DEEP BED DRYING OF MALT

by

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TO SHREMAT PANCHANAN GOSWAMI

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ABSTRACT

During the production of malt, germinated barley is dried from 70 - 85% to 2.4 - 4% moisture content (d.b.) requiring high energy and a long drying process. This study is concerned with developing a mathematical simulation model for deep bed drying of malt to provide design data and data on temperature and moisture content histories at different depth of the bed for use by the design engineers and maltsters for minimizing energy consumption and improving quality. In order to do this certain physical and thermal properties were also determined.

The properties of physical dimensions, 1000 grain weight, bulk density and dry bulk density were determined experimentally and each of these properties except bulk density was found to be linearly dependent on moisture content. Specific heat was also determined experimentally and also found to be linearly dependent on moisture content. The ratio of latent heat of malt to latent heat of free water was determined from existing experimental data on equilibrium moisture content and found to be a function of moisture content. Shrinkage of the malt bed was determined experimentally and found to be a non-linear function of moisture content reduction. The heat transfer coefficient of the malt bed was also determined experimentally and found to be a function of air flow rate.

The thin layer drying experiments were conducted under controlled conditions of the drying air using an automatic continuous weighing system. Numerical procedures were developed to fit the experimental data to the single exponential equation, the Page equation and the double exponential equation. The drying constant was expressed as a function of the drying air temperature and the dynamic equilibrium moisture content was expressed as a function of drying air temperature and relative humidity.

Two mathematical models, model 1 similar to Newcastle University model and model 2 similar to the Michigan State University model were programmed in FORTRAN to predict temperature and moisture content changes with time and position. Shrinkage and variable dry bulk density effects and a simple comprehensive condensation procedure were incorporated in both models. The set of partial differential equations for model 2 was solved by an exponential approximation and using central difference values updated by an iteration.

Five deep bed experiments were conducted in the laboratory and the suspended thermocouple technique for the measurement of temperature was found quite satisfactory. Both models agreed well with the experimental data. Reasonable agreement was also obtained with commercial kiln data. Practically there is no difference between the predictions of the two models and model 1 takes less computing time. A short section is included to illustrate the use of the programme for simulation. Typical commercial conditions are used and the effect of gas fired,indirect fired and recirculating gas fired conditions is examined.

CONTENTS

VOLUME 1 - TEXT

KEY TO SYMBOLS

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
∇^2	$\frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2} + \frac{\partial}{\partial z^2}$
Σ	summation

Lower case

a	constant
a_v	area of particle per unit volume of bed
b	constant
c	constant
d	constant
d_e	effective diameter
e	exponent of
f	constant
$f_i(x)$	residuals
g	constant
h_s	heat capacity per unit volume of solid
h_g	heat capacity per unit volume of gas
h_c	convective heat transfer coefficient, Watts/m^2 ^oK

h_{cv}	volumetric heat transfer coefficient, Joules/m^3 sec ^oK
h_{cv}	volumetric heat transfer coefficient in model 1 and model 2, kJ/m^3 min ^oK
h_{cs}	surface heat transfer coefficient
i	integer
j	integer
j_h	Colburn j-factor for heat transfer
j_d	Colburn j-factor for mass transfer
k	drying constant, 1/time
k_1, k_2	drying constants,1/time
k_s	shrinkage constant
m	integer
n	integer
n	constant
p	constant
q	constant
q_c	rate of heat transfer by convection
r	radius of sphere
r	correlation coefficient
rh	relative humidity, ratio
t	time, min.
t_{eq}	equivalent time, min.
u	constant
v	specific volume of liquid
x	space coordinate
x	independent variable
y	space coordinate

y	dependent variable
z	half thickness of a plane sheet
z	depth of bed, m
z	space coordinate

Upper case

A	constant
A	heat transfer area
A	abbreviated term in model 1
B	constant
B	abbreviated term in model 1
C	constant
C_1, C_2, C_3, C_4, C_5	constants
C_p	specific heat of wet grain, kJ/kg^oK
C_{pg}	specific heat of dry grain, kJ/kg^oK
C_{pa}	specific heat of air, kJ/kg^oK
C_{pl}	specific heat of water, kJ/kg^oK
C_{pw}	specific heat of water vapour, kJ/kg^oK
D_v	diffusivity
E	abbreviated term in model 1
F	constant
F	abbreviated term in model 1
G	mass flow rate of air, kg/m^2 sec
G	mass flow rate of air in model 1 and model 2, kg/m^2 min
H	humidity, kg/kg
I_o	modified Bessel function of first kind and zero order

K	thermal donductivity
K_{11}, K_{12}, K_{13}	
K_{21}, K_{22}, K_{23}	phenomenalogical coefficients
K_{31}, K_{32}, K_{33}	
L_a	latent heat of water in model 1 and model 2, kJ/kg
L_g	latent heat of grain in model 1 and model 2
L_{water}	latent heat of water, kJ/kg
L_{wheat}	latent heat of wheat
$L_{shelled\ corn}$	latent heat of shelled corn
$L_{soybeans}$	latent heat of soybeans
L_{malt}	latent heat of malt
M	moisture content % or ratio, (d.b.)
M_o	initial moisture content % or ratio, (d.b.)
M_e	equilibrium moisture content % or ratio, (d.b.)
M_t	moisture content at time t % or ratio, (d.b.)

$$MR = \frac{M - M_e}{M_o - M_e}$$

M_d	moisture content %, (d.b.)
M_w	moisture content %, (w.b.)
M_{wo}	initial moisture content %, (w.b.)
M_b	bound moisture content % or ratio, (w.b.)
M_{sd}	static equilibrium moisture content % or ratio, (d.b.)
M_{sw}	static equilibrium moisture content % or ratio, (w.b.)
M_{dd}	dynamic equilibrium moisture content % or ratio, (d.b.)
M_{dw}	dynamic equilibrium moisture content % or ratio, (w.b.)

$$M_n\ (YZ) = \frac{d^n M_o\ (YZ)}{d\ (YZ)^n}$$

$$M_o\ (YZ) = I_o\ (2\sqrt{YZ})$$

P	pressure, N/m^2
P_s	saturated vapour pressure
P_{ws}	saturated vapour pressure at T_{db}, N/m^2
P_w	saturated vapour pressure at T_{dp}, N/m^2
P, P'	abbreviated term in model 2
P_o, P_1, P_2 P_3, P_4, P_5	constants
P_{at}	atmospheric pressure, N/m^2
p^k	direction of search
Q	abbreviated term in model 2
R	drying rate
R_o	universal gas constant
Re	Reynolds number
RH	relative humidity, %
RH_p	maximum permissible relative humidity
S	shrinkage, % or ratio
S_p	sphericity
T	temperature
T_s	temperature of solid, ^oC
T_a	air temperature, ^oC
T_g	grain temperature, ^oC
T_{ao}	initial air temperature, ^oC
T_{go}	initial grain temperature, ^oC
T_i	initial temperature of calorimeter, ^oC
T_f	final temperature of the mixture, ^oC
T_{ab}	absolute temperature, ^ok
T_{db}	dry bulb temperature, ^oR

T_{dp}	dew point temperature, ^{o}R
V	specific volume of gas
W_t	weight at time t, g
W_g	weight of grain, g
W_w	weight of water, g
W_E	water equivalent, g
W_o	initial weight, g
W_f	final weight, g
W_d	weight of dry matter, g
Y_t	balance reading at time t, mV
Y_o	initial balance reading, mV
Y_f	final balance reading, mV
Y	dimensionless variable
Y	abbreviated term in model 1
Z	dimensionless variable

<u>Greek</u>

μ	viscosity
ε	void fraction
ϕ	shape factor
ρ_a	density of air, kg/m^3
ρ_d	dry bulk density of grain, kg/m^3
σ	standard deviation

Chapter 1

INTRODUCTION

The malting process may be divided into three stages. First, carefully selected barley is immersed in water until a moisture content of 70 to 85% (d.b.) is reached, the process is called steeping. This moisture content is sufficient to support growth and biochemical changes during the malting period. The nature of the steep water is said to affect the quality of malt and the derived products. The rate of water uptake by barley is very rapid at first, but later declines almost to zero and depends on steeping temperature. Secondly, the wetted barley is set to germinate under controlled conditions. The intensity of the germination process is controlled by regulating the moisture and temperature of the grain. The changes occurring during germination that are essential in converting barley into malt are collectively termed "modification". Finally at the end of the germination stage, when biochemical and physical changes have advanced sufficiently, the green malt is dried to a moisture content of 2.5 to 4% (d.b.) to produce a friable, readily milled and stable product for long storage. Once the malt is hand dry (moisture content 5 to 8%) the malt is cured by raising the temperature to between 80°C and 100°C to give the malt colour, flavour and aroma.

Malting barley plays an important role in the British economy. The estimated plantings of malting varieties of barley in the U.K. compared with plantings of total cereals is approximately 31%. The projected use of U.K. barley for malting, both at home and abroad in 1985, is 2.8 million tonnes. This is 1.0 million tonnes higher than in 1974 - 76 (Sturgess and Knell, 1978). Again, energy consumption in the malting industry in the U.K. is greater than that of the whole remaining cereal production industry.

The total energy consumption in the malting industry is 9.8 million G.J., out of this about 80% is used for drying malt (Energy Series Audit No. 15, 1981). Malt is dried from 70 - 85% to 2.4 - 4% moisture content which is equivalent to the evaporation of approximately 400 kg of water per tonne of malt, whereas most of the cereals are dried typically from 25% to 13% moisture content, which requires approximately 100 kg of water to be evaporated per tonne of the cereals. Thus the evaporation load per tonne of malt is about 4 times higher than that of the cereals.

Johnston (1954) has indicated that the main physical factors affecting the drying of malt are the quantity of moisture to be removed, the temperature and humidity of the air entering the kiln, the temperature to which the air is heated, the hygroscopic state of the grain and the volume of air passing through the bed. He has also shown that above about 13% (d.b.) moisture content the water evaporates freely. Logan (1954) has suggested that the free water stage is about about 25% (d.b.) and an intermediate stage is from 25% (d.b.) to 13% (d.b.). Sfat (1965) has reviewed the fundamental bio-engineering principles involved in kilning of malt and suggested further research in the areas of:

(i) Malt equilibrium moisture and moisture hysterisis. Effect of barley variety, barley kernel size, barley protein, malting process, analytical properties, surface condition, drying conditions and adsorption condition.

(ii) Determination of drying rate controlling mechanisms during falling rate period.

(iii) Economic study relating initial kiln investment, operating costs, including heat and fan power with bed depth.

(iv) Inter-relationship of bed depth with turning, drying time and product quality.

(v) Mechanism of flavour development during falling rate period, and how related to physical parameters of drying.

(vi) Rate-controlling steps for colour formation and enzyme inactivation during falling rate period, and relationship to the physical parameters of drying.

(vii) Mechanism of sulphering,especially effects of sulphur dioxide concentration in gas phase, temperature, time of contact and bed depth.

(viii) Effects of other products of combustion, fuel:air ratio, velocity and temperature.

Thin layer drying experiments have been conducted for a number of agricultural products and the data has been used by several researchers for mathematical models of the deep bed drying process. Although experiments on the deep bed drying of barley have been reported (Boyce, 1965), the design data for barley does not apply to malt drying. The main reasons are:

(i) Malt is dried at higher temperatures ($50^{\circ}C - 90^{\circ}C$).

(ii) Initial moisture content is high and final moisture content is very low.

(iii) The endosperm and cell walls of wetted barley are degraded (Pomeranz, 1972).

(iv) Final product should be brittle and have characteristic flavour.

The malting industry is now investing heavily on heat recovery and the use of microprocessor based programmable controls of kilns. Major energy saving opportunities are:

(i) Control of drying and energy re-use from kiln to kiln.

(ii) Heat recovery from exhaust

(iii) Heat pump.

But, the effectiveness of heat recovery, malt quality and microprocessor based programmable control of kilns depends fully on the theoretical knowledge of the drying process. The mathematical model of deep bed drying can be used to test and develop the microprocessor control programs for decision making such as finding the optimum rates of recirculation after the break and the optimum re-use of post-break air from one kiln for pre-break air on another kiln, when more than one kiln is in operation.

The objective of this research was to attempt to develop a mathematical simulation model for deep bed drying of malt to provide design data and data on temperature and moisture content histories at different depths of the bed for use by design engineers, operating maltsters and biochemists.

Chapter 2

PHYSICAL AND THERMAL PROPERTIES OF MALT

This chapter describes the basic properties of malt that are required for simulating the heat and mass transfer phenomena during drying and storage. The dimensions and 1000 grain weight are used to describe the physical characteristics of malt and their influence on drying is discussed. When the drying is simulated by a model using the diffusion equations to describe internal moisture movement, the above parameters are essential in order to select geometry and specify size. Bulk density, specific heat, latent heat of vaporization, shrinkage and heat transfer coefficient of a malt bed are essential in any simulation of the heat and mass transfer in a deep bed of malt during drying.

2.1 Physical Dimensions of Malt

Physical dimensions of malt are of vital importance in the design of cleaning and grading equipment. Furthermore, the dimensions of malt have an important influence on its drying characteristics. Breeders of barley need a guide in their work of developing new varieties of desirable size and shape.

2.1.1 Method

Two varieties of malt, Triumph and Sonja, were selected for determination of physical dimensions. Physical dimensions were determined at five different moisture levels for each variety.

The five moisture levels were obtained for both varieties by drying four batches of malt and using the undried malt itself. The batches were tumbled to attain uniformity and five samples were taken randomly from each batch for moisture content determination. It should be noted here that the samples used for physical dimensions, 1000 grain weight, bulk density and specific heat, were taken from these batches of known moisture content. Fifty grains were randomly selected for measurement for each moisture content and each variety. The length and width of malt grain were obtained by direct measurement through a microscope with an accuracy of 0.1 mm. The thickness was measured by a micrometer (accuracy 0.01 mm). All measurements were conducted at room temperature, 20 - 22°C.

2.1.2 Results and Discussion

The physical dimensions of the two varieties of malt determined in this study are presented in Table 2.1 and Figs. 2.1 - 2.3. Length, width and thickness appeared to be linearly dependent on moisture content on a wet basis. The following regression equations were developed for length, width and thickness; where M_w is expressed as a % and the unit of length is millimetres:

Triumph

$$\text{Length} = 7.968 + 0.02171\, M_w \qquad (r^2 = 0.88) \tag{2.1}$$

$$\text{Width} = 3.687 + 0.008269\, M_w \qquad (r^2 = 0.87) \tag{2.2}$$

$$\text{Thickness} = 3.209 + 0.002875\, M_w \qquad (r^2 = 0.95) \tag{2.3}$$

Sonja

$$\text{Length} = 8.146 + 0.02337\ M_w \qquad (r^2 = 0.95) \tag{2.4}$$

$$\text{Width} = 3.615 + 0.01392\ M_w \qquad (r^2 = 0.96) \tag{2.5}$$

$$\text{Thickness} = 3.118 + 0.008359\ M_w \qquad (r^2 = 0.96) \tag{2.6}$$

Linear regression with moisture content on a dry basis was less effective. Figs. 2.1, 2.2 and 2.3 show the experimental data and regression lines. It is quite obvious from the Figures that the physical dimensions of the variety, Sonja are more sensitive to the change in moisture content than the variety, Triumph. Fig. 2.4 and 2.5 show that the computed percentage changes of physical dimensions with respect to percentage change in moisture content. It is apparent from Figs. 2.4 and 2.5 that the percentage change in physical dimensions of Sonja is more or less uniform but higher than that of Triumph. The data of Nellist (1974) shows that the drying constant, k, for ryegrass seed varieties, Sabel and S.23 was greatest for the smaller variety, although the difference is diminished with increasing temperature. However, fertility, soil type and irrigation, may have some effect on physical dimensions of malt, unfortunately this effect is not known.

2.2 1000 Grain Weight

The 1000 grain weight is also of importance in the design of cleaning and grading equipment. One thousand grain weight also has application in the determination of effective diameter of the grain.

2.2.1 Method

The 1000 grain weight was determined at five different moisture levels for the two varieties, Triumph and Sonja. The batches at five moisture levels were prepared as described in Section 2.1.1. Five random samples were taken from the conditioned grains and 100 grains were randomly selected from each sample. The weight of 100 grains was measured by an analytical balance (accuracy 0.0001 g) and this weight was multiplied by 10 to give the 1000 grain weight. The measurements were repeated for each moisture content for both the varieties.

2.2.2 Results and Discussion

The 1000 grain weight of malt is shown in Table 2.2. The 1000 grain weight appeared to be related to moisture content (% w.b.) linearly. Linear regression with the moisture content on a dry basis was less effective. The following regression equation was developed for 1000 grain weight:

$$\text{1000 Grain Weight (g)} = 35.15 + 0.6266\, M_w \qquad 2.7$$

$$(r^2 = 0.96)$$

1000 grain weight increases with increase in moisture content and there is no significant difference between the two varieties (Fig. 2.6). The regression equation agrees more closely with experimental data at low moisture content.

