provided with levelling screws. The drying tray and its support structure were made of aluminium and galvanised iron respectively to make the system lighter and suitable for high temperature drying. The total weight of the tray support, drying tray and suspension frame was approximately 1457 g whereas the balance had a total weighing capacity of up to 5500 g. The main supporting frame of the drying chamber was also provided with levelling screws, L, to keep the structure in level position. A hinged door was provided in the outer enclosure, D, for taking the grain tray in and out of the drying chamber.

The upstream portion of the hot air pipe was all insulated with air-bubble polystyrene insulation where the pipe was flexible and with flexible foam insulation at other places to minimise heat loss from heated air.

4.1.3 Instrumentation and Microcomputer Interfacing

The most important part of thin layer drying experiments is to record the weight of drying sample with time as accurately as possible. In the earlier stages of grain drying research, it has been the practice to remove the grain sample periodically out of the drying air and to take its weight and return it again for drying to continue. Ross and White (1972) and several other investigators have used this type of arrangement. Such a procedure is known to produce significant errors in the drying data (Willitis and Ross, 1974).

Greig (1970) developed a system to repetitively and automatically record the small weight changes which occur due to mass transfer, on punched paper tape using data logging equipment. Hutchinson and Otten (1983) developed an electromagnetic balancing arrangement having a maximum capacity of 150 gm and accuracy of ± 0.1% for thin-layer drying of soybeans and white beans. Hutchinson and Otten used a digital multimeter to obtain voltage readings corresponding to the sample weight and the readings were manually recorded.

Henderson (1974), Agrawal and Singh (1977), and Misra and Brooker (1980) employed commercially available load cells for sensing weight changes of samples in thin-layer drying apparatuses and used strip chart recorders to continuously record the load cell outputs. Maximum capacity and accuracy of Henderson's (1974) and Agrawal and Singh's (1977) weighing arrangements were 400 g and ± 0.125%, respectively, whereas, the corresponding values reported by Misra and Brooker (1980) were 100 g and ± 0.5%. Stone and Kranzler (1981) also used a commercial load cell in their apparatus, however, the operating specification of their weighing system was not reported. They used a microcomputer based system for data acquisition and control of their dryer.

Menzies and O'Callaghan (1971) arranged a linear transducer above the balance so that the movement of the top pan of the balance was imparted to the slug of the transducer. The transducer was fed with an A.C. signal from a transducer-converter and the magnitude of the return signal depended on the extent to which the slug protruded into the coil of the transducer. The A.C. return signal was converted to D.C. and was fed to a datalogger, the reading of which was proportional to the loading on the balance. Nellist and O'Callaghan (1971) fitted the balance with a Photain light switch which was positioned so as to be activated by the graticule projection when the balance reads 100 g or less. Activation of the switch caused the closure of reed contacts which in turn caused the time at which it occurred to be both printed and punched onto tape and the weight dispenser to release one weight.

Khalilian et al (1983) reported using a sensitive top-loading electronic balance placed in the drying chamber. They built an elaborate system for drying multiple samples of hay in which a chain conveyor was used to carry the samples to and from the balance. The balance was interfaced to a programmable HP97 printing calculator for periodic recording of sample weights. Bruce and Sykes (1983) used a balance to support the pan and incorporated an air bearing arrangement to reduce the movement of the sample pan in the horizontal direction. They reported a weighing accuracy better than 0.02%. Data logging was done with a microcomputer which was also interfaced to a mainframe computer. Very little detail of the software and hardware was given.

Frecks et al (1973), Vedak (1974) and Willitis and Ross (1974) developed strain-gage mounted cantilever beam arrangements for sensing weight changes with accuracies ranging from 1.5% to 0.25%. In all cases the analog corresponding signal was either recorded by a strip chart recorder or a printer. Bala (1983) recorded the outputs of the balance with a multichannel datalogger. The weight change and the recorded output in mv was found to be linear with a standard error of 0.235 g. Some (1985) used an electronic balance having an asynchronous interface RS 232 for handshaking with Apple IIe microcomputer and developed an 'Applesoft Basic' program to regulate the recording of drying data onto the floppy disks which was later on transferred to IBM 370 mainframe computer for analysis.

Chinnan (1986) developed a general purpose microcomputer-based data acquisition system using Heath microcomputer and designed a high resolution cantilever beam type strain-gage weight sensing system. The software for acquiring thin layer drying experiment data with the microcomputer was also developed. The drying data was stored on the disk for further analysis on the same microcomputer.

Continuous Weight and Time Recording

For the purpose of this work an electronic balance (Satorius, MP8/1507) the same as that used by Some (1985) was employed. The accuracy of the balance was tested in the range 0 - 5500 gm. (Figure 4.6). The balance had different programming options for data transfer to a microcomputer and for transferring data at maximum speed it was programmed to operate without stability and at the fastest available baud rate of 9600 Bd. The detailed program listing for balance operating program used in the present work is given in Appendix 4.1. In some preliminary experiments, it was observed that the balance reading fluctuates due to airflow rate and hence it was decided to average several readings of weight to get a representative value. The balance had an asynchronous interface (RS 232 - specification) for handshaking with the microcomputer. It was interfacd to an Apple IIe microcomputer having 64 K RAM as the central processor via a serial interface card (CCS 7710, california computer systems). An ADA-LAB serial card (Interactive Microware, Inc.) was similarly interfaced with the microcomputer and the supplied software used to read the time from various memory locations of the computer. The transfer of weight data from balance to the computer was controlled by activating a hand switch or foot pedal connected to the serial output on the balance. A block diagram for the overall computer and data acquisition system is shown in Figure 4.7. An 'Applesoft Basic' program was developed to regulate the recording of the time and weight data onto the floppy disks. First, the time was read from various memory locations, then several weight readings were taken and again the time in hours, minutes and seconds was read from three memory locations. From this information average time and mean weight of the sample was calculated and stored on the floppy disk. The process was repeated until the end of the experiment. The developed data acquisition program together with a simplified flow chart is presented in Appendix 4.2.

An 'Applesoft Basic' program was also developed to read the data stored on floppy discs and is given in Appendix 4.3.

Airflow

The airflow was measured by an orifice plate and an inclined manometer. An orifice plate of 22 mm diameter was set in the air supply pipe of 104 mm diameter. The flow rate was calculated according to the International Standard ISO 5167 (1980). The air velocity in the grain drying tray was also frequently measured with a vane anaemometer just as a check before the start of drying.

Several investigators have examined the effect of airflow on grain drying. Simmonds et al (1953) investigated the rate of drying of single layers of wheat grain and found it to be independent of air velocity in the range 0.15 to 0.81 m/sec. Henderson and Pabis (1962) observed that variation in airflow rate between 0.018 m/sec to .68 m/sec affected the surface moisture transfer coefficient insignificantly particularly after the first two hours of drying. Pabis and Hall (1962) observed that after the air velocity is more than about 0.25 m/sec, a further increase in air velocity only slightly influences the boundary layer thickness and hence the drying process of a thin layer of corn but it is an important factor in deep bed drying. Ross and White (1972) studied thin layer drying characteristics of white corn in the airflow range of 0.22 to 0.30 m/sec. Sharaf-Eldeen et al (1980) maintained an average air velocity in ear corn drying in the range of 2.65 ± 0.5 m/sec. White et al (1981) while studying fully exposed drying of soybeans and popcorn maintained an air velocity in the range of 0.2 to 0.3 m/sec. Bala (1983) and Some (1985) maintained an air velocity in the range of 0.25 to 0.275 m/sec during thin layer experiments on malt and maize drying respectively. Mulet et al. (1987) observed that air velocities greater than 1.5 m/sec had no effect on drying rate of carrot.

In the present experiments on wheat and barley, a constant velocity between 0.350 and 0.375 m/sec was maintained for all thin layer drying work.

Drying Air Condition

A Dew Point Meter (Protimeter) probe was placed in the hot air stream below the grain mass and connected to the meter, which displayed ambient temperature and dew point temperature. Relative humidity was calculated from these two readings and displayed if it was more than 18 percent. Since the relative humidity of drying air in thin layer drying experiments was less than 18 percent, it was calculated differently from known values of ambient temperature and dew point temperature, which is described in Section 4.4. The temperature of the drying air was controlled by varying the voltage supplied to one of the air heaters which was connected through a variac. The air temperature just below the tray containing the grain was recorded using a copper-constanton thermocouple.

Moisture Content

All moisture contents were determined by the method recommended by the ASAE S352, 1977. Bowden (1984) carried out experiments to determine the relative adjustments required to values obtained for moisture content of barley and wheat as determined by three different routine oven methods ISO 712 (1979E), ASAE S 352 (1977) and NIAE (16 hr) and concluded that the ASAE method gave more consistent results, and coupled with the ease of use, recommended this method for moisture content determination in most applications. In the present work, five replications of each of the moisture content determination were made as three were found to be inadequate in some of the preliminary experiments.

4.2 Resting Apparatus

The resting apparatus is shown in Figure 4.8. It comprised of a controlled temperature hot air oven, resting container and an arrangement to measure the rise in surface moisture content of the grain during the rest period.

4.2.1 Resting Container

The container in which the grain sample was kept during the rest period consisted of a brass tube 6 mm thick, 37 mm internal diameter and 210 mm length. The brass tube was fixed on a square brass base 100 x 100 x 5 mm. A transparent sheet of glass was fixed in the centre of the square base plate so that the emptying of grains from the tube after resting could be seen properly. The container was provided with a top cap which could be screwed tightly on to the tube. This cap was also made of brass. The brass tube of 6 mm thickness was selected because brass has a higher thermal conductivity than many other materials and the thick brass tube had high thermal capacity. This could help the grains regain temperature rise quickly after transfer during the start of the rest period. Moreover, the pipe gave much more area of contact of grain with hot surface which made the regain of heat by grains much faster. The hot grains after some initial drying could hence be transferred and kept hot during resting without undergoing much temperature change during the transfer process. The resting container was at all times to be kept in the preheated air oven maintained at the same temperature as that of the drying air. The temperature in the resting container immediately before and during transfer of grains was recorded with the help of a copper-constanton thermocouple.

4.2.2 Surface Moisture Content during Resting

As described earlier, during the rest period the redistribution of moisture within the partially dried kernel of grain takes place. The surface moisture content of the grain rises during the rest period and resting is considered to be complete when the moisture content at the surface attains its maximum value in a particular two stage drying situation. Moreover to study the effect of duration of rest period, it is very important to be able to determine the moisture content at the surface of the grain. However there seems to be no direct way of experimentally measuring the moisture content at the surface. Steffe and Singh (1980) while analysing equilibrium moisture content data for rice at a fixed temperature, observed that a linear model of the form

$$M_{es} = a + b\ (RH) \tag{4.1}$$

where a and b are constants, provides a good description of the data in the range of relative humidities approximately 10 to 90 percent. This model was found to be valid for equilibrium moisture content data for wheat and barley at a fixed temperature as given by equations proposed by Nellist and Dumont (1979), Nellist (1974) and Bruce (1985). The linear equations developed were:

Wheat, 60°C $M_{es} = .02816 + 1.8202 \times 10^{-3}\ (RH)$ 4.2

$(r^2 = .9516)$

$M_{es} = .05366 + 1.5506 \times 10^{-3}\ (RH)$ 4.3

$(r^2 = .9516)$

Barley, 60°C $M_{es} = .02489 + 2.2948 \times 10^{-3}\ (RH)$ 4.4

$(r^2 = .9516)$

Solving equation 4.1 for relative humidity and writing the moisture content in terms of the surface concentration yields

$$RH = \frac{C_{s\ (t=\infty)}}{\rho b} - \frac{a}{b} \tag{4.5}$$

Since the equilibrium moisture content is determined after long exposure of the grain to the drying air, surface concentration at infinite time is taken to denote it. However, resting is a dynamic process and the humidity at time 't' is determined by the surface concentration at that time. The tempering index based on humidity may then be written as

$$I_{RH} = \frac{\frac{C_{s(t)}}{\rho b} - \frac{a}{b} - \left(\frac{C_{s(t=o)}}{\rho b} - \frac{a}{b}\right)}{\frac{C_{s(t=\infty)}}{\rho b} - \frac{a}{b} - \left(\frac{C_{s(t=o)}}{\rho b} - \frac{a}{b}\right)} = \frac{RH_t - RH_o}{RH_\infty - RH_o} \tag{4.6}$$

On simplification, this yields

$$I_{RH} = \frac{C_{s(t)} - C_{s\ (t=o)}}{C_{s(t=\infty)} - C_{s(t=o)}} \tag{4.7}$$

The right hand side of equation 4.7 has already been defined as I_c, the tempering index based on concentration in Section 3.2. It means

$$I_{RH} = I_C \qquad 4.8$$

which allows a direct comparison between experimentally collected data on relative humidity and theoretically predicted data on concentration at the surface of the grain. Efforts were hence made to collect relative humidity data during the rest period.

The relative humidity in the resting container during resting was measured with the help of a "Humidity and Temperature Probe (Vaisala - HMP 32 UT)" coupled to a "Humidity and Temperature Indicator (Vaisala - HMI 32)". This probe was selected because it had a response time of only 5 seconds (for 90% response) and could be used in measuring over the range of 0 to 100% RH. Since the rest period drying experiments were planned to be carried out at an air temperature of 60°C, the calibration of the probe was tested at this temperature, found to be unsatisfactory and hence a recalibration done.

Numerous methods for testing relative humidity in small, closed spaces have been presented in the literature and either an acid or saturated salt solution has been found to be satisfactory for chemically controlling the relative humidity in a closed container (Wexler and Hasegawa, 1954; Hall, 1970; Winston and Bates, 1960). A salt solution is more stable, less corrosive and often less expensive. A given saturated salt solution will often maintain practically the same relative humidity at different temperatures. Winston and Bates (1960) have given comprehensive information on relative humidity values over saturated salt solutions at various temperatures. It was decided to adjust the relative humidity values indicated by the probe at two values of rh, one at about 30 percent and another at around 75 percent. The saturated salt solutions of $MgCl_2 \cdot 6H_2O$ and NaCl maintain a relative humidity of 31.5 and 74.5 percent respectively at temperatures around 50°C and were hence used for calibration of the probe. The relative humidity values over saturated solutions at various temperatures for the two salts used for calibration of the probe are given in Table 4.1.

The whole resting apparatus was covered with a thick polythene sheet joined with the drying chamber so that when the grain is transferred from drying tray to resting container, it does not have to pass through the cold room air. This helped in reducing the cooling down of the grain sample during the transfer process. The enclosed space got filled up with hot air coming out of the drying chamber due to the opening of the lid to take out the partially dried sample for resting thereby reducing temperature gradient.

4.3 Experimental Procedure

The thin layer drying experiments were conducted under controlled conditions of air temperature and relative humidity. The drying air temperature used was 60°C and maintained within ±1°C, the air velocity kept between 0.35 and 0.375 m/sec and water temperature controller was set at 12°C and maintained within ±0.1°C. The flow rate of cold water from the ice bank cooler was accordingly adjusted and a constant level of water maintained in the water tank. The water circulation through the cooling tower was kept at maximum flow rate to get as close to saturation of air as possible. The water temperature was set at 12°C to simulate typical environmental conditions of 15°C ambient temperature and 80 percent relative humidity for U.K. and about 30°C ambient temperature and 30 percent relative humidity for India, during the drying season for wheat and barley. Both the sets of environmental conditions give dew point temperatures of around 12°C. These conditions are shown on a psychrometric chart in Figure 4.9.

Wheat and barley used in this study were obtained from a local grain drying plant, dried to a moisture content of around 14 percent and stored in thick polythene bags to be used for experimental work later on. For thin layer drying experiments, the samples were artificially remoistened to about 25 percent initial moisture content. Hustrulid (1962, 1963) studied the comparative drying rates of naturally moist, remoistened and frozen wheat and shelled corn and concluded that carefully remoistened grain could be used for drying experiments without any significant error. After adding a predetermined amount of moisture to the weighed grains to obtain the target moisture content, the mixture was rotated slowly for 32 hours for wheat and 48 hours in the case of barley in a tightly sealed porcelain container. Sokhansanj et al (1983) in their investigation of grain tempering on drying tests observed these mixing times to be adequate for uniform moisture distribution within the grain kernel at room temperature.

Before starting any thin layer drying experiment the instrumentation system was checked carefully and the whole apparatus was operated with a dummy grain tray for at least two hours to stabilize the air temperature, relative humidity and airflow rate. When the whole system was stabilized, one selected sample of 100g of grain was placed evenly on the drying tray. The dummy tray was quickly replaced by the sample tray and the data transfer and storage system started immediately. The wheat grain samples were dried to about 10 percent moisture content (the typical storage moisture content in tropical countries) and barley to about 13 percent. In the first set of experiments on both wheat and barley, the starting point of resting was kept fixed and only the duration of rest period was varied. In the other set, the duration of rest period was kept the same for all experiments but the starting point of rest period was varied. For the purpose of comparing rest period drying with continuous drying, a continuous drying experiment was always performed on any freshly prepared sample of wheat or barley. The equilibrium moisture content of wheat and barley was determined by continuous drying of the samples for 24 hours in the drying air stream. Three replications of each equilibrium moisture content experiment were performed. It was noticed that after 24 hours of continuous drying at 60°C, the weight change of the sample with time had become insignificant and hence drying discontinued at this stage. In the rest period drying experiments, the grain sample was dried for some predetermined initial drying time and then immediately transferred hot into preheated resting container kept in oven at 60°C, with the help of a funnel fitted on top of the container. The relative humidity probe was inserted into the sample and the top lid closed tightly so that no drying can take place while the sample is being rested. The change in relative humidity in the void space of the grain sample during the rest period was recorded. After the completion of the rest period, the sample was transferred back to the drying tray and redrying continued till the desired end moisture content. The drying rig was kept running during the rest period so that drying air conditions did not change.

In all 42 experiments on thin layer drying were performed, 18 on wheat and 24 on barley.

4.4 Data Processing

The dry bulb and dew point temperatures of the air were used to calculate relative humidity of the drying air and the weight - time data of the drying sample was processed into moisture content vs. time for equilibrium moisture content runs and into moisture ratio vs. time for comparing continuous and rest period drying. All moisture contents in analysis were expressed on dry basis.