2.3 Bulk Density of Malt

Bulk density is one measure of quality. Miles (1937) measured test weight of five varieties of corn and observed that the test weight decreases with the increase of moisture content from 10 to 25% (w.b.)

and the test weight increases with the increase of moisture content above 35% (w.b.) Chung and Converse (1971) observed that the relationship between test weight and moisture content was curvilinear for both wheat and corn but the dry bulk density was linearly dependent on moisture content. Vemuganti and Pfost (1980) observed that the test weight of corn decreases with the increase of moisture content, whereas Matouk (1976) found that the bulk density of maize grain increases with the increase of moisture content. Browne (1962) and Kazarian and Hall (1965) observed that the bulk density of wheat decreases with the increase of moisture content above 16% moisture content (w.b.). Several researchers (Wratten *et al.* 1969, Morita *et al.* 1979 and Vemuganti *et al.* 1980) found that the bulk density of rough rice increases with the increase of moisture content. Browne (1962) observed that the bulk density of barley decreases with the increase of moisture content at higher moisture content, but Vemuganti and Pfost (1980) reported that the test weight of barley decreases with the increase in the moisture content ($r^2 = 0.755$). Thus, there is no general trend in the variation of bulk density of common agricultural crops even for the same crop except rough rice.

2.3.1 Method

Bulk density was determined for the two varieties, Triumph and Sonja, at five different moisture levels. The batches at five moisture levels were prepared as described in Section 2.1.1. The bulk density of malt was determined by measuring weight of a grain sample of known volume. The grain sample was placed in a cylindrical container of volume 500 c.c. Uniform density in the cylinder was obtained by gently tapping the cylinder vertically down onto a table 30 times in the same manner in all measurements. The excess on the top of the cylinder was removed by sliding a string along the top edge of the cylinder. After the excess had been removed completely, the weight of the grain sample was measured by an electronic balance (accuracy 0.01 g). Dry weight of the grain sample was determined from the weight of the wet grain and the moisture content.

2.3.2. Results and Discussion

The bulk density of malt and dry bulk density are presented in Table 2.3. The dry bulk density of malt appeared to be linearly dependent on moisture content (w.b.). The following regression equation was developed for dry bulk density of malt:

$$\text{Dry Bulk Density (kg/m}^3\text{)} = 527.0 - 4.481\ M_w \qquad (r^2 = 0.98) \tag{2.8}$$

Linear regression with the moisture content on a dry basis was less effective. There is no significant difference between the two varieties of malt and the above equation has been developed for both varieties (Fig. 2.7). The dry bulk density is found to decrease with the increase in moisture content. Physically this means that reduction in physical dimensions during drying reduces porosity which allows more grains to be accommodated per unit volume. Equation 2.8 was converted into a general equation for bulk density. The bulk density can be estimated by the following equation:

$$\text{Bulk Density (kg/m}^3\text{)} = \frac{(527.0 - 4.481\ M_w)}{(100 - M_w)} \times 100 \tag{2.9}$$

The curve predicted by equation 2.9 along with the experimental data is shown in Fig. 2.8. It has been reported (Thompson et al. 1967, and Gustafson et al. 1972) that bulk density increases with decrease in porosity. The bulk density of malt increases with the increase of moisture content in the range 25 to 45% moisture content which means that bulk density is more influenced by the moisture present than by the porosity of malt. But the reverse effect is observed in the moisture content range 0 to 15%. There exists a critical region between these two ranges and this critical region is characterized by the counter balance effect of moisture present and porosity. Bulk density also depends on location and soil type where the crop is grown and the cultural and harvesting practices used.

2.4 Specific Heat of Malt

The specific heat at constant pressure is normally used for heat transfer problems during drying and storage of agricultural crops. The pressure dependence of specific heat is very little for solids and liquids until extremely high pressure is encountered. Specific heat is also a function of temperature. However, it has been established that at ordinary temperatures and over temperature intervals which are not too great, specific heat may be considered as a constant physical property.

The need for data on specific heat of food materials has been recognised as early as 1892. Siebel (1892) proposed that specific heat of food materials can be expressed as equal to the sum of the specific heat of the solid matter and that of water associated with the solid dry matter. Siebel proposed the following equations for food materials such as eggs, meat, fruits and vegetables:

For values above freezing:

$$C_p = 0.837 + 0.03349\ M_w \qquad 2.10$$

For values below freezing:

$$C_p = 0.837 + 0.01256\ M_w \qquad 2.11$$

where

C_p = specific heat, kJ/kg ^{o}K

M_w = moisture content, % w.b.

Kazarian and Hall (1965) measured specific heat of wheat and corn using a Dewar flask calorimeter and dropping heated grain into water used as the calorimeter fluid. Muir and Viravanichai (1972) and Matouk (1976) measured the specific heat of wheat and maize grain respectively by dropping cooled grains into the calorimeter containing water at room temperature. The use of these techniques causes undesirable heat loss or gain during transferring the grains into the calorimeter and no method is available to make correction for it.

Disney (1954) and Haswell (1954) measured the specific heats of wheat, barley, paddy, corn, oats and groats by means of a modified Bunsen calorimeter, but used the grains at room temperature. Pfalzner (1951), Alam and Shove (1973), and Morita and Singh (1979) used the method of mixtures and dropped the grains at room temperature into ice cooled water in the calorimeter for determining the specific heats of wheat, soybeans and rough rice. Vemuganti and Pfost (1980) determined the specific heat of sixteen kinds of cereals, legumes and oilseeds, and dropped the grains at room temperature into heated toluene instead of ice cooled water. Whatever the type of calorimeter used and whether the calorimeter fluid is cooled or heated, the use of grains at room temperature avoids the heat gain or loss during the transfer of the grains into the calorimeter and the only correction needed is for the final temperature in the calorimeter.

Pfalzner (1951) presented an approximate formula for correcting the temperature rise in the calorimeter for radiation and Morita and Singh (1979) used the Regnault-Pfaunder formula for temperature correction. Muir and Viravanichai (1972) provided a graphical method for temperature correction. Since the radiation loss in an insulated calorimeter is very small in comparison with the convection heat loss, the graphical method is superior to the approximate formula for radiation correction.

The researchers using toluene argued that toluene enables the grains to sink more readily and gives greater temperature rise than that of water. However, the use of ice cooled water and shaking the mixture for a while have not been proved to cause any error in the determination of the specific heat.

Pfalzner (1951) used wheat enclosed in a small copper capsule and dropped into the calorimeter water. However, Muir and Viravanichai (1972) found no difference at 5% level of significance between the two means of specific heats obtained by pouring the wheat directly and by dropping a sealed polythelene bag of wheat into the calorimeter.

There exists a general agreement among the researchers on the observations of the specific heats for common agricultural crops that the specific heat of wet grain increases linearly with moisture content. The regressions equations of some common agricultural crops are presented in Table 2.4.

2.4.1 Method

The specific heat of grain is determined by the method of mixtures using distilled water as a calorimeter fluid. The technique consists of determining the temperature change of water contained in the calorimeter when a known quantity of grain is added to it at a known different temperature. The specific heat is calculated by solving the following heat balance equation:

Heat lost by grain = heat gained by water and calorimeter

$$C_p W_g (T_g - T_f) = W_c C_{pc} (T_f - T_i) + W_w C_{pl} (T_f - T_i)$$

$$C_p W_g (T_g - T_f) = C_{pl} (W_E + W_w) (T_f - T_i) \qquad 2.12$$

where

W_E = water equivalent of the calorimeter

C_p = specific heat of grain

T_g = initial grain temperature

T_f = final temperature of the mixture

T_i = initial temperature of the calorimeter

W_g = weight of grain

W_c = weight of the calorimeter

W_w = weight of water

C_{pc} = specific heat of the calorimeter

C_{pl} = specific heat of water

In this study an ordinary thermos flask was used as a calorimeter and fibreglass insulation was added between the vacuum bottle and the outer metal walls of the container. The specific heat was determined by dropping the grain directly into the calorimeter.

The malt grains were conditioned to provide five different moisture levels for both varieties as described in section 2.1.1. One experiment with the variety Sonja was rejected due to a sudden change in room temperature. Five measurements were performed at each moisture level. The grain samples of approximately 30 g were placed in glass test tubes and sealed with a rubber stopper, through which a copper-constantan thermocouple was inserted into the grains to check grain temperature. The placing of grain into sealed test tubes avoids the addition or removal of moisture to the grain from the room. The grain temperature was in equilibrium with room temperature within 24 hours, as indicated by thermocouples inside and outside the test tube. Two copper-constantan thermocouples were used to monitor the temperature inside the calorimeter. The thermocouple reference junction was maintained at zero °C by means of the ice-cell. For each measurement 50g of ice water was placed into the calorimeter and allowed to rise to an equilibrium temperature. Then approximately 30 g of grain sample which had been held in the test tube at room temperature was quickly transferred into the calorimeter. The thermos flask and its contents were shaken for a while (5 to 10 sec) to ensure the mixing of grain and water evenly. The temperature of the mixture was printed by the datalogger every second and the temperature recording continued 4 - 5 minutes after equilibrium was obtained. The arithmetic mean of the two thermocouple readings was considered the temperature of the mixture. A correction was made to the final temperature to allow for heat loss from the calorimeter. The graphical extrapolation technique used is described by Muir et al. (1972). The correction is not critical as it causes only a 3% change in the temperature rise. The average specific heat was calculated from the equation 2.12. The mean of the five replicates was considered as the specific heat of malt at that moisture content.

The water equivalent of the thermos flask was determined by using lead shot (470 g) and distilled water (50 g) instead of the grain and then for material of known specific heat, W_E becomes the only unknown in Eqn. 2.12. Three and five replicates were made for lead shot and distilled water respectively.

2.4.2 Results and Discussion

The water equivalent of the calorimeter was determined using lead shot of known specific heat (0.1337 kJ/kg^oK) and distilled water. The mean value of water equivalent of the calorimeter for five measurements using distilled water was 14.26 g with a standard deviation of 1.713 g and the mean value obtained by using lead shot for three measurements was 14.12 g with a standard deviation of 1.635 g. There was no significant difference between the two means of water equivalent. The average value of these two means was taken as the water equivalent of the calorimeter.

The specific heats of the two varieties of malt, Triumph and Sonja, determined in this study are presented in Table 2.5. The specific heat of the two varieties of malt was found to vary linearly with moisture content (w.b.) and the following regression equation was developed.

$$C_p = 1.651 + 0.04116\, M_w \qquad (r^2 = 0.99) \tag{2.13}$$

Linear regression with moisture content on a dry basis was less effective. Fig. 2.9 shows the regression line of the two varieties of malt together with the 95% confidence band of the line. A regression equation was fitted to the data on specific heats of barley from Disney (1954). Fig. 2.10 shows the regression lines for malt and barley. It is quite obvious from Fig. 2.10 that the specific heat of malt is higher than but not far removed from that of barley. This high value of specific heat of malt might be attributed to the fact that barley is converted into malt after significant changes in physical properties and chemical composition. Johnston (1954) reported the specific heat of dry matter of malt to be 1.674 kJ/kg^{o}K which is in very good agreement with the observed value of 1.651 kJ/kg^{o}K.

The apparent specific heat of bound water was computed from equation 2.13 and was found to be 5.767 kJ/kg^{o}K. Similar results have been reported by Muir and Varavanichai (1972), Matouk (1976) and Shipley et al. (1939). Shipley et al. suggested that a rise in temperature decreases the amount of bound water and increases the freedom of some water to the corresponding extent. According to this theory, the heat that was supplied to the malt was required for two purposes, first for the heat capacity of the system as a whole and second, to supply the heat necessary to bring about a decrease in the amount of bound water with rise in temperature. This would explain why the calculated heat content of the moisture in the malt kernel is greater than the heat content of free water. Stitt and Kennedy (1945) have held the opposite view that the heat capacity of bound water is actually less than that of free water. According to their theory, the addition of water to dry solid produces changes in the inner structure of the material which results in an increase of overall specific heat exceeding the effect of the depression of specific heat caused by the bound water. The apparent specific heat of bound water of malt was calculated neglecting the contribution of the changes in the inner structure of malt to the overall specific heat of malt. This contribution might be higher than the depression caused by the bound water. This would also explain why the calculated specific heat of bound water in malt is higher than that of free water.

In fact the changes in inner structure of the malt are higher than that of barley. This would explain, according to the theory of Stitt and Kennedy (1945), why specific heat of malt is higher than that of barley.

2.5 Latent Heat of Vaporization of Malt

The latent heat of vaporization of malt is defined as the energy required to vaporize moisture from the product. The energy required to evaporate moisture from grain especially at low moisture content is higher than that of free water and depends on the type of crop. The latent heat of vaporization of wheat has been used to a great extent for other crops (Boyce, 1966, Nellist, 1974, and Matouk, 1976). The use of the latent heat of wheat for other crops is certainly better than the use of the latent heat of free water, but with crops which are dried to a very low moisture content as in the case of malt, its use may result in considerable error. Since malt is dried to a very low moisture content, the determination of its latent heat of vaporization is essential for simulating deep bed drying of malt.

Othmer (1940), starting with the Clapeyron equation, developed the following equation:

$$\text{Log } P' = \frac{L'}{L} \log P + C \qquad 2.14$$

where P and P' are vapour pressures and L and L' molal heats of the two compounds respectively, taken at the same temperatures. C is a constant. Equation 2.14 states that, if the log of the pressure of any substance is plotted against the log of the pressure of any other substance, a straight line results which will have for its slope the ratio of the molal latent heats. He made plots to illustrate the utility of this relation with various materials in checking and correlating vapour pressure data, and it gave a good fit to the data.

Gallaher (1951) using the equilibrium moisture content data for wheat, published by Gay, determined the latent heat of vaporization of wheat. He developed Othmer plots for wheat by plotting the log of the vapour pressure of the crop against the log of the vapour pressure of water at the same temperature for each moisture content. The ratio of latent heat of the crop to the latent heat of free water was calculated from the slope of the line resulting from the plot. He also found that when the ratios of the latent heat of wheat to the latent heat of free water were plotted against moisture content (d.b.), the resulting curve could be described by the following equation:

$$\frac{L_{\text{wheat}}}{L_{\text{water}}} = 1 + 23 \exp (- 0.40 M_d) \qquad 2.15$$

where M_d is the moisture content on a dry basis. This equation shows that the amount of heat required to vaporize water from wheat increases considerably as the moisture content of the wheat decreases.

Strohman and Yoeger (1967) developed an equilibrium moisture content equation utilizing the linear form of the Othmer plots of equilibrium moisture content and the solution of the equation provides information about the latent heat of vaporization. They developed the following equation for the latent heat of vaporization of shelled corn:

$$\frac{L_{\text{shelled corn}}}{L_{\text{water}}} = 1 + 0.8953 \exp (- 0.1232\, M_d) \tag{2.16}$$

Alam and Shove (1973) developed the following equation for latent of vaporization of soybeans using Strohman and Yoeger relationship for soybeans:

$$\frac{L_{\text{soybeans}}}{L_{\text{water}}} = 1 + 0.21624 \exp (- 0.06233\, M_d) \tag{2.17}$$

2.5.1 Theory

The theoretical basis for the determination of the latent heat of malt is the Othmer plot based on the Clapeyron equation. The Clapeyron equation is given by (Rogers and Mayhew, 1980) :

$$\frac{dP}{dT} = \frac{L}{(V-v)} \tag{2.18}$$

where

P = vapour pressure

T = absolute temperature

V = specific volume of water vapour

v = specific volume of liquid water

L = latent heat of vaporization

If v is disregarded in comparison with V and if it is possible to assume a perfect gas, the following equation may be used for the volume term:

$$V = RT/P \qquad 2.19$$

From the combination of equations 2.18 and 2.19 the Clausius-Clapeyron equation results:

$$\frac{dP}{dT} = \frac{LP}{RT^2} \qquad 2.20$$

$$\frac{1}{L} \times \frac{dP}{P} = \frac{dT}{RT^2} \qquad 2.21$$

The same equation may be written for water in grains at the same temperature.

$$\frac{1}{L'} \times \frac{dP'}{P'} = \frac{dT}{RT^2} \qquad 2.22$$

where

P' = vapour pressure of grain in equilibrium

L' = latent heat of vaporization of grain.

From equations 2.21 and 2.22

$$\frac{dP'/P'}{dP/P} = \frac{L'}{L} \qquad 2.23$$

It is also apparent that equation 2.23 can be integrated to give:

$$\text{Log } P' = \frac{L'}{L} \text{ Log } P + C \qquad 2.24$$

The latent heat of the material can be established from the slope of the log P' vs log P curve.

2.5.2 Data Analysis

The equilibrium moisture content data for malt from the unpublished data of Pixton and Henderson (1981) was used to determine the latent heat of vaporization of malt. For each temperature, the saturation vapour pressure was found from the Steam Tables (Rogers and Mayhew, 1980). The vapour pressure of malt at each moisture content was determined by multiplying the corresponding relative humidity by the saturation vapour pressure for the given temperature. The logarithm of the vapour pressure of malt was plotted against the logarithm of the vapour pressure of free water. These gave reasonably well defined straight lines. The slopes of the lines, namely, the ratios of the latent heat of malt to the latent heat of free water were plotted against moisture content (d.b.). An equation was developed to describe the ratio of the latent heat of vaporization of malt to the latent heat of vaporization of free water as a function of moisture content and of the form used by Gallaher (Eqn. 2.15).

2.5.3 Results and Discussion

Table 2.6 presents the equilibrium moisture content data of malt (Pixton and Henderson, 1981) along with the calculated saturated vapour pressures and vapour pressures of malt. Fig. 2.11 presents the Othmer plots for malt and shows that the plot of the log of the vapour pressures of malt against the log of the vapour pressure of free water gives a reasonably well defined straight line. The ratio of the latent heat of malt to the latent heat of free water was a function of moisture content. The following regression equation was developed:

$$\frac{L_{malt}}{L_{water}} = 1 + 0.5904 \exp (- 0.1367 M_d) \qquad 2.25$$

$$(r^2 = 0.99)$$

The equation fits the experimental data reasonably well (Fig. 2.12). This curve also indicates that the amount of heat required to vaporize water from malt increases considerably as the moisture content of the malt decreases. Fig. 2.13 shows a comparison of the latent heats of wheat, malt, shelled corn and soybeans. For moisture contents above 13.5% (d.b.), the latent heat of malt is higher than that of wheat but less than that of either shelled corn or soybeans. For moisture content below 13.5% (d.b.), the latent heat of malt is less than that of either wheat or shelled corn but higher than that of soybeans. This comparison indicates that for drying to a low moisture content below 13.5% (d.b.), an accurate determination of latent heat of the crop is essential, otherwise using the data of any other crop will result in considerable error in the deep bed simulation of drying.

Since Gallaher's form of equation (Eqn. 2.25) is not based on any physical model, any extrapolation below the 5.5% moisture level should be treated with caution. As malt is dried to 2.5 - 4%, further data below 5.5% would be useful.

2.6 Shrinkage of the Malt Bed

Shrinkage of agricultural products during drying is an observable phenomenon and it may have a significant effect on drying rate and temperature distribution especially during deep bed drying of agricultural crops. Wileman (1941) determined the shrinkage of seed corn in terms of both weight and volume during drying in the moisture content range 14.8

to 34.8%. He found the weight and volume shrinkage of ear corn to be related linearly to the percentage moisture removed from the grain during artificial drying of seed corn on the ear.

Boyce (1966) reported that the shrinkage of barley during drying in deep beds appeared to be continuous and linear over the moisture content range,16 - 34% (d.b.) being on the average 16% by volume. He determined the following relationship between the shrinkage and the average moisture content of remoistened barley drying in deep beds:

$$S = 25.21 - 0.661\ M_d \qquad 2.26$$

where

S = shrinkage of bed, %.

Nellist (1974) determined the shrinkage of ryegrass seeds and found this to be a linear function of the reduction in moisture content. The following equation was developed:

$$S = 5.34 + 0.1889\ (M_o - M_f) \qquad 2.27$$

where

M_o = initial moisture content %, (d.b.)
M_f = final moisture content %, (d.b.)

He maintained that the constant in equation 2.27 is consistent with that part of the shrinkage that is due to settling which would occur even in an undried bed.

Spencer (1972) determined overall bed shrinkage of wheat for changes in bed mean moisture contents from the data of Clark and Lamond. The following equation was developed:

$$S = 0.85\ (M_o - M) \qquad 2.28$$

where

S = change in depth per unit depth

M_o = initial moisture content, ratio, (d.b.)

M = moisture content, ratio, (d.b.)

He used the amount of bed shrinkage to alter the finite element width during the simulation of the deep bed drying of wheat. Misra and Young (1980) developed equations for simulating moisture diffusion and shrinkage in soybeans (simulated by spheres) and established finite element methodology for their simultaneous solution.

2.6.1 Theory

Several researchers, as mentioned in the above section, have reported that shrinkage is linearly dependent on moisture reduction. It was observed that the shrinkage of malt is not a linear function of moisture reduction, but the rate of shrinkage decreases with the increase of moisture reduction. The following hypothesis was made to predict the shrinkage of malt on the basis of experimental evidence.

The rate of change of the shrinkage of a malt bed with respect to the reduction in moisture content from initial moisture content is proportional to the difference between the maximum possible shrinkage and the actual shrinkage.

Mathematically

$$\frac{dy}{dx} \quad \alpha\ (y_o - y) \qquad 2.29$$

where

y = the shrinkage expressed as a percentage of the original depth

y_o = maximum shrinkage %

x = moisture reduction %

The equation 2.29 can be written as

$$\frac{dy}{dx} = k_s (y_o - y) \qquad 2.30$$

where

k_s = shrinkage constant

The solution of the equation 2.30 gives

$$y = y_o (1 - e^{-k_s x}) \qquad 2.31$$

This equation requires the determination of the shrinkage coefficient and the maximum possible shrinkage from experimental data.

2.6.2 Method

An aluminium cylinder of 15 cm diameter and 30 cm long filled with green malt was mounted on a rectangular box serving as an air mixing chamber. The whole set was placed on a balance so that the amount of moisture removed could be determined at any time during the drying process. As the balance was of the beam type fitted with a balance pan for counterweights, the effect of flexible connecting tube could be eliminated. The schematic diagram of the experimental set up is shown in Fig. 2.14. A stainless steel scale graduated in mm was placed inside the cylinder to determine the change in depth at any time during drying.

Two runs of experiments on the shrinkage of the malt bed were performed. The cylinder containing green malt was placed on the balance and heated air at a constant air flow was passed through the grains. The scale indicator was set to zero by the use of counter weights and water in a plastic cylinder. The depth of grain bed was noted. A 20 g weight was placed on the pan containing the cylinder filled with grain. When 20 g of moisture had been removed, the scale indicator was again at zero position. The bed depth and moisture removed were noted and another 20 g of weight was placed on the pan containing the aluminium cylinder. This procedure was repeated until the drying rate approached zero.

2.6.3 Results and Discussion

The shrinkage of the malt bed determined in this study is shown in Table 2.7. Shrinkage coefficient, k_s and maximum possible shrinkage were determined by direct least square fit of equation 2.31 to the experimental data. The following equation was developed for the shrinkage of the malt bed during drying:

$$S = 15.91 \left[1 - e^{-0.0966\,(M_{wo} - M_w)}\right] \qquad 2.32$$

$$(\text{S.E.} = 0.6871)$$

where

S = percentage shrinkage

M_{wo} = initial moisture content %, (w.b.)

M_w = moisture content %, (w.b.)

Standard error of estimate was higher with moisture content on dry basis.

Fig. 2.15 shows that the agreement between the theory and experiments is reasonable. Furthermore, Fig. 2.15 shows that shrinkage can be related linearly with moisture reduction in the range 0 - 10%, (w.b.).

Physically the non-linearity of shrinkage of malt can be interpreted as follows. The shrinkage of a malt bed at any instant during drying is the cumulative effect of the free shrinkage of the cells due to loss of moisture and elastic shrinkage, if any, due to constraints on the free shrinkage exerted by the adjacent cells of the grains in the bed. The rate of shrinkage of cells in the malt grains decreases as the moisture content approaches a low value. This explains why the rate of shrinkage in the malt bed (Fig. 2.15) gradually decreases to almost zero at very low moisture content.

2.7 Heat Transfer Coefficient of Malt Bed

The rate of heat transfer between a solid surface and fluid may be computed from the following relation:

$$q_c = h_c A \Delta T \qquad 2.33$$

where

q_c = rate of heat transfer by convection (Watts)

A = heat transfer area, (m^2)

ΔT = temperature difference between the surface and the fluid, (^oK)

h_c = convective heat transfer coefficient, (Watts/m^2 ^oK)

Equation 2.33 was originally proposed by Isaac Newton in 1707. Engineers have used this equation for many years, although it is a definition of h_c rather than a phenomenological law of convection. The heat transfer coefficient is actually a complicated function of the fluid flow, the thermal properties of the fluid medium and the geometry of the system.

Schumann (1929) made a significant contribution in the field of heat transfer by developing the following analysis for fluid and solid temperature distribution in a packed bed of crushed material:

$$\frac{\partial T_s}{\partial Z} = T_a - T_s \qquad 2.34$$

$$\frac{\partial T_a}{\partial Y} = T_s - T_a \qquad 2.35$$

where

$Y = k_2 x/v$

$Z = k_1 (t-x/v)$

T_a = temperature of the fluid

T_s = temperature of the solid

x = distance traversed by the fluid in the bed

t = time

$k_2 = k/h_a f$

$k_1 = k/h_s (1-f)$

k = constant of heat transfer

h_s = heat capacity per unit volume of the solid

h_a = heat capacity per unit volume of the fluid

f = free space per unit volume.

He also presented the following solution involving some interesting mathematical functions related to the well known Bessel Functions:

$$\frac{T_s}{T_o} = e^{-Y-Z} \Sigma_{n=1}^{\infty} Z^n M_n (YZ) \qquad 2.36$$

$$\frac{T_a}{T_o} = e^{-Y-Z} \Sigma_{n=o}^{\infty} Z^n M_n (YZ) \qquad 2.37$$

where

$$M_n (YZ) = \frac{d^n M_o (YZ)}{d(YZ)^n}$$

$M_o (YZ) = I_o (2 \sqrt{YZ})$

$I_o (2 \sqrt{YZ})$ = modified Bessel function of the first kind and order zero

T_o = initial temperature of the fluid

He calculated the numerical values of T_s/T_o and T_a/T_o from equations 2.36 and 2.37 for values of Y and Z ranging from zero to 10 and presented the results graphically.

Furnas (1930) developed an interesting alternative numerical method of solution for the differential equations developed by Schumann and extended the temperature history curves for values of Y up to 500. He also demonstrated the use of the computed temperature history curves to calculate the heat transfer coefficient from observed data on temperature history. He determined the heat transfer coefficients of iron ore, limestone, bituminous coal, anthracite, coke and typical blast furnace charge, and postulated the following equation:

$$h_{cv} = \frac{Av^{0.7}\, T^{0.3}\, 10^{1.68f - 3.56f^2}}{d^{0.9}} \qquad 2.38$$

where

h_{cv} = volumetric heat transfer coefficient, (cal/sec ^{o}C cm^3)

v = velocity, (litres/sec cm^2)

T = temperature, (^{o}C)

f = fractional value of voids in bed

A = constant dependent on the bed material

d = average particle diameter, (cm)

In a written discussion on the paper of Furnas particularly on the introduction of T as a variable in equation 2.38, Colburn made the following comments:

> "The effect of temperature on heat transfer coefficients of gases in pipes has not been proven by previous investigators and it seems safest to accept the theoretical equation which shows that the only effect of temperature is that on specific heat. Mr. Furnas' introduction of a temperature factor does not, therefore, seem justified."

Löf and Hawley (1948) following the measurement of the time-air temperature relationship at the exit end of a packed bed of granitic gravel, determined the heat transfer coefficient by use of the Schumann curves. He found that the results could be correlated by the equation:

$$h_{cv} = 0.79 \left(\frac{G}{d_e}\right)^{0.7} \qquad 2.39$$

where

h_{cv} = volumetric heat transfer coefficient, (btu/hr ft^3 ^oF)

G = air flow rate, (pounds/hr ft^2)

d_e = equivalent spherical diameter, (ft)

Alanis, Saravia and Rovetta (1977) measured the volumetric heat transfer coefficient of a rock pile by means of the transient method where a temperature step was applied to the bed, and the obtained time-temperature relations for fluid at different points in the pile were compared with the theoretical curves computed by Schumann and Furnas. The following equation was developed for heat transfer coefficient:

$$h_{cv} = 824 \left(\frac{G}{d_e}\right)^{0.96} \qquad 2.40$$

where

H_{cv} = volumetric heat transfer coefficient, (Wm^{-3} K^{-1})

G = mass velocity, (kg sec^{-1} m^{-2})

d_e = equivalent spherical diameter, (m)

Colburn (1933) made a significant contribution in the determination of heat transfer coefficient by proposing a general method to correlate the forced convection heat transfer data which consists in plotting, against Reynolds number, a dimensionless group representing the experimentally measured data from which heat transfer coefficient would be calculated, namely, $\left[(T_1 - T_2) / \Delta T_m\right]$ (S/A) or its equivalent h_{cs}/C_{pa} G, multiplied by two-thirds power of the group ($C_{pa}\mu/K$). He called this dimensionless group the j-factor and by definition

$$j_h = \frac{(T_1-T_2)}{\Delta T_m} \cdot \frac{S}{A} \left(\frac{C_{pa}\mu}{K}\right)^{\frac{2}{3}} = \frac{h_{cs}}{C_{pa}G} \left(\frac{C_{pa}\mu}{K}\right)^{\frac{2}{3}} \qquad 2.41$$

where

j_h = Colburn j-factor for heat transfer

T_1-T_2 = temperature change

ΔT_m = mean temperature difference between the fluid and the surface

S = cross sectional area of air flow

A = heat transfer area

C_{pa} = specific heat of the fluid

μ = viscosity of the fluid

K = thermal conductivity of the fluid

h_{cs} = heat transfer coefficient based on surface area

G = mass velocity

Gamson, Thodos and Hougen (1943) conducted a series of experiments (180 runs) on heat and mass transfer using spherical and cylindrical catalyst carrier pellets of diameters from 2.29 to 18.8 mm and cylindrical heights from 4.78 to 16.9 mm under conditions of constant drying rate, at temperatures from 26.7 to 71.1 °C and at mass velocities of air from 0.54 to 3.12 kg/sec m^2. They found a remarkable correlation of experimental data by plotting the heat transfer factor, j_h against modified Reynolds number, d_eG/μ. The results were represented by the following equations:

For turbulent flow, Re >350

$$h_{cs} = 1.064\ C_{pa}\ G \left(\frac{d_e\ G}{\mu}\right)^{-0.41} \left(\frac{C_{pa}\mu}{K}\right)^{-\frac{2}{3}} \qquad 2.42$$

For laminar flow, Re < 40

$$h_{cs} = 18.1\ C_{pa}\ G \left(\frac{d_e\ G}{\mu}\right)^{-1} \left(\frac{C_{pa}\mu}{K}\right)^{-\frac{2}{3}} \qquad 2.43$$

where

Re = Renolds number

d_e = effective particle diameter

It was also observed that for all conditions of flow, turbulent, laminar or transition, the ratio of j_h to j_d remains constant, that is

$$\frac{j_h}{j_d} = 1.076 \qquad 2.44$$

where

j_d = Colburn j-factor for mass transfer.

Yoshida, Ramaswami and Hougen (1962) recorrelated the data of Wilke and Hougen; Gamson, Thodos and Hougen; and Wakao, Oshima and Yagi, by plotting j_d values against the values of Re on a logarithmic plot. For convenience, without appreciable loss in accuracy, the correlations were divided into parts as follows:

For $0.01 < Re < 50$

$$j_d = 0.84\ Re^{-0.51} \qquad 2.45$$

For $50 < Re < 1{,}000$

$$j_d = 0.57\ Re^{-0.41} \qquad 2.46$$

where

$$Re = \frac{G}{a_v\ \phi\ \mu}$$

a_v = area of particle per unit volume of bed

ϕ = shape factor = $\dfrac{\text{geometric mean diameter}}{\text{effective diameter}}$

Again, j_h can be estimated from equation 2.44.

Barker (1965) made an extensive survey on heat transfer in packed beds. He found by plotting the Colburn j_h factor against Reynolds number that whatever the type of packing, there was a general agreement among most of the investigators. The agreement is generally within a factor of about 2 over Reynolds numbers ranging from 10 to 100,000 and especially in the most common range from 200 to 4000. He also plotted Colburn j_h factor against Reynolds number for beds of randomly packed spheres of uniform diameter and found that the pioneering work of Furnas produced data lying in the centre of data spread produced by later workers, indicating that his data was essentially correct in all important aspects.

Henderson and Pabis (1962) developed a correlation equation from Treybal's data. The equation used for drying of wheat was:

$$h_{cs} = 2.24\ V^{0.494} \tag{2.47}$$

where

h_{cs} = surface heat transfer coefficient, (Btu/hr ft^2 ^{o}F)

V = superficial velocity of air, (ft^3/min ft^2)

Boyce (1966) studied the convective heat transfer coefficient of a thin layer of barley. A thin layer of barley was dried to equilibrium with the airstream and then cooled to a lower temperature. The change in moisture content was assumed to be zero during the heating process. He developed an equation of volumetric heat transfer coefficient of the form:

$$h_{cv} = a \left[\frac{G\ (T + 460)}{P_{at}} \right]^{b} \tag{2.48}$$

where

h_{cv} = volumetric heat transfer coefficient

G = mass flow rate of drying air

T = temperature

P_{at} = atmospheric pressure

a, b = constants.