Calculation of Relative Humidity

The relative humidity was calculated using the mathematical model proposed by Lerew (Brooker *et al*. 1974). This model is valid for 0 - 260°C. The following relationships were used

$$P_{WS} = 6894.76\ F \exp\left[\frac{P_o + P_1 T_{db} + P_2 T_{db}^2 + P_3 T_{db}^3 + P_4 T_{db}^4}{P_5 T_{db} - P_6 T_{db}^2}\right] \qquad 4.9$$

$$P_W = 6894.76\ F \exp\left[\frac{P_o + P_1 T_{dp} + P_2 T_{dp}^2 + P_3 T_{dp}^3 + P_4 T_{dp}^4}{P_5 T_{dp} - P_6 T_{dp}^2}\right] \qquad 4.10$$

$$RH = \frac{P_W}{P_{WS}} \times 100 \qquad 4.11$$

Where

P_{WS} = saturation vapour pressure of the drying air, N/m^2

P_W = saturation vapour pressure at dew point, N/m^2

T_{db} = dry bulb temperature in °R

T_{dp} = dew point temperature in °R

$P_o = -0.274055 \times 10^5$

$P_1 = 0.541894 \times 10^2$

$P_2 = -0.451370 \times 10^{-1}$

$P_3 = 0.215321 \times 10^{-4}$

$P_4 = -0.462027 \times 10^{-8}$

$P_5 = 0.241613 \times 10$

$P_6 = 0.121547 \times 10^{-2}$

$F = 0.320618 \times 10^4$

Calculation of Moisture Content

In the calculation of moisture content, static weights in the absence of any air effect have to be considered but the weights given by the balance during thin layer drying experiments include the aerodynamic effect of air on the grain being dried in the tray. It was observed that the apparent weight shown by the balance is slightly different from the static weight taken on an ordinary balance and hence both apparent and actual static weight were accounted for in the calculation of moisture content. The following relationship was used.

$$M_t = M_f + \frac{W_t - W_f}{DM} \qquad 4.12$$

where M_t = moisture content (decimal d.b) at any time t

M_f = final moisture content (decimal db) at the end of the run

W_t = apparent weight recorded from balance at any time t

W_f = final apparent weight of the sample recorded by the balance at the end of the run

DM = dry matter content calculated from final static weight and final moisture content of the dried sample.

An 'Applesoft Basic' program was written to process the date stored on the floppy discs. The inputs to this program are: final moisture content of the sample, apparent weight of the sample at the end of the run, static weight of the sample at the end of the run, starting time and initial drying time if redrying after resting. This program could open the data files on the disc to read the information and then process it and print the results in the form of moisture content vs time tables or moisture ratio vs time tables if initial moisture content and equilibrium moisture content of the dried samples are also provided. The moisture ratio can be calculated as

$$MR_t = \frac{M_t - M_{es}}{M_o - M_{es}} \qquad 4.13$$

taking all moisture contents on dry basis. The program is given in Appendix 4.4.

4.5 Results and Discussion

It was observed while performing the experiments that dry bulb and dew point temperature of the drying air on entry to the drying chamber varied from 59 to 61°C and 11.6 to 12°C respectively. The relative humidity calculations in these temperature ranges using equations 4.9 to 4.11 are shown in Table 4.2. It can be seen that average drying air condition may be considered as 60°C dry bulb temperature and 7 percent relative humidity. It can also be noticed from this table that the variation in dry bulb and dew point temperatures in the ranges observed during experimentation do not have much effect on relative humidity of the drying air. Moreover, McEwen and O'Callaghan (1955) have observed that for air humidities not exceeding 70%, the drying rate constant is unaffected by humidity.

4.5.1 Equilibrium Moisture Content of Wheat and Barley

The continuous drying curves for three replications of the experiment to determine equilibrium moisture content of wheat, are shown in Figure 4.10 and the computer printout and details of drying data are given in Appendix 4.5. The average value of equilibrium moisture content of wheat at 60°C was found to be 5.9 percent (wet basis). A comparison of this value of e.m.c. with values obtained by using different e.m.c. equations available in the literature is presented in Table 4.3. It can be seen from comparison that the closest values to this experiment are the values obtained using Nellist's equation. The experimental values are still a little less than the values from Nellist's equation. Smith (1979) made a similar observation and mentioned that Nellist's equation for e.m.c. of wheat gives a dynamic equilibrium moisture content which is somewhat higher than the equilibrium value reached after long exposure to the drying conditions but Nellist's values of equilibrium moisture content are appropriate to the early part of the drying curve. However, for the purpose of detailed analysis of continuous and rest period drying curves in the later sections, the experimentally obtained values of equilibrium moisture content of wheat have been used.

The continuous drying curves for three replications of the experiment to determine the equilibrium moisture content of barley, are shown in Figure 4.11 and the computer printout and details of drying data are given in Appendix 4.6. The average value of equilibrium moisture content for barley at 60°C was found to be 5.4 percent (wet basis). A comparison of this value of e.m.c. with values obtained by using different e.m.c. equations available in the literature is presented in Table 4.4. It can be seen from this table that experimental values are quite close to the values obtained using Bruce's equation. For the purpose of detailed analysis of continuous and rest period drying curves in the later sections, the experimentally obtained values of equilibrium moisture content of barley have been used.

4.5.2 Rest Period Drying of Wheat

The experimental data on thin layer drying for redrying stage was also processed starting from end moisture content and end weights and then calculating the initial and subsequent moisture contents with time of the drying sample. The weight of the sample was assumed to be constant during the rest period. The drying curves are presented as moisture ratio vs time so that the results become independent of initial, final and equilibrium moisture contents of a particular sample. The drying curves are analysed for various drying requirements presented in terms of final moisture ratio, MR_f. The values of MR_f for typical drying requirements of wheat generally encountered in practice are shown in Table 4.5. The comparison of rest period drying with continuous drying is presented as the ratio of drying time with resting to drying time required for continuous drying i.e. $t_d/t_{cont.}$ for the same particular drying requirement.

4.5.2.1 Duration of Rest Period

The thin layer drying curves showing the effect of duration of rest period, when resting is done at a fixed point, are shown in Figure 4.12. These curves were analysed for different drying requirements and the results are presented in Figure 4.13 and Figure 4.14. The rise in relative humidity in the void space of the grain mass during an experiment involving five hour rest period is shown in Figure 4.15 and the relevant data is given in Table 4.6. Since it is difficult to read the exact drying time for different drying requirements from Figure 4.12, computer printouts of the drying data are given in Appendix 4.7. The reduction in drying time as affected by duration of rest period, calculated from the printed data is presented in Table 4.7. A perusal of Table 4.7 and Figure 4.14 shows that for most of the drying requirements considered, there is not much reduction in drying time by resting the grains for more than two hours. The further reduction in drying time by increasing the rest period duration from two to five hours varies from 0.3 to 2.2 percent and in some cases there is no benefit at all. It can also be seen from Figure 4.13 that the maximum reduction in drying time is 18.3 percent and this much reduction is obtained when drying requirement is $MR_f = .4204$. The reason for this is that resting in all these experiments was done at $MR_{rest} = .5558$ which is the optimum resting point only for $MR_f = .4204$. (The optimum resting point for various drying requirements of wheat is discussed at length in the next section.) It can also be observed that when resting is done at $MR_{rest} = .5558$, the benefit of resting is diminishing as the drying requirement gets increased i.e. as MR_f gets reduced and the effect of duration of rest period becomes unclear due to only marginal reductions in drying time. If MR_f is greater than MR_{rest}, the ratio of two drying times is one because it just becomes continuous drying as far as that particular value of MR_f or drying requirement is concerned. The rise in relative humidity during rest period is shown in Figure 4.15 and the tempering or resting index based on relative humidity observations is also plotted in the same figure. It can be clearly seen that there is very little change in relative humidity and hence tempering index beyond the resting time of two hours. Table 4.6 shows that this index after two hours is 99.1% of the tempering index after five hours which in other words means that tempering is 99.1% complete in two hours if accepted as fully complete in five hours. Keeping in view this index and the relative reduction in drying time between two and five hours of rest period even at optimum rest point, resting duration of two hours appears to be enough for two stage drying of wheat.

4.5.2.2 Optimum Point of Resting

The drying curves for thin layer drying of wheat with a rest period of two hours at different resting points are shown in Figure 4.16. The redrying curves are not so distinct as to enable reading of drying time for various drying requirements and hence the computer printouts of the drying data are given in Appendix 4.8. This data was analysed to study the effect of point of resting on reduction in drying time for various drying requirements of wheat and the results are presented in Table 4.8. The minimum value of $\frac{t_d}{t_{cont.}}$ which can be observed in this table, appears to be .809 which means that maximum reduction in drying time is of the order 19.1 percent for $MR_f = .6074$. This data is shown graphically in Figure 4.17. It can be clearly seen from this figure, that for each drying requirement, there is a point at which the reduction in drying time is maximum and this point can be defined as $\hat{MR}_{rest}$, the optimum point to commence resting. It is further observed from this figure, that maximum reduction in drying time is different for various drying requirements and as MR_f decreases, i.e. the drying requirement increases, the reduction in drying time becomes comparatively less. This indirectly means that for drying over a wider range of moisture content, the relative benefit of providing a rest period gets diminished.

The optimum resting point as observed from Figure 4.17 for various drying requirements is shown in Figure 4.18. It can be noted clearly that as MR_f increases, $\hat{MR}_{rest}$ also increases. In other words this means that the less the drying requirement, the earlier the optimum point for providing a rest period. The final drying point and the optimum resting point are related by the equation

$$\hat{MR}_{rest} = 0.126187 + 1.04853\ MR_f \qquad 4.14$$

$$(r^2 = .9828)$$

and the two are highly correlated. The maximum percent reduction in drying time for various values of MR_f is given by the equation

$$MPR = 6.102 + 23.31\ MR_f \qquad 4.15$$

$$(r^2 = .8965)$$

and the data is plotted in Figure 4.19. It can be seen from the two values of the coefficient of correlation that $\hat{MR}_{rest}$ has much higher degree of correlation with MR_f as compared to MPR.

4.5.3 Rest Period Drying of Barley

The experimental data on thin layer drying of barley was processed and is presented in the same way as that of wheat discussed earlier. The values of MR_f for typical drying requirements of barley generally encountered in practice are shown in Table 4.9.