Menzies (1971) plotted the j_h factor against Reynolds number from the results obtained by a number of workers for heat transfer coefficients in packed beds, together with the original data of Boyce. He found that the relationship proposed by Boyce does not reduce to the form of equation 2.41, but the original data of Boyce is not very far removed from the data obtained by other workers for non-organic materials.

Nellist (1974) made an attempt to use the method of Boyce to determine the heat transfer coefficient of ryegrass seeds, but abandoned it due to comparatively large heat losses during the measurement of heat transfer coefficient. He also compared the values of heat transfer coefficients obtained by the Gamson, Thodos and Hougen equation for barley and ryegrass seeds. He found that the Gamson, Thodos and Hougen equation always gives larger estimates. He developed the deep bed drying model of ryegrass seeds using Boyce equation multiplied by a constant.

Matouk (1976), using Boyce's method, determined the volumetric heat transfer coefficient at a temperature of 29°C and air flow rates from 0.1588 to 0.776 kg/m^2 sec and developed the following equation:

$$h_{cv} = 372600.0 \left[\frac{G \times T_{ab}}{P_{at}} \right]^{0.5217} \qquad 2.49$$

where

h_{cv} = volumetric heat transfer coefficient, (Joules/m^3 sec ^{o}K)

G = mass flow rate of air, kg/m^2 sec)

T_{ab} = temperature, (^{o}K)

P_{at} = atmospheric pressure, (N/m^2)

Wang, Rumsey and Singh (1979) studied convective heat transfer coefficient in a packed bed of rice. The basic equations used in their study were developed by Schumann. They compared the experimental results with the Schumann curves to compute heat transfer coefficients at different air flow rates. The computation procedure was similar to that developed by Furnas (1930); Löf and Hawley (1948). They developed the following correlating equation:

$$h_{cv} = 8.69 \times 10^4 \, G^{1.30} \qquad 2.50$$

where

h_{cv} = volumetric heat transfer coefficient, (Joules/m^3 sec ^oK)

G = mass flow rate of air (kg/m^2 sec)

2.7.1 Method

There are two general methods available for the determination of convective heat transfer coefficients in the malt bed:

(1) Dimensional analysis correlating existing data

(2) Direct measurement of heat transfer coefficient on a malt bed by comparing the temperature curves with Schumann's exact solution.

Dimensional analysis is mathematically simple and has a wide range of application. This method is useless and incomplete without sufficient experimental data and contributes little to our understanding of the transfer process, but it facilitates the interpretation and extends the range of application of experimental data by correlating them in terms of dimensionless groups.

Schumann's mathematical solution of the simultaneous equations are quite complicated. The method presupposes that the physical mechanisms are sufficiently well understood to be described in the form of partial differential equations. The solution in the dimensionless form is compared with the experimental data to compute convective heat transfer coefficient. Exact solutions are important because the assumptions made in the course of the analysis can be specified accurately and the validity can be checked by experiment.

In this study convective heat transfer coefficients were determined by both methods .

(1) Dimensional Analysis

The correlating equation developed by Yoshida, Ramaswami and Hougen (1962) was selected for this study. This equation was developed by recorrelation of the data of Wilke and Hougen; Gamson, Thodos and Hougen; and Wakao, Oshima and Yagi. Thus this equation has been supported by sufficient experimental data.

For Re < 50 < 1,000.

$$j_h = 0.61 \ \mathrm{Re}^{-0.41} \qquad 2.51$$

Again

$$j_h = \frac{h_{cs}}{C_{pa} \ G} \left(\frac{C_{pa} \ \mu}{K} \right)^{\frac{2}{3}} \qquad 2.52$$

Equating equations 2.51 and 2.52

$$h_{cs} = 0.61\, C_{pa}\, G \left(\frac{G}{a_v\, \phi\, \mu}\right)^{-0.41} \left(\frac{C_{pa}\, \mu}{K}\right)^{-\frac{2}{3}} \qquad 2.53$$

where

$$a_v = \frac{6\ (1-\varepsilon)}{d_e S_p}$$

s_p = sphericity = $\dfrac{\text{surface area of sphere}}{\text{surface area of particle}}$

ε = void fraction

d_e = effective particle diameter

Assuming $\phi = S_p$ and $\dfrac{C_{pa}\mu}{K} = 0.735$, equation 2.53 can be reduced to the form:

$$h_{cv} = a_v h_{cs} = 9.3679\, C_{pa} \left(\frac{1-\varepsilon}{d_e}\right)^{1.41} \left(\frac{\mu}{\phi}\right)^{0.41} G^{0.59} \qquad 2.54$$

The effective diameter of malt was calculated from the average bulk density and 1000 grain weight in the Sections 2.3 and 2.2 respectively.

For malt

$d_e = 4.07$ mm , $\varepsilon = 0.59$ (assumed) ,

$\phi = 0.90$ (assumed)

For barley

$d_e = 4.57$ mm (Bakker-Arkema et al.1971)

$\varepsilon = 0.51$ (assumed) $\phi = 0.90$ (assumed)

Substituting the values of C_{pa} and μ at $60^{o}C$, d_e, ε and ϕ in equation 2.54, the following equations for heat transfer coefficient were obtained:

For malt

$$h_{cv} = 82.25 \times 10^{3} G^{0.59} \tag{2.55}$$

For barley

$$h_{cv} = 89.83 \times 10^{3} G^{0.59} \tag{2.56}$$

(2) Experiments on a Malt Bed

The formulation of Schumann's equations with the underlying assumptions are derived by a comparatively simpler method in Appendix 2.1.

Schumann's equations for malt are:

$$\frac{\partial T_a}{\partial Y} = T_g - T_a \tag{2.57}$$

$$\frac{\partial T_g}{\partial Z} = T_a - T_g \tag{2.58}$$

where

$$Y = \frac{h_{cv} x}{G C_{pa}} \tag{2.59}$$

$$Z = \frac{h_{cv} t}{C_{pg} \rho_d} \tag{2.60}$$

with boundary conditions:

$$T_a\ (0,Z) = T_{ao}$$

$$T_g\ (Y,0) = T_{go}$$

The exact solution of Equations 2.57 and 2.58, as presented by Schumann, is:

$$\frac{T_a - T_{go}}{T_{ao} - T_{go}} = e^{-Y-Z} \sum_{n=o}^{\alpha} Z^n M_n\ (YZ) \qquad 2.61$$

$$\frac{T_g - T_{go}}{T_{ao} - T_{go}} = e^{-Y-Z} \sum_{n=1}^{\alpha} Z^n M_n\ (YZ) \qquad 2.62$$

where

$$M_n\ (YZ) = \frac{d^n\ M_o\ (YZ)}{d\ (YZ)^n}$$

$$M_o\ (YZ) = I_o\ (2\ \sqrt{YZ})$$

$$= 1 + YZ + \frac{(YZ)^2}{2!} + \frac{(YZ)^3}{3!} + \ldots.. \qquad 2.63$$

$I_o\ (2\ \sqrt{YZ})$ is a modified Bessel function of first kind and zeroth order.

The heat transfer coefficient was determined by comparing the experimentally determined results with these analytical solutions.

An insulated aluminium cylinder 15 cm diameter and 30 cm long, used as the sample container, was mounted on a rectangular box serving as a mixing chamber. The whole set was placed on an Avery balance. The schematic diagram of the experimental set up is shown in Fig. 2.14 and the experimental cylinder is shown in Fig. 2.16. Malt grain was used to fill the cylinder up to 24 cm. Shielded thermocouples were placed at 6 cm, 12 cm, and 18 cm to measure air temperature. In addition, shielded thermocouples were used to measure inlet and outlet temperatures.

Malt grains were dried to equilibrium moisture content with an air stream and then cooled to room temperature by placing the grains inside two thin plastic bags for at least 48 hours. A dummy insulated cylinder filled to the same depth of malt was placed on the rectabgular box and air at the temperature and relative humidity used to dry the original sample was blown up through the dummy malt grains. It took about two hours to stabilise the temperature and relative humidity of the air. After the heated air temperature and relative humidity had stabilized, the dummy container was quickly replaced with the experimental container and the air temperatures were recorded at one minute intervals on the data logger. The recording was continued for about 30 minutes . A total of nine runs were performed at a flow rate ranging from 0.35 to 0.62 $kg/m^2/s$ and air temperatures ranging from 50.8 to 70.8 ^oC.

The method to calculate heat transfer coefficient requires the comparison of the air temperature at different times and depths from the inlet. The theoretical curves for non-dimensional air temperature were plotted against the logarithm of Z for several values of Y on tracing paper. The experimental nondimensional air temperatures at a particular position were then plotted against the logarithm of time on separate paper and the tracing paper containing the theoretical curves was placed on it. The theoretical curves were shifted along the time axis of the experimental curves until the experimental curve lined up with one of the theoretical curves. The Y value of the theoretical curve that lines up with the experimental curve was used to calculate heat transfer coefficient from Equation 2.59. This procedure was repeated for each of the runs.

2.7.3 Results and Discussion

Calculated heat transfer coefficients are shown in Table 2.8. Fig. 2.17 shows the theoretical non-dimensional air temperatures for different values of Z and for values of Y ranging from 2 to 16. The comparisons between the experimental non-dimensional air temperatures and theoretical non-dimensional air temperatures are shown in Figs. 2.18 to 2.26, for the nine runs of experiments conducted. It is obvious from these figures that the agreement between the experimental and theoretical curves is good. The heat transfer coefficients appeared to be a function of mass flow rate of air and the following regression equation was developed:

$$h_{cv} = 49.32 \times 10^3 \ G^{0.6906} \qquad (r^2 = 0.90) \tag{2.64}$$

The regression line along with experimental data is shown in Fig. 2.27.

The heat transfer coefficients were determined under isomoisture conditions . To check the validity of the isomoisture condition the reading of the balance was checked during experimental runs. No noticeable change was observed in the balance reading. Changes of 2 g could be detected on the balance. This confirms that the error due to moisture transfer was negligible.

Comparison of Equations 2.55 and 2.64 shows that the heat transfer coefficient determined by the empirical equation gives an estimate about 1.66 times higher than the experimentally determined heat transfer coefficient. Also, Gamson, Thodos and Hougen (1943) reported that their estimate of heat transfer coefficient of a coal bed using the data of Furnas was 2.36 times higher than the experimentally determined value of Furnas. Nellist (1974) also observed that empirical equations give higher estimates of heat transfer coefficient.

Equation 2.55 considers surface film temperature whereas equation 2.64 considers mean temperature of the grain. In practice, the heat transfer resistance of the grains is not only on the surface of the grains but also inside the grain. This would explain the higher values of heat transfer coefficient predicted by equation 2.55.

The heat transfer coefficients of malt and barley determined by empirical equations are very close to each other. But the experimentally determined heat transfer coefficient of malt is about 1.8 times higher than that obtained by Boyce (1966) for barley. The regression lines for the heat transfer coefficients of barley, malt and rough rice are shown in Fig. 2.28. It is evident from Fig. 2.28 that the regression line of heat transfer coefficient of malt obtained from experimental data lies in the middle of the regression lines of malt and barley obtained by empirical equations and Boyce's equation for barley.

The determination of heat transfer coefficient by the empirical equation (Eqn. 2.55) requires an accurate determination of the effective diameter, sphericity and shape factor which are very difficult to achieve. For any empirical equation for forced convection applied to practical problems, Kreith (1973) has mentioned that the accuracy of a heat transfer coefficient predicted from any available equation or graph may be no better than 30 per cent.

Physically the high value of the heat transfer coefficient of malt in comparison with that obtained by Boyce for barley may be attributed to the following facts. Partial degradation of the endosperm and cell walls, and breakdown of hulls may be considered to increase the effective surface area of malt grain. Again the specific heat of malt was found to be higher than that of barley. Finally, the heat transfer coefficient of barley was determined from a thin layer isomoisture condition rather than a packed bed isomoisture condition. In order to determine the heat transfer coefficient, Boyce used an inverted funnel-like attachment terminating in a small insulated box, enclosing a thermocouple which could be closed at either end and was push fitted over the top of the shallow drying box. He placed grain which had been dried to the equilibrium moisture content of the drying air and then cooled in a sealed container to ambient temperature in the drying tray and placed the special funnel over it. Heated air at a known rate was then forced through it for a given time after which the assembly was removed and the top of the funnel closed with an insulated plug. The assembly was then inverted, the drying tray removed and the bottom of the insulated box was closed by an insulated plug. During this procedure the temperature inside the box was continuously recorded by the thermocouple and the highest reading after the box was closed was considered to be the grain temperature. It is apparent that there was some heat loss during the removal of the tray and closing the insulated box. The moisture content range for Boyce's work was very similar to the range for malt and this would therefore not account for the difference.

Chapter 3

THIN LAYER DRYING OF MALT

Thin layer drying equations and expressions for the drying parameters as a function of drying conditions are required for the mathematical modelling of the deep bed drying of malt. This chapter deals with:

(1) thin layer drying of malt under controlled conditions of temperature and relative humidity

(2) development of thin layer drying equations

(3) development of expressions for drying parameters.

3.1 Thin Layer Drying Equations

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

(1) the development of empirical equations

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

The theoretical approach concerns either the diffusion equation or the simultaneous heat and mass transfer equations. The semi-theoretical approach concerns approximated theoretical equations. 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. 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 provide some understanding of the transfer process.

Based on the differential equation for diffusion and making certain approximations, Lewis (1921) derived the following expression for drying under constant conditions.

$$\ln\left(\frac{M - M_e}{M_o - M_e}\right) = - kt \qquad 3.1$$

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, Hall and Rodriguez-Aris, 1958, Boyce, 1966, Kachru, Ojha and Kurup, 1971, and Watson and Bhargava, 1974) have proposed the following equation for wheat, rice, barley and shelled corn.

$$\frac{M - M_e}{M_o - M_e} = \exp\ (-kt) \qquad 3.2$$

The above equation was based on the assumption that all resistance to drying is at the outer layer of the kernel.

Page (cited by Hall, 1970, and Van Rest and Issacs, 1968), proposed the following empirical equation for shelled corn

$$\frac{M - M_e}{M_o - M_e} = \exp\ (kt^u) \qquad 3.3$$

Several investigators (White, Ross and Westerman, 1973, Matouk, 1976, Misra and Brooker, 1980, and White, Bridges, Loewer and Ross, 1981) have reported that the Page equation adequately predicts the thin layer drying of shelled corn and soybeans. Van Rest and Issacs (1968) investigated exposed layer drying rates of shelled corn, wheat and oats for a variety of conditions. They found that the basic logarithmic model proved moderately adequate for wheat, but it failed to provide adequate fit for corn. The Page equation described the experimental data better than the logarithmic model for each of the crops. They tested the following form of the equation

$$\frac{M - M_e}{M_o - M_e} = p - q \log t \qquad , \qquad 3.4$$

They found that this equation is more useful than the logarithmic model. Troeger and Hukill (1971) developed the following model for shelled corn

$$\frac{dM}{dt} = -k \ (M - M_e)^a \qquad 3.5$$

where

a = arbitrary constant.

They also observed that the use of three regions rather than a single region allows a good fit of the entire drying curve. Thompson, Peart and Foster (1968) developed the following second order differential equation for corn

$$t = A \ln (MR) + B \ (\ln \ (MR) \ )^2 \qquad 3.6$$

where

t = time in hours

A = -1.862 + 0.00488 T

B = 427.4 exp (-0.033 T)

T = temperature in ^{o}F

They found reasonable agreement with experimental results for the wide range of temperatures used.

Hussain, Chen and Clayton (1973) applied Luikov's equations to the drying of rough rice and found that the prediction agrees well with the experimental data. Fortes, Okos and Barret (1981) analysed wheat drying and rewetting by applying a model based on non-equilibrium thermodynamics. The proposed model predicted single kernel drying rates and centre temperatures in the dry bulb range between 26.7 and 87.8°C and moisture contents between 0.1 and 0.35 dry basis. Fortes and Okos (1981) developed a set of transport equations incorporating both the mechanistic and non-equilibrium thermodynamic approaches to heat and mass transfer in porous media. A comparison between the non-equilibrium thermodynamic equations and those obtained from the mechanistic viewpoint led to the evaluation of the phenomenological coefficients. They found the model gave good predictions of drying and average kernel temperature in a broad range of drying conditions (26.7 to 150°C) for corn.

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 satisfactory results. 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 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 with 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. Wang and Singh (1978) applied four equations for single layer drying of rough rice. These models are the single exponential equation, diffusion equation for a sphere, Page equation and Thompson's quadratic equation. They observed that the diffusion model gave the worst fit and Thompson's equation was found to be the best. Steffe and Singh (1980) have applied the mathematics of diffusion for rough rice. They considered rough rice as three concentric shells - endosperm, bran and hull. Good agreement was found with experimental observations.