4.5.3.1 Duration of Rest Period

The thin layer drying curves showing the effect of the duration of the rest period when rested at a fixed MR_{rest} are shown in Figure 4.20. The rise in relative humidity in the void space of the grain mass during the two hours rest period is shown in Figure 4.21 and the relevant data for purpose of clarity is given in Table 4.11, along with the tempering index at various resting times. The reduction in drying time as affected by duration of rest period, calculated from the thin layer drying and redrying curves is presented in Table 4.10. A perusal of Table 4.10 along with Figure 4.22 and Figure 4.23 indicates that most of the reduction in drying time for all drying requirements is obtained in the first hour of resting. The additional reduction in drying time by prolonging the rest period duration to two hours instead of one hour is of the order of 1.2 to 3.9 percent only. The reduction in drying time obtained by increasing rest period from 30 minutes to one hour is up to 5.7 percent. In fact, a rest period of 30 to 60 minutes appears to be enough for most of the drying requirements of barley involved in this analysis. It can also be observed from Figure 4.22 and Figure 4.23 that maximum reduction in drying time is obtained for $MR_f = .5481$ when resting is done at $MR_{rest} = 0.70$ because this resting point is in fact the optimum point of resting for $MR_f = .5481$. (This is discussed in detail in the next section.) Another observation which could be made from these two figures is that the relative effect of duration of rest period is different for different values of MR_f e.g. when $MR_f = .6190$, there is no effect of increasing rest period from 30 minutes to 60 minutes and similarly when $MR_f = .3828$, there is comparatively much less effect of increasing rest period duration from one hour to two hours. This is possibly because resting is basically a mass diffusion process and the value of diffusivity varies with moisture and hence with MR_f. The tempering index is 99.6 percent after one hour if full tempering is assumed after 90 minutes or two hours and hence there was little justification in performing further experiments with a rest period of more than an hour.

4.5.3.2 Optimum Point of Resting

The drying and redrying curves for thin layer drying of barley with a rest period of one hour at different resting points are shown in Figure 4.24 to Figure 4.27. The analysis of these curves to study the effect of the point of resting on reduction in drying time for various drying requirements of barley is presented in Table 4.12. The minimum value of $\frac{t_d}{t_{cont.}}$ which could be observed in this table, appears to be .607 which means that maximum reduction in drying time is of the order of about 39% for $MR_f = .6190$. This data is plotted as a function of MR_{rest} in Figure 4.28. It can be clearly seen from this figure that, as in the case of wheat, for each drying requirement, the reduction in drying time depends on MR_{rest}. The optimum resting point for various MR_f is shown in Figure 4.29 and the two can be related by an equation

$$\hat{MR}_{rest} = .1921 + .99347\ MR_f \qquad 4.16$$

$$(r^2 = .9724)$$

The maximum percent reduction in drying time for various drying requirements of barley is shown in Figure 4.30 and can be expressed by the following relationship

$$MPR = 13.2736 + 41.55\ MR_f \qquad 4.17$$

$$(r^2 = .9925)$$

It can be seen that optimum point of resting and the maximum reduction in drying time (if resting is done at the optimum point) are both highly correlated to the extent to which the grains are to be dried.

A comparison of Figures 4.14 and 4.23 shows that the trends of the effect of duration of rest period on reduction in drying time for various drying requirements of wheat and barley appear to be inconsistent. It may be mentioned here that in Figure 4.14 resting was done at MR_{rest} = 0.5558 whereas in Figure 4.23, the resting point is at MR_{rest} = 0.70. In the case of wheat, MR_{rest} = 0.5558 is actually $\hat{MR}_{rest}$ for MR_f = .4204 and hence it is for this MR_f that the reduction in drying time is the maximum. It can be seen from Figure 4.14 that as the deviation of a particular MR_f from MR_f = 0.4204 increases, the reduction in drying time, in general, decreases because the resting point is moving further and further away from the optimum. There is no reduction in drying time when MR_f = 0.6074 because as far as this MR_f is concerned, resting at MR_{rest} = 0.5558 is of no use and the grain has dried to its final moisture content before the commencement of rest period, since if $MR_{rest} < MR_f$ then drying becomes just continuous drying. It can be further seen from this figure that if MR_f is too close to MR_{rest} (e.g. MR_f = .5343 in this case), the effect of duration of rest period on reduction in drying time becomes insignificant.

Similarly in Figure 4.23, MR_{rest} = 0.70 is actually optimum point of resting only for MR_f = 0.5481 and hence reduction in drying time is maximum for this drying requirement. As the deviation of MR_f from MR_f = 0.5481 increases, the reduction in drying time or the benefit of resting, in general, decreases because the resting point moves further and further away from the optimum point of resting for that particular value of MR_f. Although the trends of these two figures appear to be dissimilar from appearance, yet there is complete descriptive agreement between the two as far as rest period drying of wheat and barley is concerned.

4.6 Error Analysis and Accuracy

Apart from the limited accuracy of different measuring instruments used in recording the data, there are two sources of error which were identified as important while recording and analysing the experimental data on drying of wheat and barley:

(1) error in determination of moisture content

(2) aerodynamic error in weight loss during drying.

The balance used in taking weights of the sample for determination of moisture content had an accuracy of 0.1 g and it was found that it could introduce an error of up to 0.2% (db) in moisture content. The grain drying data was, however, all to be experessed as moisture ratio which is the ratio of the difference of two moisture contents. It was calculated that a random error of 0.2% (db) in moisture content could cause a maximum error of 1.5% in the value of moisture ratio calculated from different moisture contents.

The aerodynamic error in weight loss during drying is a systematic error which is introduced due to the decreasing resistance of the drying sample to airflow. The result of this decreasing resistance is that the actual weight loss could be up to 1 to 2 g more, in a 100 g sample taken for drying, than the weight loss recorded by the continuous weighing system. Nellist and O'Callaghan (1971) from a consideration of the aerodynamic error readings, chose the following general form of the error correction function

$$ER = a\,e^{-bt} + c\,e^{-dt} \qquad 4.18$$

where t is the drying cycle time and a, b, c and d are constants chosen such that ER = 1 at t = o and approaches zero at drying cycle times indicated by experiment. The authors further pointed out that by appropriate choice of constants, the function can be reduced to a single exponential and can even be made to be very nearly linear for the whole run. Bruce and Sykes (1983) while conducting grain drying experiments concluded that the discrepancy in weight loss due to aerodynamic error varies linearly during most of the drying time in the ranges of moisture contents generally encountered during grain drying.

The aerodynamic weight loss observed during various experiments on continuous drying of wheat and barley in the present work is shown in Table 4.13. It can be seen that the maximum value of aerodynamic weight loss during the whole of the drying run is about 1.1 g for run no. 6. This additional loss in weight, assuming the loss to be linear over the complete drying run is calculated to be 0.00061 g per minute of drying time. It was found that this unaccounted weight loss could cause a maximum error of 1.42% (db) in moisture content at time t = o with the error continuously decreasing as drying progresses. It was calculated that this error in moisture content could cause a maximum error of about 4.9% in moisture ratio in the range of moisture contents included in the present work.

The maximum combined error in moisture ratio due to limited accuracy of balance for moisture content determination and aerodynamic weight loss could thus be up to 6.4%. However, this estimate of error is a very conservative one because this much error could be there only in the beginning of the drying curve as the data on drying has been processed starting from the end of the run. This error is in fact continuously decreasing as drying progresses and will be much less in the central zone of the drying curve i.e. in the range of moisture ratios included in the analysis of results. The range of this error is hence 6.4% to 1.5% and the average value could be taken as around

4%. It can be seen from Figures 4.17 and 4.28, that a 4% drift in the optimum point of resting does not have much effect on reduction in drying time as the curves are quite flat around the optimum resting point. It can also be calculated from equations 4.15 and 4.17 that a variation of up to 4% in MR_f could introduce a maximum error in percent reduction in drying time of the order of 0.9 and 1.6% in the case of wheat and barley respectively which is just 4 to 4.5% of the total reduction in the range of 20 to 40%.

It could hence be concluded that limited accuracy of weights in moisture content determination and exclusion of aerodynamic weight loss in data processing does not have any considerable effect on the reduction in drying time in a two-stage drying process in comparison to continuous drying.

Chapter 5

COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

The theoretical and experimental results on continuous and rest period drying of wheat and barley are compared and probable reasons for the difference along with the introduction of a mathematical factor to explain this difference are discussed in this chapter. The reasons for varying response of wheat and barley to rest period drying are examined in the context of their biological structure.

The three crop parameters which are input to the theoretical model developed in Section 3.1.5 are: equivalent diameter of the grain kernel, equilibrium moisture content at the drying air conditions and mass diffusivity of the grain. The e.m.c. of wheat and barley as determined experimentally is reported in Section 4.5.1 and the mass diffusivity of crops is difficult to be found directly and accurately. The equivalent diameter of the kernel can however be evaluated.

5.1 Equivalent Particle Diameter

The grain kernel has been assumed to be spherical in shape in the theoretical analysis but actually it is an irregular solid. Several methods have been proposed to find out the equivalent linear dimension of the grain for use as the diameter of a sphere. For problems concerning heat and mass transfer, Gamson, Thodos and Hougen (1943) defined the equivalent diameter as the diameter of a sphere the surface area of which is equal to that of the particle.

$$d_e = \left(\frac{a_p}{\pi}\right)^{\frac{1}{2}} \qquad 5.1$$

They used the following expression for correlating heat transfer data for spheres and cylinders

$$d_e = \sqrt{d_c l_c + \frac{d_c^2}{2}} \qquad 5.2$$

where d_c and l_c are diameter and length of the cylinder. Morcom (1946) used the equivalent diameter as the diameter of a sphere, the volume of which is equal to that of the particle

$$d_e = \left(\frac{6\ V_p}{\pi} \right)^{1/3} \qquad 5.3$$

Brownell and Katz (1947) defined the equivalent linear dimension as the arithmetic or geometric mean of the two smaller dimensions, which is the result obtained in sieving tests if it is assumed that the longest dimension is brought into the vertical plane by the sieve motion. Heywood (1947) and Rose and Rizk (1949) defined the equivalent diameter as the diameter of a sphere the surface area/volume ratio of which is equal to that of the particle

$$d_e = \frac{6\ V_p}{a_p} \qquad 5.4$$

McEwen _et al_. used this method to find out the equivalent diameter for wheat grains since both the surface area and the volume of the particle are taken into consideration.