Sharaf - Eldeen, Hamdy and Keener (1979) developed a two term exponential equation in the following form

$$\frac{M - M_e}{M_o - M_e} = A \exp(-kt) + (1 - A) \exp(-Bkt) \qquad 3.7$$

They observed that the two term exponential model adequately describes the drying behaviour of fully exposed shelled corn, rough rice and soybeans. They also observed that the Page equation gives a better description than the basic logarithmic model. Sharaf - Eldeen, Hamdy and Blaisdell (1979) found that a two term exponential model adequately describes the drying behaviour of ear corn and shelled corn over the entire drying period. The logarithmic drying model and its modified form fail to describe the drying behaviour for ear corn and shelled corn throughout the entire drying period.

Sharma, Kunze and Tolley (1982) developed a two term exponential model for rough rice and explained rough rice drying more logically by considering the drying equation to be a two compartment model. This two-compartment model is similar to Nellist's two term exponential model in all respects.

3.1.1 Theory

The physical mechanism of drying in capillary porous products such as cereal grains is quite complicated and it 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.

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11}M + \nabla^2 K_{12}T_g + \nabla^2 K_{13}P \qquad 3.8$$

$$\frac{\partial T_g}{\partial t} = \nabla^2 K_{21}M + \nabla^2 K_{22}T_g + \nabla^2 K_{23}P \qquad 3.9$$

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31}M + \nabla^2 K_{32}T_g + \nabla^2 K_{33}P \qquad 3.10$$

The moisture flow due to a total pressure gradient is not significant in the temperature 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

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11}M + \nabla^2 K_{12}T_g \qquad 3.11$$

$$\frac{\partial T_g}{\partial t} = \nabla^2 K_{21}M + \nabla^2 K_{22}T_g \qquad 3.12$$

The system of equations 3.11 and 3.12 is the most general system of equations. It is valid not only for drying processes but also for any type of moisture transfer.

Thermal diffusion is negligible for cereal grains and may be assumed to be zero. Again the contribution of $\nabla^2 K_{21}M$ to $\frac{\partial T_g}{\partial t}$ is also negligible. Therefore, equations 3.11 and 3.12 become

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11}M \qquad 3.13$$

$$\frac{\partial T_g}{\partial t} = \nabla^2 K_{22}T_g \qquad 3.14$$

For cereal grains the thermal diffusivity is large compared to moisture diffusivity. Neglecting the temperature gradient leads to the following general equation of diffusion based on Fick's law.

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11}M \qquad 3.15$$

The diffusion equation 3.15 can be expressed in terms of the nomenclature of vector analysis as

$$\frac{\partial M}{\partial t} = \text{div}\ (D_v \text{ grad } M) \qquad 3.16$$

where the transfer coefficient K_{11} is called the diffusion coefficient. Sherwood (1931) and Newman (1931) suggested that the physical mechanism of drying is diffusion as described by Eqn. 3.16 and solved for different shapes of solids.

The solutions of the diffusion equation (3.16) in cartesian, spherical and cylindrical coordinates have been discussed in detail by Crank (1979). Thus, the solution for a sphere is

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\Pi^2} \sum_{n=1}^{\alpha} \frac{1}{n^2} \exp\left(- n^2 \frac{D_v \Pi^2}{r^2} t\right) \qquad 3.17$$

and the solution for a plane sheet of half thickness, z is

$$\frac{M - M_e}{M_o - M_e} = \frac{8}{\Pi^2} \sum_{n=1}^{\alpha} \frac{1}{(2n-1)^2} \exp\left(-(2n-1)^2 \frac{D_v \Pi^2}{z^2} t\right) \qquad 3.18$$

This equation converges rapidly because of the omission of alternate terms. If only the first term of either Eqn. 3.17 or 3.18 is considered, each of these equations can be approximated to the form

$$\frac{M - M_e}{M_o - M_e} = a \exp\ (-kt) \qquad 3.19$$

when a = 1, this equation reduces to the equation 3.2.

Green malt contains high moisture content and the aleurone layer and cell walls are degraded (Pomeranz, 1972). In addition, the rate of drying is also influenced by the previous history of steeping and germination. It is also quite reasonable to assume that the thermal diffusivity is large compared to the moisture diffusivity for malt. Considering all these factors, it was proposed to develop the thin layer drying equation in the following forms

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt) \qquad 3.20$$

$$M = A \exp(-k_1 t) + B \exp(-k_2 t) + M_e \qquad 3.21$$

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt^u) \qquad 3.22$$

The first two equations are approximated diffusion equations and the third one is an empirical equation (Page equation).

Repeated solution of the thin layer drying equation is the whole basis of deep bed drying simulation. The complicated equations might give greater accuracy but will take much more computing time. A compromise should be made between the degree of accuracy required and computing time. Thus, the first choice always should be the simpler equation if the prediction is reasonably good.

3.2 Drying Parameters

Moisture content at any time can be predicted by any of the proposed equations if the drying parameters such as drying constant and dynamic equilibrium moisture content are known. Thus, an accurate determination of the drying parameters is necessary for better prediction of the equations.

3.2.1 Drying Constant

O'Callaghan (1954) observed that drying constant is independent of the relative humidity of drying air but is dependent on air temperature for wheat in the temperature range, 80 - 150°F. He proposed an equation for drying constant in the form

$$k = A \exp (BT) \qquad 3.23$$

Subsequently O'Callaghan, Menzies and Bailey (1971) modified it into the form proposed by Henderson and Pabis (1961). Henderson and Pabis proposed that the drying constant could be expressed by an Arrhenius type equation of the form

$$k = d \exp (-^{f}/T) \qquad 3.24$$

They verified the relationship with experimental data on wheat and maize. Boyce (1966) has shown that the drying constant of barley is highly correlated to air temperature in the form proposed by Henderson and Pabis. Nellist (1974) observed that inclusion of the initial moisture content and air humidity in the form

$$k = a \exp (b\, T_a + cH + dM_o) \ . \qquad 3.25$$

improves the fit for the drying of ryegrass seeds but these factors are not as important as the air temperature. Allen (1960) and Westerman, White and Ross (1973) observed that air temperature and relative humidity affect the drying constant of paddy rice and shelled corn. Greig (1971) has shown that the drying constant of barley is highly correlated to the difference between air temperature and the dew point temperature of the air in the temperature range, ambient to 60°C.

Moisture is assumed to be contained in small grains as adsorbed moisture, i.e. held in the system by molecular attraction, being more closely linked with adsorbing substance and therefore being held more firmly. The general term sorption is used to denote such interaction. The term adsorption and desorption are used specially to denote the process of taking up or giving off of moisture. The energy required to desorb moisture can be considered analogous to the energy of chemical reaction and an Arrhenius type equation would apply. This empirical equation is

$$k = a \exp \left(-b/(273.15 + T_a)\right) \tag{3.26}$$

The temperature in equation 3.26 actually refers to grain temperature. Since the temperature difference is not significant after a short transient period and the measurement of drying air temperature is relatively simple, drying air temperature has been used in the thin layer determination of k.

3.2.2 Equilibrium Moisture Content

The equilibrium moisture content of a cereal grain is defined as the moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time. The equilibrium moisture content is dependent upon the relative humidity and temperature conditions of the environment as well as on the species, variety and maturity of the grain. The concept of dynamic equilibrium moisture content was introduced by McEwen, Simmonds and Ward (1954). The concept of dynamic equilibrium moisture content is a hypothetical one and has been doubted by Chu and Hustrulid (1968). However, they have suggested that it may represent some average of surface moisture content over a certain period. Dynamic equilibrium moisture content is obtained by the best fitting of the thin layer drying equations to experimental data, whereas static equilibrium moisture content is obtained after a long term exposure to a constant admosphere. McEwen, Simmonds and Ward further suggested that dynamic and static equilibrium moisture content should be used for drying and storage design respectively. Allen (1960) also mentioned that the dynamic equilibrium moisture content is a logical choice for the grain drying process, but the static equilibrium moisture content is more relevant for storage problems.

Smith (1947) has shown that the final portion of the water isotherms of biological materials such as starch and cellulose are described by the following equation

$$M_{sw} = M_b - b\ln(1-rh) \qquad 3.27$$

where M_b is the bound moisture content and b is a constant. He has shown that Eqn. 3.27 fails to take into account the progressive enlargement of the effective sorbing surface of the gel which accompanies swelling when moisture content is expressed on a dry basis. He also demonstrated that the plot of moisture content (w.b.) vs. $-\ln(1-rh)$ is linear between relative humidities of 0.5 to 0.95 for cellulose. Becker and Sallans (1956) have shown that the Smith equation is applicable for desorption isotherms of wheat for the relative humidity range 0.5 to 0.95, when moisture content is expressed on a wet basis.

Henderson (1952) proposed the following semi-empirical model for the equilibrium moisture content of cereal grains

$$1 - rh = \exp(-cTM_{sd}^{n}) \qquad 3.28$$

Henderson's equation, in the form described above, has been found inadequate for cereal grains (Pichler, 1957, and Brooker et al. 1974). Day and Nelson (1965) modified Henderson's equation to describe wheat

$$1 - rh = \exp\ (-aM_{sd}^{b}) \qquad 3.29$$

where a and b are functions of temperature.

Strohman and Yoeger (1967) proposed the following equation to represent the equilibrium relative humidity of corn at various moisture content

$$rh = \exp\ (a \exp\ (bM_{sd})\ \ln P_s + c \exp\ (dM_{sd})\ ) \qquad 3.30$$

This equation was valid over the whole range of moisture content, relative humidity and temperatures.

Chung and Pfost (1967) developed the following equilibrium moisture content equation based on potential theory and a simplified equation of state

$$\ln\ (rh) = \frac{-A}{(R_o\ T_{ab})} \exp\ (-B\ M_{sd}) \qquad 3.31$$

This equation assumes that the free energy function or useful work decreases exponentially with the increasing thickness of adsorbed layer and the adsorbed layer is directly related to moisture content. The Chung and Pfost equation fits grain equilibrium moisture content data well over the 20 to 90% relative humidity range. Gustafson and Hall (1974) have shown that the constants A and B are temperature dependent for shelled corn.

O'Callaghan (1954) proposed the dynamic equilibrium moisture content equation for wheat in the following form

$$M_{dd} = f + g \frac{H^{\frac{1}{2}}}{T^{2}} \qquad 3.32$$

This equation cannot predict equilibrium moisture content at extremely high relative humidities. Nellist (1974) used the modified Smith equation for dynamic equilibrium moisture content of ryegrass seeds in the following form

$$M_{dd} = a - b \ln T_a - c \ln (1-rh) \qquad 3.33$$

This equation gives weaker correlations than that given by the Smith equation, but this modification is justified for the inclusion of the temperature effect.

Pixton and Howe (1983) examined the suitability of the following equations for cereals and other products

(1) BET Equation (Brunaur, Emmet and Teller Equation)
(2) Iglesias and Chirife Equation
(3) Harkins and Jura Equation
(4) Smith Equation
(5) Chung and Pfost Equation
(6) Halsey Equation
(7) Henderson Equation.

They observed that the Chung and Pfost formula gives an excellent fit to the observed data relating moisture content and equilibrium relative humidity data of tapioca starch and can be used to fit the relationship using only three experimental points between 25 and 70% relative humidity. They also found that the Chung and Pfost equation is adequate for representing the moisture content/equilibrium relative humidity relationship for cereal grains between 20 and 90% relative humidity and the lines for cereal grains at different temperatures are reasonably parallel. None of the other transformations were found suitable for cereal grains, but the Henderson equation was suitable for flour. They maintained that "only the Chung and Pfost transformation can be used for cereals".

Tuerlinckx, Berckmans and Goedseels (1982) determined the equilibrium moisture content of malt, variety Carina, by using saturated salt solutions for the temperature range 15 - 50°C and drying in thin layers for 4 to 5 days for temperatures of 70°C and 90°C. They applied the Henderson equation, modified Henderson equation, Day and Nelson equation, and Chung Pfost equation to the data of malt. They observed that the residual sum of the squares for fitting the Chung Pfost equation was lowest but still rather high. They developed an empirical equation for equilibrium moisture content of malt into the form of

$$M_{sd} = \frac{C_3}{T_a} \exp\left[- \frac{C_1}{T_a} \exp\left(C_2\ rh\right)\right] + C_4\left(\exp\left[(0.3)\ C_2 \exp(C_2\ rh)\right]\right) \mathrm{Arctan} \left[\exp\left(C_5\ rh\right) -1\right] \qquad 3.14$$

This equation is for static equilibrium moisture content and their determination of moisture content does not conform with the recommended method of the Institute of Brewing. However, their experimental results show that the prominent effect of temperature on equilibrium moisture content is at low relative humidity for temperature variations of 15 - 50°C. Their results are not in good agreement with that of Pixton and Henderson (1981), especially in this range.

3.3 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 experimental thin layer drying equipment available in the department of Agricultural Engineering has been described in detail by Greig (1971). For the purpose of the present work it was necessary to adapt this apparatus for thin layer drying of malt. Malt is dried at high temperatures (50 - 90°C) for both rapid drying and structural changes in the grains. To meet this requirement a new drying chamber was designed and constructed.

The schematic diagram of the apparatus is shown in Fig. 3.1. To dry malt under controlled conditions of air temperature, 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 raschig rings, C. At the top of the tower water was sprayed at the required dew point temperature of the air. At the exit of the air from the tower dry bulb and wet bulb temperature were measured. The air passing through the packed tower was approximately saturated and was heated to the required temperature by an electric heater, D. The air was then passed through the tray, G, containing a malt layer of one grain thickness via gauze, E, and honeycomb flow straightener, F. The tray was suspended from a balance, H, in an oil bath. The balance was capable of producing an electric signal in proportion to the weight suspended from the balance. The apparatus is shown in Figs. 3.2 to 3.4.

3.3.1 Moisturising Column

The moisturising column consists of a vertical glass tower packed with raschig rings. The desired air condition may be defined by dew point temperature and dry bulb temperature. The desired dew point temperature of the air was obtained by passing the air through the packed tower from the bottom and water was allowed to pass down the tower in the opposite direction to the air so that the air was humidified. The desired dew point temperature of the air was obtained by controlling the temperature of the water being passed down from the top of the tower. The water was circulated to the tower from a 70 gal. insulated tank and the water temperature was maintained by a thyristor activated control unit. A refrigeration unit whose evaporator was located in the tank was used to cool the water, so that dew point temperatures below the ambient temperature could be obtained. This unit works in opposition to the heating coil in the tank, the latter maintaining the set dew point temperature.

3.3.2 Drying Chamber

The drying chamber consists of an inner cylinder of 230 mm diameter suspended in an oil both from an electric balance and supporting the tray containing the sample to be dried. The outer cylinder causes the air leaving the grain to flow down through an annular space between the two cylinders. This air was further ducted through the annular space between the pipe and a polythene tube. This arrangement ensures minimum heat loss from the chamber and a portion of the upstream piping. The rest of the pipe was insulated. As the plastic frame tray was found to melt down at high temperature, the inner cylinder and the tray frame were made of aluminium to make the system lighter and suitable for high temperature drying. The total weight of the inner cylinder and the tray with nylon net was approximately 935 g. The balance had a total weight capacity of 1000 g with 900 g tare capacity. To increase the tare capacity of the balance, the top of the balance was removed, giving a tare capacity of 1400 g.

3.3.3 Instrumentation and Accuracy

A number of checks were made to determine the accuracy of the apparatus. These will be discussed under the following headings: the continuous weighing system, temperature, air flow and moisture content.

The Continuous Weighing System

A tray containing a range of weights was suspended from the balance and heated air was passed through the tray. The outputs of the balance were recorded by the data logger. The weight change and the recorded output in mV was found to be linear with a standard error of 0.235 g. Unfortunately, during the first nine experiments some random fluctuation in the balance reading was observed due to zero shifting of the balance. The balance was checked and repaired. The accuracy of the balance was again tested (Table 3.1). Weight change and recorded output in mV was found to be linear. The standard error of weight change was found to be 0.015 g. To check the zero shift, a constant weight was suspended from the balance and the balance output was recorded at five minute intervals for about 20 hours. Very little change in the balance reading was observed (Fig. 3.5).

Temperature

An IMP data logger was used and the accuracy of the analogue to digital converters of the data logger is ± 0.05% f.s.d. The f.s.d. used was 10 mV for all the recording on the data logger with an error of ± 0.005 mV, which is equivalent to 0.12°C when using Copper/Constantan thermocouples. To check the suitability of the data logger to record thermocouple outputs in mV the following test was conducted.

The hot junction of a thermocouple and calibration thermometer (graduated $^1/10$ of 1°C) were placed in well stirred water bath. Thermocouple outputs were simultaneously displayed by the data logger and a digital voltmeter and at the same time the thermometer reading was noted. The temperature of the water was lowered gradually and the whole procedure was repeated. The millivolts were converted into degrees centigrade by interpolation using standard data. The results are shown in Table 3.2. The standard error of the data logger and digital voltmeter compared with the thermometer were found to be 0.323°C and 0.542°C respectively. The standard error of the data logger compared with the digital voltmeter was found to be 0.127°C. All the temperature outputs were recorded in millivolts and converted into degrees centigrade by fitting a spline to the British Standard data (BS.4937: Part 5: 1974).

Air Flow

Air flow was measured by an orifice plate and an inclined manometer. An orifice plate of 2 inches diameter was set in the air supply pipe of 4 inches diameter. The flow rate was calculated according to the British Standard (1042: Part 1: 1964). Several researchers (Sharaf - Eldeen *et al.* 1981, and White *et al.* 1981) have reported that the drying rate becomes independent of air velocity if the velocity exceeds 0.25 m/sec. The velocity was maintained constant for each thin layer experiment between 0.250 m/sec and 0.275 m/sec. The accuracy of the measurement of pressure drop across the orifice was ± 0.5 mm of water.

Moisture Content

All moisture contents were determined by the method recommended by the Institute of Brewing (Appendix 3.1).

3.4 Procedure

Thin layer drying experiments were conducted under controlled conditions of air temperature and relative humidity covering the whole range of drying operations. Some of them were replicated to check the degree of experimental error.

Green malt used in this study was sent from Grantham and it was collected within 5 hours. The collected sample had a moisture content between 60% (d.b.) and 80% (d.b.) Samples were sent in sealed containers and were stored in the sealed container in a domestic refrigerator. Each lot was used for thin layer drying experiments within three days of arrival.

All thin layer experiments were carried out with the variety Triumph. Before starting any experiment the instrumentation system was checked carefully and the whole of the apparatus was operated with a dummy grain tray for at least two hours to stabilize the air temperature, relative humidity and air flow rate. When the whole system was stabilized, one randomly selected sample of 100 g of malt was placed evenly on the drying tray and another 100 g of randomly selected sample was placed in three previously weighed petri dishes for moisture content determination. The dummy tray was quickly replaced by the sample tray and the data logger was switched on to record air temperature below the grain tray, dry bulb and wet bulb temperature at the top of the tower, water temperature in the tank and the change in weight of the experimental sample. The data logger was programmed to record the change in weight at 1 minute intervals and temperatures at 5 minute intervals for drying air temperature of approximately 50°C and above. For drying air temperatures below 50°C, the data logger was programmed to record the weight change at 5 minute intervals and temperature at 10 minute intervals. The results were recorded on a strip printer. The experiments were continued for 3 - 10 hours for high temperature (> 50°C) and 20 hours for low temperatures (> 50°C). At the completion of each thin layer drying experiment, final moisture content was determined.

3.5 Data Processing

The temperatures were recorded in mV using copper/constantan thermocouples and the change in weight in the balance was also recorded in mV. The data on air temperature just below the tray containing the grain, the dry bulb and wet bulb temperatures at the top of the tower, and the change in weight in the balance were recorded by the data logger on the strip printer. The data was converted into the following forms.

(1) The balance reading was converted into moisture content (d.b.)

(2) The temperature data in mV was converted into degrees centigrade

(3) Relative humidity was calculated from the air temperature below the grain tray and the dew point temperature at the exit from the saturation column.

A FORTRAN program was written to convert the data recorded in mV into temperature, relative humidity and moisture content. Flow chart and the program with a typical run of experiment are given in Appendix 3.2.

Calculation of Moisture Content

The weight on the balance at any time can be calculated from the following relationship

$$W_t = W_o - \frac{(W_o - W_f)}{(Y_o - Y_f)} (Y_o - Y_t) \qquad 3.35$$

where

W_t = weight at time, t

W_o = initial weight

W_f = final weight

Y_t = balance reading at time, t

Y_o = initial balance reading

Y_f = final balance reading

Dry weight of the sample was assumed constant and was determined from initial weight of the sample and initial moisture content (d.b.). Moisture content at any time of the experimental run was calculated from the relationship

$$M_t = \frac{(W_o - W_d) - \frac{W_o - W_f}{Y_o - Y_f} (Y_o - Y_t)}{W_d} \qquad 3.36$$

where

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

W_d = weight of dry matter of the sample

Calculation of Relative Humidity

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

$$P_{ws} = 6894.76\ F \exp\left[\frac{P_o + P_1 T_{db} + P_2 T_{db}^2 + P_3 T_{db}^3 + P_4 T_{db}^4}{P_5 T_{db} - P_6 T_{db}^2}\right] \quad 3.37$$

$$P_w = 6894.76\ F \exp\left[\frac{P_o + P_1 T_{dp} + P_2 T_{dp}^2 + P_3 T_{dp}^3 + P_4 T_{dp}^4}{P_5 T_{dp} - P_6 T_{dp}^2}\right] \quad 3.38$$

$$RH = \frac{P_w}{P_{ws}} \quad 3.39$$

where

P_{ws} = saturated 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 = -0.274055×10^5

P_1 = 0.541894×10^2

P_2 = -0.451370×10^{-1}

P_3 = 0.215321×10^{-4}

P_4 = -0.462027×10^{-8}

P_5 = 0.241613×10

P_6 = 0.121547×10^{-2}

F = 0.320618×10^4

3.6 Data Analysis

The processed data was analysed in order to

(1) fit the proposed thin layer drying equations to the experimental data to determine the constants

(2) determine relationships between the drying constants and drying air temperature. This is equivalent to correlating with grain temperature apart from the short period when the grain is heated

(3) define dynamic equilibrium moisture content as a function of air temperature and relative humidity.

3.6.1 Curve Fitting

The proposed equations in section 3.1.1 were fitted to the experimental data by the Modified Gauss - Newton Method proposed by Gill and Murray (1978). They developed a comprehensive modified Gauss - Newton algorithm for finding an unconstrained minimum of a sum of squares of m non-linear functions in n variables ($m \geqslant n$) whose first derivatives are known.

Fortunately, the modified Gauss - Newton algorithm for finding the unconstrained minimum of a sum of squares of m non-linear functions in n variables ($m \geqslant n$) programmed in FORTRAN was available as the NAG library subroutine E04GDF. The routine is applicable to problems of the form

$$\text{Minimize } F(\underline{X}) = \sum_{i=1}^{m} \left[f_i(\underline{X}) \right]^2$$

where

$f_i(\underline{X})$ = residuals

$\underline{X} = (x_1, x_2 .. x_n)^T$

A subroutine must be supplied by the user to calculate the values of $f_i(\underline{X})$ and their first derivatives, $\frac{\partial f_i}{\partial x_i}$ at any point $\underline{X}$.

From a starting point $\underline{X}$ supplied by the user, the routine generates a sequence of points $\underline{X}^{(2)}$, $\underline{X}^{(3)}$ ....., which is intended to converge to a local minimum of $F(\underline{X})$. The sequence of points is given by

$$\underline{X}^{(k+1)} = \underline{X}^{(k)} + \alpha^{(k)} \underline{P}^{(k)} \qquad 3.41$$

where the vector, $\underline{P}^{(k)}$ is a direction of search, and the vector, $\alpha^{(k)}$ is chosen such that $F(\underline{X}^{(k)} + \alpha^{(k)} \underline{P}^{(k)})$ is approximately a minimum with respect of $\alpha^{(k)}$. The vector, $\underline{P}^{(k)}$ used depends upon the reduction in the sum of the squares obtained during the last iteration. If the sum of the squares was sufficiently reduced then $\underline{P}^{(k)}$ is the Gauss - Newton direction; otherwise finite difference estimates of the second derivatives of $f_i(\underline{X})$ are taken into account. This method has been designed to ensure that steady progress is made whatever the starting point, and to have the rapid ultimate convergence of Newton's Method.

A FORTRAN program incorporating NAG library subroutine (EO4GDF) was written to evaluate the constants in the proposed thin layer drying equations. The inputs to the program were moisture content (d.b.) and time, and the starting values of the constants were supplied. Flow chart and programmes with a typical example are given in Appendix 3.3. Another FORTRAN program, incorporating a graphics package, was written to plot the predicted curve and experimental points on one graph for each of the proposed equations for thin layer drying. The program is given in Appendix 3.4.

Standard Error of Estimate

The standard error of estimate is a measure of the average discrepancy between the experimental points and the fitted curve. It measures goodness of fit in the unit of dependent variable. To compare the goodness of fit of each of equations 3.20 to 3.22, the standard error of estimate σ, (%, d.b.) was calculated from the following equation

$$\sigma = \sqrt{\frac{\Sigma\,(M_{pred} - M_{obs})^2}{\text{No. of date points}}} \qquad 3.42$$

where

M_{pred} = predicted moisture content

M_{obs} = observed moisture content

3.7 Results and Discussion

In the first set of experiments, 9 experimental runs were conducted. There was random fluctuation in the balance reading due to zero shift and buffeting effect of the air flow. Only the single exponential equation was fitted to the experimental data. Summarised results of the first 9 experiments are shown in Table 3.3. The second set of experiments consisted of 22 experimental runs. The proposed equations were fitted to the experimental data. The summarised results of the second set of experiments are shown in Tables 3.4 to 3.6. The results of all the thin layer drying experiments are discussed under the headings of thin layer drying equations, drying constant and dynamic equilibrium moisture content.

3.7.1 Thin Layer Drying Equations

The single exponential equation was fitted to the first set of 9 experiments by the method proposed in section 3.6.1. Although the standard error of estimate of fitting the equation to the data was high (mean standard deviation = 1.22% (d.b.)), the overall fitting of the equation was good. An example of the overall fitting of the equation is presented in Fig. 3.6. This high standard error of estimate may be attributed mainly to the fact that the zero of the balance was shifting randomly after a certain time for short periods and later returning to the original position. The fact was confirmed by operating the balance without any load. The fitting of the single exponential equation to this set of data suggested that it may be adequate to describe the thin layer drying of malt.

The problem with the zero shifting was sorted out (see section 3.3.3) and the second set of 22 experimental runs were conducted covering the whole range of drying conditions normally encountered in the malting industry. The single exponential equation was fitted to 20 of the sets of experimental data. The standard error of estimate was considerably lower (mean value of standard error = 0.61% (d.b.). Two experimental runs were abandoned because the period of the runs was too short to give the proper shape of the drying curve. The Page equation was fitted to 17 experimental runs and the fitting was better than that of the single exponential equation. The mean standard error of estimate was 0.46% (d.b.). The double exponential equation was fitted to 8 experimental runs and the best fitting was obtained by the double exponential equation with a mean standard error of estimate of 0.30% (d.b.). The fitted curves and experimental points for three experimental runs at three positions of the experimental range are shown in Figs. 3.7 to 3.10. The results of experimental runs 28 and 31 in Tables 3.4 to 3.6 and in Figs. 3.9 and 3.10 illustrate the good agreement between replicate experiments. Dynamic equilibrium moisture contents for the single exponential equation and the Page equation for high temperature drying were higher than final moisture content (Figs. 3.9 and 3.10), but the dynamic equilibrium moisture content for the double exponential equation is in good agreement with final moisture content. It is worth noting that the overall fitting of the equations was good.

The double exponential equation could not be fitted to all experimental runs. The program failed to converge to all the experimental runs mainly due to the fact that the program finds the local unconstrained minimum. In the case of fitting the double exponential equation there was more than one minimum and the starting values caused convergence to a minimum which is physically unrealistic but mathematically possible.

The double exponential equation always gave the best fit but the drying constants did not show consistent effect of temperature and the proportion of the two components was found to vary randomly (Table 3.6). Because of this inconsistency and the partial failure of the program to converge to the actual minimum, no further attempt was made to fit the double exponential equation.

The resistance to the drying of malt may be explained in terms of structural changes of malted barley as follows;

It has been observed by Pomeranz (1972) that

(1) The surface of aleurone cells in steeped barley is highly pitted.

(2) The walls of the aleurone cells are progressively degraded during malting and kilning.

(3) The cell walls in the centre of the starchy endosperm of malted barley break down partially.

(4) In the central endosperm of kilned barley malt, the cell wall dissolution is extensive and is accompanied by mechanical breakdown of the large starch grannules.

It has also been reported by McLeod (1967) that

(1) Pericarp-testa is semi-permiable to the passage of water and the resistance to moisture transfer into and out of the corn is abolished if pericarp-testa is removed.

(2) During germination the root sheath breaks pericarp-testa and protrudes from the base of the corn.

From this experimental evidence, it is logical to assume that the resistance to the drying is mainly in the pericarp-testa and partially in the starchy endosperm. The resistance offered by pericarp-testa and starchy endosperm is influenced by the steeping and germination of malted barley. The experimental evidence indicates that the main resistance to drying of malt is in the pericarp-testa and this is confirmed by the fact that the single exponential equation adequately fits the experimental data of malt. The Page equation gives a slightly better fit than that of the single exponential equation. These two equations were selected for the deep bed drying simulation of malt.

3.7.2 Drying Constant

The drying constant of malt was found to be function of drying air temperature and the following Arrhenius type equation was fitted to the experimental data on drying constant.

$$k = a \exp(-b/(273.15 + T_a)) \qquad 3.43$$

Although several researchers (Boyce, 1966, Becker and Sallans, 1955, and Pabis and Henderson, 1962) have discussed the importance of correlating drying constant to the grain temperature, the measurement of the malt temperature is extremely difficult during thin layer drying. However, Pabis and Henderson (1962) have shown that grain comes to thermal equilibrium with drying air temperature very rapidly (3 - 4 min.). It is relatively simple to measure air temperature and in these experiments it can be considered equal to grain temperature.

The following equation for drying constant was obtained by correlating the drying constants of the first set of experiments to drying air temperature

$$k = 9.5294 \times 10^{6} \exp\left(\frac{-6725.02}{273.15 + T_a}\right) \quad (\text{min}^{-1}) \qquad 3.44$$

$$(r^2 = 0.98)$$

The following equations were developed for the drying constants for the second set of experiments

(1) The equation of drying constant for the single exponential equation is given by

$$k = 1.196 \times 10^{7} \exp\left(\frac{-6819.52}{273.15 + T_a}\right) \quad (\text{min}^{-1}) \qquad 3.45$$

$$(r^2 = 0.96)$$

(2) The equation for drying constant for the Page equation is given by

$$k = 1.794 \times 10^{9} \exp\left(\frac{-8473.63}{273.15 + T_a}\right) \quad (\text{min}^{-1}) \qquad 3.46$$

$$(r^2 = 0.95)$$

The exponent u of the Page equation was found to be a function of air temperature and relative humidity. The following equation of the exponent u was developed

$$u = 1.8258 - 0.0115\ T_a - 0.006487\ (RH) \qquad 3.47$$

$$(r^2 = 0.71)$$

The predicted and experimental drying constants are shown in Figs. 3.11 to 3.13. Comparison of Eqn. 3.44 and 3.45 shows that there is very little difference between the two sets of experiments (Fig. 3.14). This confirms that the zero error on the continuous balance was random and/or relatively small. It also gives an extensive check on the reproducibility of the work.

Comparison of the drying constants of barley and malt is shown in Fig. 3.14. The drying constant of barley below 52°C is slightly higher than that of malt and above 52°C the drying constant of malt increases rapidly with increase in temperature. This might be explained as follows.

Below 52°C the chemical changes and internal damage to the malt kernel are not the dominant factors and the size of the malt is higher than that of barley. Since k is inversely proportional to the square of the characteristic dimension, the smaller grains (barley) dry faster than the malt. Above 52°C the chemical changes and internal damage to the malt kernel progressively increases and decreases the drying resistance. The difference below 52°C is very small and the difference in drying constant increases progressively with temperature due to progressively higher structural changes in the malted barley.

3.7.3 Dynamic Equilibrium Moisture Content

Smith (1947) has suggested that equilibrium moisture content expressed on a wet basis provides an approximate correction to the isotherm equations for shrinking materials. Becker and Sallans (1956) have demonstrated that the equilibrium moisture content for wheat on a wet basis is a linear function of -ln (1-rh) between relative humidity 0.50 to 0.95. Again the derivation of the Chung and Pfost equation assumes that thickness of adsorbed layer is directly related to the moisture content on a dry basis which is only valid for non-shrinking materials. For shrinking materials it may be better to relate the thickness of the adsorbed layer to the moisture content on a wet basis. To provide an approximate correction for shrinking and include the effect of temperature, the dynamic equilibrium moisture content of malt on a wet basis was expressed as a function of temperature and relative humidity.

The modified Smith equation proposed by Nellist (1974), and the Chung and Pfost equation (1967) were fitted to the dynamic equilibrium moisture content data of the second set of experiments obtained by fitting the single exponential equation and Page equation. The values of dynamic equilibrium moisture content given by the fits of the single exponential equation and the Page equation are plotted in Figs. 3.15 and 3.16 respectively. Since the first set of experiments were conducted for a narrow band of relative humidity and the balance reading caused higher values of standard error, no attempt was made to fit these equations for dynamic equilibrium moisture content.