The problem with irregularly shaped grains is approximating the shape for the calculation of the surface area and volume from measurement of the principal dimensions. Brownell and Katz (1947) defined a sphericity factor as the ratio (surface area of a sphere having the same volume as the particle) to (surface area of the particle). McEwen _et al_. (1954)

analysed various dimensions of wheat, barley and oats and concluded that the surface area and volume of wheat can be quite accurately calculated from the formulae for ellipsoids. The various lengths and diameters of more irregularly shaped particles can be obtained from frequency distributions of dimensions obtained by methods like sieving (Cadle, 1955). Becker (1959) working with wheat introduced the concept of a sphericity factor and Chu and Hustrulid (1968) introduced a shape factor for maize. Pabis and Henderson (1962) and Nellist (1974) used the geometric average of the three principal dimensions of the grain as being the diameters of an equivalent sphere.

Pabis (1969) defined the equivalent diameter of the spherical kernel as:

$$d_e = \sqrt[3]{\frac{6 \cdot W_{1000}}{1000\ \rho\ \pi}} \qquad 5.5$$

where ρ = density of the grains and W_{1000} = 1000 seed weight. Since this method involves density and 1000 grain weight, the two important physical properties of grain, this was used to determine equivalent diameter in the present analysis.

The grains at a known moisture content were taken in a conical flask of known volume. The flask was completely filled with grains without any tapping and weight of the grains in the flask was found. Again the flask was filled with grains but with tapping from time to time and the maximum weight of grains that could be filled in the flask was determined. From these two values, the average weight of grains to fill the flask was calculated. The value of porosity was taken as 31 and 36% for wheat and barley respectively which is the average of the range in porosity observed by McEwen <u>et al</u>. (1954) for these two materials. From the volume of the flask, the average weight of grains to fill the flask and the values of porosity, the true density of the grains was calculated. The 1000 seed weight was determined thrice by weighing the counted seeds to within 0.01 g and the average of the three readings was taken. The equivalent diameter of the sphere was then calculated by using equation 5.5. The value of particle diameter for wheat and barley at 25% (wb) was found to be 4.836×10^{-3} metres and 4.679×10^{-3} metres respectively.

5.2 Continuous drying of wheat and barley

The theoretical and experimental results on continuous drying of wheat and barley in a thin layer are shown in Figures 5.1 and 5.2 respectively. It is observed from these two figures that the diffusion model does not adequately describe the thin-layer drying of either wheat or barley particularl in the initial stages of drying.

The theoretical model developed to predict drying is based on diffusion and the value of diffusivity has been assumed to be constant during drying for the sake of simplicity in the numerical analysis. Hougen et al. (1940) in their discussion of the limitations of diffusion equations in drying have, however, pointed out that in the drying of a solid body liquid may flow by a number of methods besides diffusion, such as, by capillarity, by gravity, by external pressure, or by convection and a sequence of vaporization - condensation phenomena where temperature gradients are present. These additional methods certainly do not follow the laws of diffusion. The indiscriminate use of diffusion equation has resulted largely because of the wrong impression conveyed by standard texts and the periodical literature of chemical engineering in falsely referring to the movement of water in a solid during drying as a diffusional process without due regard to the actual mechanism of liquid movement and its complex nature. The authors have further pointed out that the differential diffusion equations could be applied to calculate moisture distribution and rates of drying only under certain conditions but integrations must allow for the variable nature of mass diffusivity. The mass diffusivity, in fact, decreases with decreasing moisture content, with decreasing temperature, with increasing pressure, and with increasing density. The above authors also observed discrepancy in moisture distribution during drying when theoretical predictions were compared with experimental observations. Sherwood (1940) in his discussion on the work of the above investigators has pointed out that it is a fact that the relation between time and average moisture concentration fits the diffusion equations very well indeed for the drying of some materials, but it is a rather crude procedure to look at the diffusion equation from the point of view of the moisture distribution in the solid. The author has further mentioned that the diffusion equations have never been advocated for fibrous or granular materials.

Chinnan (1984) in his investigation on the evaluation of selected mathematical models for describing thin layer drying of in-shell pecans has also concluded that the diffusion model does not describe the thin layer drying data well. Byler et al. (1987) while studying thin layer drying of parboiled rice found that the fit of the spherical model to several data sets was poor and concluded that spherical diffusion model was not adequate for parboiled long grain rice. Even the infinite cylinder model was found not to work well.

In addition to this, there is also a considerable variation in the value of the diffusion coefficient for various crops reported in the literature. The value of the diffusion coefficient to be used in the theoretical analysis becomes further complicated by the fact that it is different for various components of the grain like endosperm, bran, hull, pericarp, etc. (Steffe and Singh, 1980; and Syarief et al. 1987) and such data for wheat and barley is not presently available.

5.3 Rest period drying of wheat and barley

A comparison of the theoretical and the experimental results on rest period drying of wheat and barley is presented in Figures 5.3 and 5.4. It can be seen from Figure 5.3 that there is good agreement between the results as far as the optimum point of resting is concerned. However, it is observed from Figure 5.4 that the theoretical model overpredicts the reduction in drying time due to resting. The difference in the predicted benefit of resting is not much in the case of barley, but appears to be quite substantial in the case of wheat.

The discrepancy observed in the present work between the theoretical and experimental results in regard to the benefit of rest period for reduction in drying time may be well attributed to the inadequacy of the constant diffusivity diffusion model to describe thin layer drying as well as the moisture distribution at various shells of the kernel during drying for all crops. This moisture distribution will subsequently affect redistribution during resting.

The difference in the response of wheat and barley to two stage drying could possibly be interpreted in terms of their varying biological structure. There is however no clearly conclusive evidence found in the literature to explain the role of biological structure in drying. McEwen et al. (1954) produced evidence to prove that the chief resistance to the drying of wheat lies in the aleurone layer beneath the surface of grain. MacMasters (1962) while differentiating wheat and corn, observed that in wheat there are four layers of seed coat whereas in corn the number of layers may vary from one to four and the seed coat acts as a semi-permeable membrane, controlling the kind of molecules which can pass through it and the rate at which they can enter the kernel. It was also noticed that the aleurone layer, seed coat and pericarp are thinner over the face of the germ than over other parts of the kernel, so moisture change may take place more easily here than elsewhere. The germ of the kernel takes up water more quickly than does the endosperm. The endosperm is the hardest part of the kernel from which to remove moisture. Not only does it lie surrounded by other tissues, but it contains only small, unconnected, intercellular spaces. Hence moisture must traverse many cell walls before it can reach the outer layer. Kumar (1973) studied moisture movement in a kernel of corn and concluded that this movement occurs primarily through the base end of the cap only although researchers are employing radial diffusion models to approximate single kernel drying. Wellington (1965) observed that huskless grains like wheat and rye are less water-sensitive than barley and oats. Brooker et al. (1974) noticed that the pericarp layer of the grain is a major barrier to the exchange of moisture with the endosperm. Palmer (1970) observed that the aleurone layer of wheat usually consists of a single cell layer whereas that of barley is invariably 2-3 cells deep.

Suffice is to say that wheat and barley differ in terms of the biological structure of the kernel and there is resistance to exchange of moisture within various parts of the grain, as well as on the outer skin of the kernel. This internal and external resistance will affect moisture redistribution in the kernel during the rest period as well as the drying/redrying (after resting), characteristics of the grain. Since wheat and barley differ in structure, so the effect of resistance offered by the two grains to moisture imbalance is bound to be different. From a mathematical point of view, this behavioural difference of wheat and barley to drying and resting could be expressed by a lumped parameter named as "Skin Resistance Factor".

5.4 Introduction of Skin-Resistance

5.4.1 Skin-Resistance Factor and Revised Model

The overall effect of various parameters affecting drying with regard to the biological structure of the grain could be considered in the form of a film surrounding the grain surface. The effect of this fictitious film presumably is that the grain actually does not get fully exposed to drying air immediately on the the onset of drying and the surface moisture content of the kernel is not equal to the equilibrium moisture content of drying air at the start of drying. This film resistance will slow down drying and hence the moisture gradient within the kernel gets reduced. If there is less moisture gradient within various shells of the kernel, the comparative effect of moisture redistribution during resting is reduced.

The existence of film resistance on the surface of grain is represented schematically in Figure 5.5. Applying Fick's law of diffusion between the last shell of the kernel and the film on the surface, gives:

$$\left(\frac{C_{m-1} - C_m}{\Delta x}\right) D = \left(\frac{C_m - C_e}{\Delta l}\right) D' \qquad 5.6$$

$$\text{or} \quad C_m = \frac{(C_{m-1} + \emptyset\, C_e)}{(1 + \emptyset)} \qquad 5.7$$

$$\text{where} \quad \emptyset = \frac{D'}{D}\,\frac{\Delta x}{\Delta l} \qquad 5.8$$

and C_m, C_{m-1} and C_e are respectively the concentrations at the surface of the kernel, the last but one shell of grain and the equilibrium moisture content of the drying air; D and D' are the mass diffusivities of the grain and the film respectively, and Δx and Δl are the thickness of the last shell and the film on the surface of the kernel. The term ϕ is denoted as skin-permeability factor and

$$S_r = \frac{1}{\phi} \qquad 5.9$$

where S_r is called the skin-resistance factor of the grain during drying. The revised section of the computer program incorporating the skin-permeability concept is given in Appendix 5.1.

5.4.2 Continuous drying with skin-resistance factor

The effect of mass diffusivity on drying time of a spherical kernel of grain is shown in Figure 5.6. It can be seen from this figure that drying time is inversely proportional to the value of diffusivity for all drying requirements. Similarly the effect of the skin-resistance factor on drying time is presented in Figure 5.7. The relationship between drying time and skin-resistance factor for a particular drying requirement does not seem to be linear. However, it can be seen that as the skin-resistance factor increases, the drying becomes slower and hence the time required to dry the grains to a particular level of moisture content increases. It could be concluded from these two figures that continuous drying of grain is affected by the value of mass diffusivity as well as skin-resistance factor. The moisture gradient developed during continuous drying affects the redistribution of moisture during resting and hence the benefit of rest period drying. The two parameters D and S_r hence affect both the continuous and the rest period drying. The values of these two parameters were determined from the theoretical model by trial and error.

The improvement in predicting the continuous drying of wheat and barley by introducing skin-resistance factor is shown in Figures 5.8 and 5.9 as compared with Figures 5.1 and 5.2. It can be seen that except for some initial drying of barley, there is now much better agreement between theoretical prediction and experimental observations on continuous drying. The disagreement in initial drying phase does not seem to be of much importance because most of the drying under practical situations takes place for moisture ratio of 0.60 to 0.35 for barley and 0.60 to 0.20 for wheat.

There is, thus, a distinct improvement in predicting the continuous drying of grains by incorporating a skin-resistance factor in the analysis.

5.4.3 Rest-period drying with skin-resistance factor

The effect of the skin-resistance factor on the theoretical results on rest period drying is shown in Figures 5.10 and 5.11. It can be seen from these figures that more is the value of S_r, less is the maximum reduction in drying time. It is also observed that with skin-resistance, the curves have become flatter. The theoretical results with skin-resistance are compared with the experimental results on wheat and barley in Figures 5.12 and 5.13. It can be seen from these two figures that the incorporation of a surface resistance into the diffusion model has improved the description of the experimental results. It can be observed from Figure 5.13 that there is now complete agreement between theoretical and experimental results for both wheat and barley as far as the maximum reduction in drying time at the highest considered value of MR_f is concerned. There is good agreement over the whole range of MR_f considered in the analysis in the case of barley but in the case of wheat, the theoretical results indicate less dependency of reduction in drying time on MR_f.

The theoretical results on wheat predict a reduction in drying time from 15 to 20% whereas the experimental results indicate this reduction to be in the range of 10 to 20% depending upon the drying requirement. The difference in the theoretical prediction and the experimental results on reduction in drying time in two-stage drying of wheat decreases as the value of MR_f increases.

5.5 Results and Discussion

Suffice is to say that surface or skin-resistance of the grain does affect the benefit of introducing a rest period in a two-stage drying process. The greater is this resistance, the lesser is the reduction in drying time due to resting phase in comparison to a continuous drying process. The values of various parameters for two-stage drying of wheat and barley, which have been established from this analysis are:

	Wheat	Barley
D (m^2/min)	7.36×10^{-9}	3.86×10^{-9}
R_p (m)	2.418×10^{-3}	2.34×10^{-3}
t_r (min)	120	60
ϕ	0.045	0.600
S_r	22.22	1.67
Dt_r/R_p^2	151.06×10^{-3}	42.3×10^{-3}

It can be seen from these values that although the mass diffusivity of wheat is greater than that of barley and the duration of rest period provided is two hours in the case of wheat as compared to one hour for barley, yet the benefit of rest-period drying is more for barley because it offers much less surface or skin-resistance to drying. If the surface resistance offered to drying is less, then there will be more moisture gradient developed inside the kernel during drying which in turn will let the grain redistribute its moisture more effectively during the rest period and hence two-stage drying with an intervening rest period will be comparatively more beneficial under such situations.

Chapter 6

DRYERATION EXPERIMENTS

Dryeration experiments were conducted to determine the moisture removal during the aeration part of this two-stage drying process, as affected by grain temperature and air flow rate. The effect of air flow rate on the time required to cool the hot grain was also investigated. The grain moisture content used in analysis has been expressed on dry basis.

6.1 Dryeration Apparatus

The same apparatus as used in thin layer drying experiments was also used in the dryeration experiments for conditioning the ambient air to the desired condition of temperature and relative humidity. However, a different drying chamber was designed for the removal of moisture from hot grains. The dryeration apparatus is shown in Fig. 6.1 and a schematic diagram of the equipment is presented in Fig. 6.2.

The drying chamber for dryeration work consisted of an aluminium cylinder 150 mm in diameter and 340 mm in height. A piece of wire mesh was fitted 40 mm from the base of the cylinder to let the air distribute properly through the grain mass. The bottom end of the cylinder was sealed off with an aluminium plate. The air entered from the side of the cylinder underneath the wire mesh. The whole aluminium cylinder including the base was insulated with a 75 mm thickness of flexible polystyrene foam type insulation applied in three layers each of 25 mm thickness with all ends thoroughly joined with suitable polypropylene adhesive, to keep the heat loss due to conduction to a bare minimum. By reducing the heat losses, most of the available heat of the grain could be used to evaporate the maximum possible amount of moisture from the hot sweating grain. The top of the insulated cylinder was covered with another aluminium plate with a 19 mm diameter hole in the centre for the exit of the moisture vapours coming out of the hot grains during aeration. To reduce the chances of condensation of water vapours,the top of the cover plate was kept a little heated with the help of a 100 watt reflector type bulb, the height of which could be adjusted. The cover plate was painted black on the top to absorb maximum heat from the bulb rather than reflecting it back. The temperature difference between this plate and the air underneath the plate and above the grain surface was maintained at around 1°C by adjusting the height of the bulb and by moving it sideways to different positions. This temperature difference was constantly monitored with the help of a copper-constanton thermocouple, one junction of which was fixed to the plate and the other kept in the air above the grain surface. This difference in temperature was kept as about 1°C because an overheated plate could radiate some heat on to the surface of the grain thereby introducing an error.

An airflow meter (Parkinson Cowan Meter-Thorn EMI Flow Measurement) was used to measure the airflow at the entry to the insulated aluminium cylinder whereas very small airflow rates were measured with the help of a rotameter (GCE-Marconi 1100 series). The airflow through the grains could be varied by diverting the air from the other side of the air distributor, installed just before the airflow meter, and fitted with a rotating side valve.

6.2 Experimental Procedure

The dryeration experiments on barley were conducted at grain temperatures of 40°, 60° and 80°C; and air flow rates ranging from 30 to 960 $m^3/hr/m^3$ of grain with an initial moisture content of barley of 16% (w.b.). The experiments on wheat were performed at grain temperatures of 40°, 60° and 80°C; and air flow rates in the range of 60 to 960 $m^3/hr/m^3$ with an initial moisture content of 16% (w.b.). The moisture content of 16% for both wheat and barley was chosen because the reduction in moisture content during dryeration was expected to be around 2% as reported in literature in Section 2.2 and grains are generally dried to a final moisture content of 14% under U.K. conditions. Some experiments on wheat at 60°C were conducted with an initial moisture content of 12% (w.b.) to investigate whether the same moisture reduction during dryeration could be obtained with comparatively drier grains before the start of aeration relating to Indian conditions.

The ambient air was conditioned to 80 percent relative humidity, which is a typical average relative humidity in the U.K. during the drying season, by controlling the water temperature with which the air was saturated in the moisturising column. The drying air conditions during dryeration experiments were 24±1°C and 80±2% relative humidity and were recorded with the help of the "Dew Point Meter". The dead weight of the dryeration apparatus was about 2900 g and since the balance had a total capacity of 5500 g, the sample size used was 2500 g of grains at the initial moisture content.

The initial moisture content of wheat and barley was about 14% (w.b.) and the grains were conditioned to 16% (w.b.) moisture by adding predetermined amount of water to a weighed amount of grains and then rotating the mixture for about 24 hours in a big airtight and well sealed aluminium drum rotating slowly at about 2-3 RPM with the help of a gearbox and an electric motor. A weighed amount of conditioned grains was well wrapped up in thick polythene bags and heated for at least twelve hours in an air-oven set at the required temperature. This duration of time was found to be satisfactory for uniform heating of 2500 g of grains to the set oven temperature. For performing the experiments with wheat at 12% moisture, the grains were dried from 14 to 12% (w.b.) moisture in ventilated hot air oven, then wrapped in thick polythene sheet bags, heated to the desired temperature and used for dryeration.

A fan was kept running during the performance of dryeration experiments to supply a small velocity of air in the vicinity of the insulated grain cylinder to carry away the exhausted moisture vapours from the hot grains.

The data was recorded with the same instrumentation and interfacing as described in the chapter on thin layer drying experiments. The dryeration runs were continued until the grain sample started rewetting. All moisture content determinations were made as per standard ASAE:S352.1. In all, 38 experiments on dryeration were performed, 18 on wheat and 20 on barley.