The following equations were obtained by fitting the modified Smith equation

(1) For the data obtained from the fit of the single exponential equation

$$M_{dw} = 5.87 - 0.0086\ T_a - 5.349 \ln (1-rh) \qquad 3.48$$

$$(r^2 = 0.88)$$

(2) For the data obtained from the fit of the Page equation

$$M_{dw} = 9.80 - 0.0609\ T_a - 3.374 \ln (1-rh) \qquad 3.49$$

$$(r^2 = 0.96)$$

The fitting of equations of this form was found to be less effective when the moisture content was expressed on a dry basis. The equations for the dynamic equilibrium moisture content show a shift in equilibrium moisture content due to temperature in the direction normally observed, but the effect of temperature is not significant in Eqn. 3.48. When the static equilibrium moisture content of malt data from the report of Pixton and Henderson (1981) was fitted to the modified Smith equation, an absence of temperature effect similar to that of Eqn. 3.48 was observed (Fig. 3.17). Nellist (1974) observed that the effect of temperature on the dynamic equilibrium moisture content, derived from the fitting of the diffusion equation for a plane layer to the data for ryegrass seeds, variety Sabel, is not significant.

The following equations were obtained by fitting the Chung and Pfost equations

(1) For the data obtained from the fit of single exponential equation

$$\ln (rh) = \left[\frac{-37357.91}{R_o (273.15 + T_a)} \right] \exp (-0.2999 M_{dw}) \qquad 3.50$$

$$(r^2 = 0.84)$$

(2) For the data obtained from the fit of the Page equation

$$\ln (rh) = \left[\frac{-49891.20}{R_o (273.15 + T_a} \right] \exp (-0.3320 M_{dw}) \qquad 3.51$$

$$(r^2 = 0.94)$$

Both the Eqns. 3.50 and 3.51 show an absence of temperature effect similar to Eqn. 3.48. An examination of the plots of the logarithm of the change in free energy vs. moisture content of the isotherms for corn (Chung and Pfost, 1967) reveals that these plots are almost parallel to one another. This suggests that the Chung and Pfost equation might be modified in the following form to include a further temperature effect

$$M_{dw} = a - b\, T_{ab} - c \ln \left[-R_o\, T_{ab} (\ln (rh) \right] \qquad 3.52$$

The following equation was developed for the dynamic equilibrium moisture content for the data obtained by the fit of the Page equation

$$M_{dw} = 34.45 - 0.0201 (273.15 + T_a) - 2.438 \ln (-R_o (273.15 + T_a) \ln (rh)) \qquad 3.53$$

$$(r^2 = 0.95)$$

The fitting of equations of the form of Eqns 3.50, 3.51 and 3.53 were found to be less effective when the moisture content was expressed on a dry basis. The comparison of the plots of the Eqns. 3.49 and 3.53 is shown in Fig. 3.16. The prediction of both equations are comparable, but the modified Chung and Pfost equation gives the correct shape of the experimental data reasonably well. Equations 3.50, 3.51 and 3.53 were chosen as the most effective description of dynamic equilibrium moisture content.

Johnston (1954) measured the equilibrium moisture content of malt during drying studies, employing air temperatures in the range 60 to 93.33°C. He also measured the equilibrium moisture content of barley during drying. He plotted the equilibrium moisture content (w.b.) as a function of restriction of vapour pressure (relative humidity). From these plots he showed that the equilibrium moisture content of malt and barley at observed deep bed saturation temperature (break through of temperature) were to be 12% (w.b.) and 17% (w.b.) respectively. The observed deep bed saturation temperature was in the range 22 - 29.5°C. He explained this low value of the equilibrium moisture content of malt by considering the fact that in the case of malt the presence of sugars reduces the vapour pressure by 40%. Since the vapour pressure of a solution is always less than that of the pure solvent. Boyce (1966) reported that at 26.7°C, about the average value of the observed deep bed saturation temperature when drying at air temperatures of 60 - 68.33°C, the indicated grain equilibrium moisture content when the air is saturated is about 15.25% (w.b.). This is 3.25% (w.b.) lower than the observation of Johnston. Logan (1954) suggested that there was a free water stage above about 20% (w.b.) moisture content. Narziss (1976) found that an emergence of heating front (break through of temperature) into the upper layer also occurs earlier, at about 18 - 20% (w.b.) moisture content, than would be expected from the figures of Johnston (about 13%).

The dynamic equilibrium moisture content of malt at saturation obtained by the Chung and Pfost equation and its modified form were in good agreement with Logan and Narziss. The equations have the correct overall shape over the entire practical range and the use of these equations might be expected to give more realistic values. The validity of the equations is limited to the normal range of temperature and relative humidity in the malt kilning process. The Chung and Pfost equation gives a sigmoid shape and it has been recommended by Pixton and Howe (1983) for cereals. The Chung and Pfost type equations developed for malt were selected to be used in the deep bed drying simulation of malt.

Chapter 4

SIMULATION OF DEEP BED DRYING

The conditions of the grain and air change with position and time during the deep bed drying of agricultural crops. Mathematical models have been widely accepted for studying such complex phenomena. The models for deep bed drying may be classified as (Morey et al. 1978):

(i) Graphical and Logarithmic Models
(ii) Heat and Mass Balance Models
(iii) Partial Differential Equation Models

This study is concerned with Partial Differential Equation Models. These models are developed by deriving a set of four partial differential equations to describe heat and mass transfer within a thin layer during a small time increment. The analytical solution of this set of partial differential equations is either extremely difficult or beyond the reach of today's mathematics. The solution procedure is basically a numercial integration with respect to time and position, the deep bed being considered as a series of thin layers. This process of step by step solution is called simulation. Simulation does not give a general solution, but a simulation model can be used in place of the real system and it can rapidly and inexpensively give useful information about its dynamic behaviour.

4.1 A Review of the Literature

McEwen and O'Callaghan (1954) were the first to propose that the deep bed drying of grain can be represented by a number of thin layers in series and developed a semi-graphical method of solution. At about the same period Van Arsdel (1955) developed a partial differential equation model and solved the partial differential equations by predictor-corrector methods. He has not presented any comparison with experimental data. The graphical solution of the McEwen and O'Callaghan model and the solution of the Van Arsdel model without a digital computer were quite laborious for general use.

About a decade after the publication of these models, Boyce (1965, 1966) was the first to develop a digital computer model for the deep bed drying of barley and validated the model with experimental results. Thompson, Peart and Foster (1967), and Henderson and Henderson (1968) used the same semi-empirical approach as Boyce and their results are similar. Bloome and Shove (1971) developed a model based on a finite difference method for low temperature drying of shelled corn. This model assumes that temperature equilibrium is achieved during each time increment and uses only a heat balance equation. Sharma and Muir (1974) applied Bloome and Shove's model for low temperature drying of wheat and rape seed. Good agreement was observed between the predicted values and experimental results. Thompson (1972) developed a low air flow and low temperature drying simulation model for shelled corn which takes into account the dry matter decomposition of grain. Morey, Cloud, Gustafson and Petersen (1979) added several modifications to the Thompson's model, as a result of validation procedures, and found it suitable for predicting moisture content changes using either 1 hour or 24 hour time increments for low air flow and near ambient temperature deep bed drying of corn.

Baughman, Hamdy and Barre (1971) modified Hukill's logarithmic model (Hukill, 1974) and simulated the model on an analogue computer. They observed that the diffusion model gives better results than the basic logarithmic model for shelled corn. Barre, Baughman and Hamdy (1971) applied a modified Hukill's model for cross flow deep bed drying and obtained quite good agreement between observed and predicted mean moisture contents for ear corn.

Bakker-Arkema, Bricket and Patterson (1967) developed a set of partial differential equations for heat and mass transfer in a deep bed of biological materials and solved them numerically with aid of a digital computer. Bakker-Arkema, Lerew and Evans (1970) developed partial differential equation models for the four basic grain drier types at Michigan State University. The system of equations for each of the fixed bed, concurrent flow, cross flow and counter flow driers was solved numerically and the results were compared with experimental corn drying data. The agreement between the predicted values and experimental results was satisfactory. Hamdy and Barre (1970) developed a partial differential equation model and solved the equations on a hybrid digital/analogue computer. The agreement between the model predictions and experimental results was quite good. Spencer (1969) developed a set of partial differential equations to describe deep bed drying of wheat and solved numerically by the method of Runge Kutta. The agreement between the experimental results and model predictions were quite good. Spencer (1972) further improved the model by incorporating the equations for latent heat of vaporization of moisture, bed shrinkage and an improved equation for surface moisture content.

At Newcastle University the semi-empirical model of Boyce was further developed by Menzies (1971) and Bailey (1972) by replacing the semi-empirical model by a set of 4 partial differential equations directly formulated into finite difference form. The simulation model was validated by comparing the predicted values with those measured in static and fluidized beds, and cross, contra and co-flow grain driers. Comparisons were also made with both static and drum type grass driers (O'Callaghan, Menzies and Bailey, 1971). Nellist (1974) further developed the Newcastle model by incorporating the diffusion equation and improved condensation procedure. He applied this model to the drying of ryegrass seeds and the model gave reasonable overall agreement with experimental results. Matouk (1976) modified the Newcastle model for low temperature drying and storage of maize grain, but the model has not been validated with experimental results. Chinnan and Young (1978) developed a deep bed drying model similar to the Newcastle model for peanut pods. This model incorporates a vapour-liquid diffusion thin layer model and takes into account heat losses to the surroundings and to the walls of the drier. They also obtained deep bed drying predictions employing the liquid diffusion thin layer model. In most cases the deep bed model with the vapour-liquid diffusion thin layer model gave a better estimate of change in condition of the pods and the condition of the air leaving the layer than the liquid diffusion model.

Ingram (1976) developed a partial differential equation model for the deep bed drying of grains. He developed a series method of solution of the diffusion equations, which were incorporated into the model and made an exponential approximation to the solution of the partial differential equations. He avoided the prediction of impossible relative humidities by replacing the equation

$$G \frac{\partial H}{\partial z} = - \rho_d \frac{\partial M}{\partial t} \qquad 4.1$$

by $$\frac{\partial M_e}{\partial z} = - \frac{R\rho_d}{G} \frac{\partial M_e}{\partial H} - \frac{h_{cv} - R\rho_d C_{pw}}{G (C_{pa} + C_{pw} H)} \left(T_a - T_g \right) \frac{\partial M_e}{\partial T_a} \qquad 4.2$$

He validated the model against the experimental results of Boyce (1965, 1966) and Woodforde and Lawton (1965), the predictions were better than those of O'Callaghan, Menzies and Bailey (1971) for the former and were in good agreement with the latter. This improvement is probably due to the increased accuracy of the numerical approximation and the provision for the reduction of the space increment in the areas of the bed with high gradients. Smith (1982) modified Ingram's model for non-parallel flow of air and used two methods for simulating the drying of any shape of grain heap. He observed a general similarity between the experimental and computer results, although there were some differences.

Kachru and Matthes (1976) developed a completely different type of model for rough rice on the basis of dimensional analysis and similitude to predict drying time and instantaneous moisture content. The predicted values from the suggested model and experimental values were in relatively good agreement.

More recently Bowden, Lamond and Smith (1983) used the following four models to simulate low temperature deep bed drying of barley:

(i) Moisture deficit model
(ii) Logarithmic model
(iii) Near equilibrium model
(iv) Ingram model

As a process of validation of the models, they compared the predicted and experimental results. The Ingram and Near-equilibrium models gave good predictions for the drying process but the Ingram model used considerably more computing time. The logarithmic model was adequate and the moisture deficit model only of use for rapid calculation.

All of the partial differential equation models described above have been shown to predict moisture content and temperature changes with a reasonable amount of accuracy either for shallow bed (up to 0.30 m) and/or short duration (2 - 4 hours) (Spencer, 1969, Bakker-Arkema *et al*. 1967, 1970, Menzies, 1971 and Ingram, 1976). Nellist (1974) and Chinnan and Young (1978) observed good agreement between the predicted and observed moisture content changes for deep beds (1 - 1.5 m) and long duration, but their models over predicted the rate of passage of the heating front. Spencer (1972) reported good agreement between the predicted and observed mean moisture content and exhaust air temperature for a deep bed (0.70 m) and long duration (24 hours). Although Ingram (1976) has shown that his model agrees quite well with the experimental data of Boyce for both temperature and moisture content, it has not been validated against deep bed data (above 0.30 m) and for a long duration. As far as the author is aware no model has been reported to predict the temperature changes for a deep bed (above 0.3 m) and for a long duration (above 4 h) with reasonable amount of accuracy.

4.2 Development of Models for Deep Bed Drying

Two mathematical models were used for this study. Model 1 is similar to the Newcastle University model described by Nellist (1974) and Model 2 is similar to the Michigan State University model described by Ingram (1976).

The following simplifying assumptions were made for deriving the deep bed drying equations for both the models:

(a) The airflow is one dimensional.

(b) There is no heat loss perpendicular to the direction of air flow.

(c) Conduction heat loss within the bed is negligible.

(d) Specific heat of dry grain, moisture and air are constant.

(e) Latent heat of vaporization of moisture is dependent on moisture content.

(f) Shrinkage of the malt bed is dependent on moisture content.

(g) Bulk density of dry malt depends on the shrinkage.

(h) Contributions from $\frac{\partial H}{\partial t}$ and $\frac{\partial T_a}{\partial t}$ are negligible.

4.3 Heat and Mass Transfer Equations for Model 1

Consider an elemental layer, dz, of unit cross section and average moisture content M (Fig. 4.1). Air at a temperature, T_a and a humidity, H is flowing up through the bed at a mass flow rate, G. There are four variables T_a, H, T_g and M; so four equations are required to solve the problem.

4.3.1 Mass Balance Equation

Moisture lost by the grain = Moisture gained by the air

$$\rho_d \cdot dz \left(- \frac{\partial M}{\partial t}\right) dt = G\, dt \left(\frac{\partial H}{\partial z}\right) dz \qquad 4.3$$

$$- \left(\frac{\partial H}{\partial z}\right) dz = \rho_d \frac{dz}{G} \left(\frac{\partial M}{\partial t}\right) \qquad 4.4$$

which in the finite difference form is

$$\Delta H = - \rho_d \frac{\Delta Z}{G} \left(\frac{\Delta M}{\Delta t}\right) \qquad 4.5$$

4.3.2 Drying Rate Equation

The single exponential equation in differential equation form is given by

$$\frac{dM}{dt} = -k\ (M - M_e) \tag{4.6}$$

which in the finite difference form is

$$\Delta M = -k\ (M - M_e)\ \Delta t \tag{4.7}$$

when M is replaced by M + ΔM/2, the equation becomes

$$\Delta M = \frac{-k\ (M - M_e)}{(1 + (k/2)\ \Delta t)}\ \Delta t \tag{4.8}$$

The Page equation can be written as

$$\ln\left(\frac{M - M_e}{M_o - M_e}\right) = -kt^u \tag{4.9}$$

$$t_{eq} = \left[-\ln\left(\frac{M - M_e}{M_o - M_e}\right) / k\right]^{\frac{1}{u}} \tag{4.10}$$

Where t_{eq} is the equivalent drying time.