6.3 Results and Discussion

The experimental data on dryeration was processed in the same way as thin layer drying data described in Section 4.4. The drying-cooling curves for various runs are shown in Figs. 6.3 to 6.9. The initial moisture content, final minimum moisture content, maximum moisture reduction obtained and time for maximum drying effect at various grain temperatures and different airflow rates are presented in Tables 6.1 to 6.7. At very low airflow rates, it was observed that the removal of the last ten percent of total moisture reduction took a much longer time and the time for maximum reduction could not be obtained very specifically, in some cases, so the time needed for 90% of maximum moisture reduction was also obtained from the dryeration curves and is presented in Tables 6.1 to 6.7.

It can be seen from the dryeration results in general that air flow rate affects moisture reduction during cooling as well as the time required to cool the grain. As cooling starts and cooling air passes through hot grain, heat is transferred from grain to air in two forms, sensible and latent. The rate of sensible and latent heat transfer are governed by both internal and external resistances. External resistances are dependent on air velocity or airflow rate. The internal resistance to sensible heat transfer is very low and can be neglected, thus sensible heat transfer depends mainly on air velocity. Internal resistance to moisture transfer is dependent on mass diffusivity which is a function of grain temperature and moisture content. Thus, rate of moisture removal and accordingly, rate of cooling attributed to moisture removal depends on temperature and moisture content of grain and on air velocity.

The amount of heat that can be removed during cooling is limited depending on the specific heat of grain at a given moisture content and temperature and the temperature difference between grain and air. Thus as air flow rate increases, cooling attributed to sensible heat transfer increases and cooling attributed to moisture removal decreases. Hence increasing air flow speeds up the cooling process but at the same time forces the heated air out of the grain before it has had enough time to pick up a full moisture load thereby causing less moisture reduction in dryeration.

It could also be observed that in most of the dryeration experiments (except those at very low airflow rates), the grain starts picking up moisture from the air after some particular time. The reason for this is that the experiments were conducted with air at 80% relative humidity at which the equilibrium moisture content of wheat and barley is about 18% (w.b.). So when the grain had lost all its heat and its moisture content was less than the emc of the air, it started gaining weight and will continue to do so till it reaches the emc of air. The rate at which the moisture is picked up depends on the airflow rate. The moisture pick up point could not be noticed at very low airflow rates (30 $m^3/hr/m^3$ for example) because at this airflow, it may be several days or even months after cooling that an increase in moisture content is appreciable enough to be observed clearly.

6.3.1 Dryeration of Wheat

The effect of temperature difference between grain and air on moisture reduction during cooling of wheat is shown in Fig. 6.10. It can be seen that moisture reduction is directly proportional to this temperature difference. It has been calculated that when the initial moisture content of wheat is around 16% (w.b.), the maximum moisture reduction during dryeration is of the order of 0.652% (d.b.) per 10°C temperature difference between grain and air. The U.K. wheat is generally considered as soft wheat (Kent, 1975) and using the following equation for specific heat of soft wheat (Kazarian and Hall, 1965)

$$C_p = 1.398 + 0.04080\ M_w \qquad 6.1$$

the moisture reduction for 10°C temperature difference, assuming all available heat to have been utilised for removal of moisture, is found to be 0.87%. The theoretical value of moisture reduction is more than the experimental value and the comparison shows that only about 75% of the available heat has been utilised for evaporation of moisture. The remaining heat has been lost through the system as conduction heat loss in the cylinder or as sensible heat carried away by the air.

It can be further seen from Fig. 6.10, that at an initial moisture content of 12%, the moisture reduction during dryeration is much less compared with wheat at 16% moisture, although the difference in temperature of grain and air is the same in both cases. The reason for this difference in moisture reduction could be that at 12% moisture, the mass diffusivity of grain is much less compared with diffusivity at 16% moisture. The drier the grain, the slower is the rate of travel of moisture from inside of the grain to the outer surface of the grain and hence in the same duration of time, more heat of the grain is lost as sensible heat carried away by the air and hence less efficient moisture reduction. The moisture reduction per 10°C temperature difference at an initial moisture content of 12% is about 0.25% (d.b.) whereas theoretically it should be around 0.80% per 10°C, giving an efficiency of only 31.25%. It could hence be concluded that the drier the grain the less efficient is the technique of dryeration for moisture reduction from wet grains.

The effect of airflow rate on maximum moisture reduction during cooling of wheat is presented in Fig. 6.12. It can be seen that an airflow rate of 120 to 240 $m^3/hr/m^3$ of grain could be used for dryeration of wheat in most of the cases, although an airflow rate of even up to 480 $m^3/hr/m^3$ could well give about the same moisture reduction if grain moisture content is around 16%. The effect of airflow rate on time required for maximum and 90% moisture reduction from wheat is shown in Figs. 6.13 and 6.14. It can be observed that beyond an airflow rate of 240 $m^3/hr/m^3$, the airflow rate has very little effect on cooling time.

At this airflow rate, there is maximum moisture reduction in about 200 minutes whereas 90 percent of this reduction can be obtained in just 100 minutes. So for 90 percent moisture reduction, cooling time needed is just half the time for maximum reduction of moisture in most of the cases. The initial moisture content of grain also appears to have some effect on cooling time or time for moisture reduction, for example, at the same airflow rate (i.e. 240 $m^3/hr/m^3$), the time for maximum and 90 percent moisture reduction is reduced to 120 and 60 minutes respectively when the initial moisture content is 12% (Fig. 6.14) instead of 16%. The grain temperature appears to have varying effect on cooling time at different airflow rates. At higher airflow rates, the cooling time just becomes independent of grain temperature.

6.3.2 Dryeration of Barley

The effect of difference between temperature of grain and that of air on moisture removal during aeration of barley is shown in Fig. 6.11. It can be observed that maximum moisture reduction is directly proportional to this temperature difference and is about 0.786% (d.b.) per 10°C. The theoretical value of moisture reduction during aeration assuming all available heat to have been utilised for removal of water, comes out to be 1.00753% (d.b.) by using Boyce (1966)'s following equation for specific heat of barley

$$C_p = 1.445 + 0.04885\ M_d \qquad 6.2$$

This means that about 78 percent of available heat was actually utilised for evaporation of water in our experimental set up. A perusal of Fig. 6.12 indicates that for dryeration of barley an airflow rate in the range of 60 to 180 $m^3/hr/m^3$ may be used but 60 $m^3/hr/m^3$ of grains appears to provide maximum reduction in moisture content for barley at 40 and 80°C. The low airflow rate however increases the time required for cooling the grain. It can be seen from Fig. 6.15 that at an airflow rate of 180 $m^3/hr/m^3$, barley will attain 90% of maximum moisture reduction in 100 to 130 minutes, whereas for maximum removal of moisture, the time required is 280 to 400 minutes depending upon initial temperature of grain. So for the last 10% of moisture reduction, cooling time gets increased by 180% and the first 90% moisture reduction can be obtained in just 35% of the time required for maximum moisture reduction. As in the case of wheat, the grain temperature appears to have varying effect on time required for moisture removal at different airflow rates with the effect of temperature minimising with increased airflow.

Chapter 7

SUMMARY AND CONCLUSION

7.1 Summary

This research aimed at improving the technique of drying of wheat and barley in commercial grain drying plants. The overall objective was to compare the continuous drying of grain followed by immediate cooling with drying in two stages. Two techniques of two-stage drying were included namely rest period drying and dryeration. In rest period drying, the grain was dried for some time, then rested and finally dried again until the required moisture content was reached. The two important factors affecting rest period drying which were considered in this study were: the stage of resting, i.e. when to provide the rest period and the duration of rest period. In dryeration, the objective was to determine the effect of airflow rate and the temperature of the grain on moisture removal during in-bin cooling stage. The two-stage drying techniques were compared with the traditional continuous drying from the point of view of reduction in drying time to achieve a particular drying requirement, i.e. decrease in moisture content of the grain during drying. The work was carried out under three main headings namely: numerical solution and theoretical results; rest period drying of wheat and barley; and dryeration. The essential features of the results of each section are now drawn together and their general implications are discussed. Finally some suggestions are put forward for possible directions of further research into theoretical and experimental aspects of alternate drying techniques.

7.1.1 Numerical solution and theoretical results

The grain kernel was assumed to be spherical in shape for the purpose of theoretical analysis. The diffusion equation was solved numerically in order to predict the moisture distribution at various points within the grain during drying and resting stages. The sphere was divided into ten shells of varying shell thickness with the outermost shell being the thinnest of all. The thickness of various shells decreased in a fixed ratio starting from the centre of the grain and proceeding towards the surface. This procedure enabled to keep down the instant drop in moisture content of the kernel on the start of drying to less than 0.1%. The numerical solution utilised Crank-Nicolson approximation for derivatives for better accuracy. The Gauss-Seidel iterative procedure was employed to solve the numerically approximated concentration equations for various shells of the kernel since this technique provided a faster rate of convergence of the equations for updating the concentration with time as compared to Jacobi's method. The developed numerical solution was found to be in close agreement with high accuracy analytic solution employing as much as 100 or more terms of the infinite series solution of the diffusion equation. The numerical solution was used to study the effect of duration of rest period and the point at which rest period is provided on the reduction in drying time over continuous drying for various drying requirements of grains.

The drying requirement i.e. moisture reduction during drying was expressed as MR_f and the point of resting was indicated as MR_{rest} to incorporate the effect of variation in initial, final and equilibrium moisture content of the grain. An optimum moisture content for commencing resting indicated by $\widehat{MR}_{rest}$ was specified which was chosen to minimise the actual drying time not including resting for a particular drying requirement. The effect of the variation in mass diffusivity, the diameter of the spherical kernel and the duration of the rest period was included in the form of a dimensionless parameter Dt_r/R_p^2. All the results of the theoretical analysis were hence expressed in the form of dimensionless groups.

It was observed that for each drying requirement, there is an optimum point at which the benefit of rest period drying is maximum. If the rest period is provided at the optimum point of resting, there could be a reduction in drying time of as much as 46% depending upon the duration of rest period and the requirement of moisture reduction during drying. It was concluded that if the drying requirement is less, then there is comparatively more benefit of introducing a single rest period in a two-stage drying process. Before this research, it was thought that the benefit may be more in the case of drying very wet grains and vice versa. The rest period of about 1 to 2 hours duration was found to be adequate for most of the commonly encountered drying situations in practice whereas prior to this work, rest period duration of about 8 hours was expected to be essential for any appreciable reduction in drying time. It was also concluded that at higher values of MR_f, the value of the dimensionless parameter, Dt_r/R_p^2, has very limited effect on reduction in drying time. This means that if the required reduction in moisture content during drying is not much, then the duration of rest period, the size of the kernel and the mass diffusivity of the grain are not of much importance in rest period drying. The rest period drying appears to be an attractive alternative to continuous drying since the reduction in drying time by as much as 46% could increase the throughput of a continuous dryer by up to 85% if all other factors affecting the dryer output are considered to be the same in both the situations. The analysis showed the technique of two-stage drying to be particularly promising where large volumes of grains are to be dried over a shorter range of moisture contents in a limited period of time.

7.1.2 Rest period drying of wheat and barley

The drying and resting was performed on a thin layer of wheat and barley at a temperature of 60°C. An automatic continuous recording system was developed. It was based on a microcomputer (Apple IIe) and was capable of recording the changing weight of the sample with time. It was also able to store the data on floppy disks for the duration of the experiment for subsequent analysis. The grains were conditioned to initial moisture of 25% (w.b.) for conducting these experiments.

In the first set of experiments, the duration of rest period was varied. During the rest period, the grains after fixed initial drying time, were transferred to the resting container made of brass and the rise in relative humidity in the void space of the grain mass was observed with the help of a calibrated probe. A tempering index based on relative humidity observations was defined to determine the extent to which moisture redistribution has taken place within the kernel during the resting stage. In the second set of experiments, the duration of rest period was kept the same but the point of start of rest period i.e. the initial drying time of the samples was varied. After resting stage, the redrying of the same sample was continued until the sample reached the required final moisture content. The same procedure was followed in the case of wheat as well as barley. The wheat samples were dried to a final moisture content of about 10% (w.b.) whereas the drying of barley samples was discontinued at a moisture content of around 13% (w.b.).

The results indicate that the moisture redistribution during resting is well advanced after a period of two hours for wheat and one hour for barley. There is good descriptive agreement between theoretical and experimental results on rest period drying of wheat as well as barley.

However, the theoretical model was found to overpredict the reduction in drying time with the introduction of a rest period. The maximum reduction in drying time was found to be 20% in the case of wheat and 39% in the case of barley depending upon the reduction in moisture content required during drying. The overall response to rest period drying was observed to be much better in the case of barley as compared to wheat. It was found that the incorporation of a surface or skin resistance into the diffusion model improved the description of the experimental results. The optimum resting point and the maximum percent reduction in drying time were expressed as a function of the drying requirement by separate linear equations for wheat and barley.

7.1.3 Dryeration

An experimental set up was developed for conducting dryeration work on a laboratory scale. The experiments on dryeration were carried out on wheat and barley artificially conditioned to a moisture content of 16% (w.b.) and preheated to 40°, 60° and 80°C in an unventilated controlled temperature oven. Some experiments were conducted on wheat at 12% (w.b.) and 60°C. The airflow rate ranged from 30 to 960 $m^3/hr/m^3$ of grain. It was found that an airflow rate of 60 to 120 $m^3/hr/m^3$ gives the maximum reduction in moisture content during cooling in most of the cases. The reduction in moisture content from initial moisture content of 16% (w.b.) was found to be 0.652% (d.b.) for wheat and 0.786% (d.b.) for barley per 10°C temperature difference between air and grain. In the case of wheat at moisture content of 12% (w.b.), the decrease in moisture content during cooling was observed to be only 0.25% (d.b.) per 10°C temperature difference. Before this research work, the change in moisture content during cooling was generally accepted as 1% per 10°C temperature difference regardless of crop and its initial moisture content. It was found that for maximum reduction in moisture content, the grains should be cooled slowly in about 10 to 12 hours as faster cooling just carries away the heat from hot sweating grains without being able to pick up full moisture load thereby reducing the thermal efficiency of the dryeration system. The insulation of the dryeration cylinder in these experiments was observed to be helpful in reducing moisture condensation along its walls.

7.2 Conclusion

7.2.1 Main Conclusions

1. There is an optimum moisture content at which the grains need to be rested for maximum benefit of rest period drying. This moisture content is a function of initial, final and equilibrium moisture content and can be expressed by the relationship

   For Wheat $\hat{MR}_{rest} = 0.126187 + 1.04853\ MR_f$ 7.1

   For Barley $\hat{MR}_{rest} = 0.1921 + 0.99347\ MR_f$ 7.2

2. The maximum percent reduction in drying time by introducing rest period depends upon the drying requirement i.e. the reduction in moisture content of the grain during drying and can be expressed as

   For Wheat $MPR = 6.102 + 23.31\ MR_f$ 7.3

   For Barley $MPR = 13.2736 + 41.55\ MR_f$ 7.4

3. The moisture redistribution during rest period is well advanced after a period of two hours for wheat and one hour for barley.

4. The numerical solution incorporating surface or skin-resistance of the grain unifies the experimental and theoretical results on the two-

stage drying of grains with an intervening rest period. It appears that wheat offers more surface resistance and under-reacts to rest period drying as compared to barley.

5. A drying strategy can be specified that reduces actual drying time by as much as 39% in the case of barley and 20% in the case of wheat depending upon the drying requirement. This reduction in drying time could increase the throughput of the drier by up to 64% if all other factors affecting drier output are held constant.

6. An airflow rate of about 60-120 m^3/hr/m^3 of grain gives the maximum reduction in moisture content during cooling. This moisture reduction is found to be 0.65% (d.b.) and 0.78% (d.b.) per 10°C temperature difference between grain and air for wheat and barley respectively at an initial moisture content of 16% (w.b.). The reduction in moisture content in the case of wheat at 12% (w.b.) is much less and is only 0.25% (d.b.) per 10°C temperature difference. This indicates that dryeration effect also depends on the initial moisture content of the grain.

7. The two-stage drying process appears to be an attractive alternative to continuous drying to enhance the capacity of a grain drying plant to handle wet grains.

7.2.2 Application

A comparison of continuous drying, rest period drying and dryeration for different drying requirements of wheat and barley is presented in Figures 7.1 and 7.2 respectively. It can be seen from these two figures that for all drying requirements of wheat and barley, dryeration technique takes least time for high temperature drying but the time needed to complete drying in store is much more as compared to rest period drying. Another point of difference which could be mentioned here is that in rest period drying no air flow is required during storage phase whereas in the case of dryeration, the storage has to be ventilated to remove moisture due to aeration or evaporative cooling.

In fact, these two techniques of drying have applications in different situations. The technique of dryeration appears to be more useful for drying on the farm where the farmer does not possess complex grain handling equipment like conveyors and elevators for repeated loading and unloading of the grains into the high temperature drier. The problem of moisture condensation along the roof and walls of storage bin due to vapours coming out of hot grains in dryeration can also be easily taken care of by the farmer by mixing the grains at the top of the bin or by insulation of the dryeration bin or by transferring the grains at the end of drying from ventilated dryeration bin to an unventilated storage bin.

The rest period drying can be adapted for in-plant drying of wet grains in commercial grain drying plants. The grains could be dried from initial moisture content to the optimum moisture content for commencement of rest period, then conveyed to the storage bin for resting and brought back to the high temperature drier for continuation of drying to the final moisture content. The optimum moisture content for start of rest period for drying of wheat and barley under different situations can be determined from Figures 7.3 and 7.4. The initial drying time can then be found from the performance characteristics of the drier. The application of two-stage drying for drying of wheat and barley is illustrated in Appendix 7.1 with the help of two examples.

7.2.3 Future Work

Based on this investigation, the following areas are suggested for further work:

1. The mass diffusivity of wheat, barley and rapeseed needs to be determined at different moisture contents and drying air temperatures. The results could be expressed in the form of a mathematical relationship for incorporatioı into models. There appears to be no work done on this aspect in the case of wheat and rapeseed while the only work on barley appears to be that of Bruce (1985).

2. The thickness of various layers like endosperm, aleurone, germ, testa and their mass diffusivity values need to be determined for various grains for better understanding of moisture distribution during drying and redistribution during rest period.

3. The multi-stage or cyclic drying of grains needs to be evaluated thoroughly. Although some work appears to have been done here and there, yet there is no systematic study carried out so far. The developed computer program can be used for such a study and the effect of the ratio of drying time to total cycle time and the number of stages on reduction in drying time could be investigated. A typical prediction of multi-stage drying in a thin layer with the developed model is shown in Figure 7.5. The increase in drying rate after second rest period shows up clearly for this drying to total time ratio of 1 : 3, i.e. 30 min. drying, 60 min. resting, 30 min. drying, 60 min. resting and so on...

4. The rest period drying of various grains at different drying air temperatures, with varying initial moisture contents, in thin layers and subsequently in deep beds needs to be evaluated conclusively.

5. The experiments on dryeration need to be conducted for different grains at various initial moisture contents since the data on moisture reduction during cooling under various conditions is not presently available. The effect of reversal of airflow direction to reduce condensation could also be included in such studies.

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