This equivalent time, t_{eq}, is the time required on the new drying curve to dry to the present moisture content. The Page equation in the differential equation form incorporating t_{eq} is

$$\frac{dM}{dt} = -\ (M - M_e)\ k\ u\ (t_{eq} + \Delta t)^{u-1} \tag{4.11}$$

Equation 4.11 in the finite difference form is

$$\Delta M = -\ (M - M_e)\ k\ u\ (t_{eq} + \Delta t)^{u-1}\ \Delta t \tag{4.12}$$

4.3.3 Heat Balance Equation

Change in enthalpy of air = Change in enthalpy of grain

The change in enthalpy of air

$$\begin{aligned} = G.\Delta t \Big[&(C_{pa}.T_a + C_{pw}.\ H.\ T_a + L_a.H) - (C_{pa}\ (T_a + \Delta T_a) \\ &+ C_{pw}\ (H + \Delta H)\ (T_a + \Delta T_a) + L_a\ (H + \Delta H) \Big] \end{aligned} \qquad 4.13$$

The change in enthalpy of grain

$$= \rho_d.\Delta z \left[T_g\ (C_{pg} + C_{pl}.M) - ((T_g + \Delta T_g)(C_{pg} + C_{pl}(M + \Delta M)) \right] \qquad 4.14$$

Substituting $\Delta H = -\ \rho_d\ \frac{\Delta z}{G}\ (\frac{\Delta M}{\Delta t})$ in Eqn. 4.13 and equating equation 4.13 and equation 4.14 gives

$$\begin{aligned} &G.\Delta t \left[-\ \Delta T_a\ (C_{pa} + C_{pw}\ (H - \rho_d\ \frac{\Delta z}{G} . \frac{\Delta M}{\Delta t})) + \rho_d\ .\ \frac{\Delta z}{G}\ .\ \frac{\Delta M}{\Delta t}\ (C_{pw}.T_a + L_a) \right] \\ &= \rho_d.\ \Delta z \left[T_g.\ \Delta M.C_{pl} + \Delta T_g\ (C_{pg} + C_{pl}\ (M + \Delta M)\ ) \right] \end{aligned} \qquad 4.15$$

Equation 4.15 gives

$$\begin{aligned} \Delta T_a = \Big[&- \frac{\rho_d.\ \Delta z}{G.\ \Delta t}\ .\ \Delta T_g\ (C_{pa} + C_{pl}\ (M + \Delta M)\ ) \\ &+ \frac{\rho_d.\ \Delta z}{G.\ \Delta t}.\ \Delta M\ \ (C_{pw}\ .\ T_a + L_a - C_{pl}\ T_g) \Big]\ / \\ &(C_{pa} + C_{pw}\ (\ H - \rho_d\ .\ \frac{\Delta Z}{G}\ \ .\ \ \frac{\Delta M}{\Delta t}\ )) \end{aligned} \qquad 4.16$$

4.3.4 Heat Transfer Rate Equation

Heat transfer rate between air and grain = Change in sensible heat of grain + (Enthalphy in evaporated moisture - Enthalphy of moisture prior to evaporation).

$$h_{cv} \cdot \Delta z \left[(T_a + \tfrac{1}{2}\,\Delta T_a) - (T_g + \tfrac{1}{2}\,\Delta T_g) \right] \Delta t$$

$$= \rho_d \cdot \Delta z .\, \Delta T_g \,(C_{pg} + C_{pl} \,.\, M) + \rho_d \,\Delta z\, (-\,\Delta M)\,(L_g + C_{pw} \cdot T_a - C_{pl} \cdot T_g) \qquad 4.17$$

$$2\,(T_a - T_g) + \Delta T_a - \Delta T_g$$

$$= \frac{2.\rho_d}{h_{cv}} \cdot \frac{\Delta T_g}{\Delta t}\,(C_{pg} + C_{pl} M) - \frac{2\rho_d}{h_{cv}} \cdot \frac{\Delta M}{\Delta t}\,(L_g + C_{pw} \cdot T_a - C_{pl} \cdot T_g) \qquad 4.18$$

Let $A = 2\,(T_a - T_g)$ $\quad B = (C_{pg} + C_{pl} \cdot M)$ $\quad Y = (L_g + C_{pw} \cdot T_a - C_{pl} \cdot T_g)$

$$\Delta T_a = -A + \Delta T_g \left(1 + \frac{2B\rho_d}{h_{cv} . \Delta t} \right) - \frac{2\rho_d}{h_{cv}} \cdot \frac{\Delta M}{\Delta t} \,.\, Y \qquad 4.19$$

Let $E = \left(C_{pa} + C_{pw} \left(H - \frac{\rho_d . \Delta z}{G} \,.\, \frac{\Delta M}{\Delta t}\right)\right)$

$F = (C_{pw} \,.\, T_a + L_a - C_{pl}\, T_g)$

Equation 4.16 now reduces to the form

$$\Delta T_a = - \frac{\rho_d \,.\, \Delta z}{G.E.\Delta t}\,(\Delta T_g\,(B + C_{pl} \cdot \Delta M) - \Delta M.F) \qquad 4.20$$

Equating equation 4.19 and equation 4.20

$$-A + \Delta T_g \left(1 + \frac{2\,B\rho_d}{h_{cv} \cdot \Delta t}\right) - \frac{2\rho_d \cdot \Delta z}{h_{cv} \cdot \Delta t} \,.\, Y$$

$$= - \frac{\rho_d . \Delta z}{G.E.\Delta t}\,(\,\Delta T_g\,(B + C_{pl} \cdot \Delta M) - \Delta M.F) \qquad 4.21$$

Equation 4.21 gives

$$\Delta T_g = \frac{A + \rho_d \cdot \frac{\Delta M}{\Delta t}\left[\frac{2Y}{h_{cv}} + \frac{\Delta z}{G.E.} \,.\, F\right]}{1 + \frac{\rho_d}{\Delta t}\left[\frac{2B}{h_{cv}} + \frac{\Delta z}{G.E.}\,(\,B + C_{pl} \cdot \Delta M)\right]} \qquad 4.22$$

4.3.5 Method of Solution

The bed is divided into a number of layers so that the properties of the material are constant or nearly so within each layer. The time interval should be small enough for the air conditions to be constant at the inlet to and exit from the layer. But for economy of computing time, a compromise between the acceptability of the results and intervals must be used.

Having selected Δz and Δt, drying constant, k, and equilibrium moisture content, M_e, at the inlet air conditions are determined. The change in moisture content in the first layer during the time interval Δt is computed from either equation 4.8 or equation 4.12. The change in grain temperature, ΔT_g, and the change in air temperature, ΔT_a, are calculated from equations 4.22 and 4.20 respectively. The change in air humidity ΔH is given by equation 4.5. This process is repeated layer by layer until the top of the bed is reached. For each time increment bed depth, z, and dry bulk density, ρ_d are assumed to be constant. At the end of each time increment, the amount of bed shrinkage is calculated from the estimated mean moisture content using equation 2.32, and dry bulk density is recalculated simply considering the volume occupied by the bed and the initial estimate of the weight of dry matter. The amount of shrinkage is used to alter the finite element width, Δz for the next time interval. This process is repeated for each time increment. When the relative humidity exceeds 98%, the condensation routine deposits back the moisture from the over saturated air and avoids this unrealistic situation. The condensation procedure will be described in the following section.

4.3.6 Condensation Procedure

The principle of the condensation procedure is that, whenever the relative humidity of the air exceeds the maximum permissible relative humidity, the excess moisture from the air is condensed back to the grain. Nellist (1974) developed an iterative procedure to find the balance between the air and freely available water. The principle of his procedure was that whenever the relative humidity exceeded the saturation value, the moisture that evaporated from the layer was adjusted until the evaporated moisture gives a temperature change predicting 100% saturation. He adjusted the evaporated moisture by using an interpolating polynomial to find the zero of the function

$$y = f(x) \tag{4.23}$$

where

y = (maximum permissible rh - predicted exhaust rh)

and x = moisture loss, ΔM.

The condensation procedure used in this study finds the balance between air and freely available water by a set of three simple steps. The condensation procedure is illustrated with reference to a skeleton psychrometric chart in Fig. 4.2. Suppose T_{a2} and H_2 at state 2 have been predicted from state 1 (T_{a1}, H_1). At state 2 the relative humidity is in excess of the maximum permissible relative humidity, RH_p. To achieve T_{ap} and H_p at maximum permissible relative humidity, RH_p $|\Delta M|$ is reduced by a small amount which in turn reduces H_2 by a small amount and the new estimates of T_a and H are predicted by the heat and mass transfer equations. This process is repeated until the predicted relative humidity is less than the maximum permissible relative humidity. Finally, the temperature and humidity at maximum permissible relative humidity is obtained by the method of bisection and secant method (James, Smith and Wolford, 1977).

Determination of temperature and relative humidity at maximum permissible relative humidity is finding the zero of the function

$$y = f(x) \tag{4.24}$$

where

y = (predicted exhaust relative humidity
- maximum permissible relative humidity)

and x = moisture loss, ΔM

The zero of the function $y = f(x)$ is obtained in the following three steps:

(i) $|\Delta M|$ is reduced by a small increment Δx until the function is of opposite sign using the method of incremental search.

(ii) An approximate root of the function is obtained by the bi-section method.

(iii) A more accurate root of the function is determined by the secant method until $|y| = |f(x)|$ is less than 0.1% RH_p.

T_a and H in all the steps are recalculated using the heat and mass transfer equations.

Nellist (1974) observed that the setting of maximum permissible relative humidity in excess of 98% caused the exhaust relative humidity to oscillate from layer to layer because of the steepness of the equilibrium moisture content curve. In later versions of his programme he allowed the maximum permissible relative humidity and the maximum relative humidity for the evaluation of M_e to be set independently to control layer to layer oscillation. In this study these provisions were incorporated in the programmes.

4.3.7 The Computer Programme

The programme is presented in Appendix 4.1. Some of the important features of the programme are summarised below:

(i) Inlet air temperature and humidity, and air flow rate could be used as time dependent arrays and interpolated linearly to initialize inlet air conditions and air flow rate at the start of each time iteration.

(ii) Initial moisture content and temperature profiles could be used as depth dependent arrays and interpolated linearly to initialize the layer conditions.

(iii) Bed depth, depth increments and dry bulk density were adjusted automatically in the programme for shrinkage of the bed.

(iv) A modified condensation routine has been incorporated in the model.

(v) The programme would provide an error message if the condensation routine fails to find the zero of the function $y = f(x)$.

4.4 Heat and Mass Transfer Equations for Model 2

Consider an element of the bed (z, z+dz) and of unit cross section with air flow, G, from z to z+dz (Fig. 4.1). There are four unknowns: moisture content, M, humidity, H, air temperature, T_a, and grain temperature, T_g. Thus, two conservation equations and two rate equations are made resulting four equations.

4.4.1 Mass Balance Equation

In unit time the flow of moisture into the element is

$$GH\ (z)$$

and out of the element is

$$GH\ (z + dz)$$

The difference between these is moisture added to air from grain. Thus, for unit time

$$GH\ (z + dz) - GH\ (z) = -\rho_d \frac{\partial M}{\partial t} \cdot dz$$

using Taylor series expansion for H terms and ignoring all terms of dz^2 and higher, this reduces to

$$G \frac{\partial H}{\partial z} \cdot dz = -\rho_d \frac{\partial M}{\partial t} \cdot dz \qquad 4.25$$

cancelling dz

$$G \frac{\partial H}{\partial z} = -\rho_d \frac{\partial M}{\partial t} \qquad 4.26$$

in the finite difference form equation 4.26 is

$$\frac{\Delta H}{\Delta z} = - \frac{\rho_d}{G} \left(\frac{\Delta M}{\Delta t} \right) \qquad 4.27$$

With reference to the grid in Fig. 4.3

$$H_4 = H_2 - \frac{\rho_d}{G} \left(\frac{\Delta M}{\Delta t} \right) \Delta z \qquad 4.28$$

4.4.2 Drying Rate Equation

The single exponential equation in differential form is

$$\frac{dM}{dt} = -k\ (M - M_e) \qquad 4.29$$

Integrating this equation from State 1 to State 2 (Fig. 4.3)

$$\frac{M_2 - M_e}{M_1 - M_e} = e^{-k\ (t_2 - t_1)} \qquad 4.30$$

since $t_2 - t_1 = \Delta t$

$$M_2 = M_1 e^{-k\Delta t} + M_e\ (1 - e^{-k\Delta t}) \qquad 4.31$$

Again the Page equation from Eqn. 4.12 can be written as

$$M_2 = M_1 - (M_1 - M_e)\ ku\ (t_{eq} + \Delta t)^{u-1} \cdot \Delta t \qquad 4.32$$

4.4.3 Heat Balance Equation

Change in enthalphy of air

= convective heat transfer to the grain

- heat carried by the vapour to the air.

Heat flowing into the element (z, z + dz) in unit time is

$$G\ \left[(C_{pa} + C_{pw}\ H\ (z)\ )\ .\ T_a\ (z) + L_a .\ H\ (z)\right]$$

and heat flowing out is

$$G\ \left[(C_{pa} + C_{pw}\ H\ (z + dz)\ \ T_a\ (z + dz) + L_a\ H\ (z + dz)\right]$$

The difference is equal to the difference between the convective heat transfer to the grain and the heat carried by the vapour to the air.

$$G\left[(C_{pa} + C_{pw} H\,(z + dz))\ T_a\,(z + dz) + L_a . H\,(z + dz)\right]$$

$$- G\left[(C_{pa} + C_{pw} H\,(z))\ T_a\,(z) + L_a\, H\,(z)\right]$$

$$= -h_{cv}\,(T_a - T_g)\,dz - (\rho_d\, C_{pw} \frac{\partial M}{\partial t}\, T_g + \rho_d \frac{\partial M}{\partial t} . L_a)\,dz \qquad 4.33$$

Applying the Taylor series expansion and neglecting higher order terms.

$$G\left[C_{pa} \frac{\partial T_a}{\partial z} dz + C_{pw} T_a \frac{\partial H}{\partial z} dz + C_{pw} H \frac{\partial T_a}{\partial z} dz + L_a \frac{\partial H}{\partial z} dz\right]$$

$$= -h_{cv}\,(T_a - T_g)\,dz - (\rho_d\, C_{pw} \frac{\partial M}{\partial t}\, T_g + \rho_d \frac{\partial M}{\partial t}\, L_a)\,dz \qquad 4.34$$

Substituting $\frac{\partial H}{\partial z} = - \frac{\rho_d}{G} \left(\frac{\partial M}{\partial t} \right)$

$$G\,(C_{pa} + C_{pw} H) \frac{\partial T_a}{\partial z} - C_{pw}\, \rho_d \frac{\partial M}{\partial t} . T_a - \rho_d \frac{\partial M}{\partial t} . L_a$$

$$= - h_{cv}\,(T_a - T_g) - \rho_d\, C_{pw} \frac{\partial M}{\partial t}\, T_g - \rho_d \frac{\partial M}{\partial t} . L_a \qquad 4.35$$

Equation 4.35 gives

$$\frac{\partial T_a}{\partial z} = \frac{(-h_{cv} + C_{pw}\, \rho_d . \frac{\partial M}{\partial t})\,(T_a - T_g)}{G\,(C_{pa} + C_{pw} H)} \qquad 4.36$$

Let $P = - (h_{cv} - \rho_d . C_{pw} \frac{\partial M}{\partial t}) / G\,(C_{pa} + C_{pw} H)$

Assuming P and T_g constant over the interval Δz (Fig. 4.3), equation 4.36 reduces to the form

$$\frac{dT_a}{dz} = P\,(T_a - T_g) \qquad 4.37$$

Integrating equation 4.37 from State 2 to State 4, one gets

$$\frac{T_{a4} - T_g}{T_{a2} - T_g} = e^{P\,(z_4 - z_2)} \qquad 4.38$$

Since $z_4 - z_2 = \Delta z$

$$T_{a4} = T_{a2}\; e^{P.\Delta z} + T_a\,(1 - e^{P.\Delta z}) \qquad 4.39$$

4.4.4 Heat Transfer Rate Equation

Change of enthalphy of grain

= convective heat transfer to grain

- heat supplied to evaporate the moisture to the air

At the beginning of the time step, dt, the grain heat is

$$\rho_d\,(C_{pg} + C_{pl}.\,M\,(t)\,)\,T_g$$

and at t + dt is

$$\rho_d\,(C_{pg} + C_{pl}\,.\,M\,(t + dt)\,)\,.\,T_g\,(t + dt)$$

The difference is equal to the difference between the heat transferred convectively to the grain and the heat required to evaporate the moisture

$$\rho_d\,[(C_{pg} + C_{pl}\,.\,M\,(t + dt)\,)\,.\,T_g\,(t + dt) - (C_{pg} + C_{pl}\,.\,M\,(t)\,)\,.\,T_g\,(t)]$$
$$= h_{cv}\,(T_a - T_g)\,dt + \rho_d\,\frac{\partial M}{\partial t}\,(C_{pw}\,T_g + L_g)\,dt \qquad 4.40$$

Applying the Taylor series expansion and ignoring higher terms

$$\rho_d \; (C_{pg} + C_{pl} \; M) \; \frac{\partial T_g}{\partial t} = h_{cv} \; (T_a - T_g) + \rho_d \; (L_g + (C_{pw} - C_{pl}).T_g) \; \frac{\partial M}{\partial t} \qquad 4.41$$

Equation 4.41 gives

$$\frac{\partial T_g}{\partial t} = \frac{h_{cv} \; (T_a - T_g)}{\rho_d (C_{pg} + C_{pl}.M)} + \frac{\rho_d \; (L_g + (C_{pw} - C_{pl}) \; T_g) \; \frac{\partial M}{\partial t}}{\rho_d \; (C_{pg} + C_{pl} \; . \; M)} \qquad 4.42$$

Let $P' = - h_{cv}/\rho_d \; (C_{pg} + C_{pl} \; . \; M)$

$$Q = \rho_d \; (L_g + (C_{pw} - C_{pl}) \; T_g) \; \frac{dM}{dT} \; / \; \rho_d \; (C_{pg} + C_{pl} \; . \; M)$$

Assuming P' and Q constant over the time interval dt

$$\frac{dT_g}{dt} = P' \; (T_g - T_a) + Q \qquad 4.43$$

Integrating from State 1 to State 2 (Fig. 4.3)

$$T_{g2} = \left[T_{g1} - (P'T_a - Q) \; /P'\right] \; e^{P' \; (t_2 - t_1)} + (P'T_a - Q) \; / \; P' \qquad 4.44$$

Since $t_2 - t_1 = \Delta t$

$$T_{g2} = T_{g1} \; e^{P'\Delta t} + (P' \; T_a - Q) \; (1 - e^{P'\Delta t}) \; / \; P' \qquad 4.45$$

4.4.5 Method of Solution

Depth and time increments should be small for the reasons mentioned in section 4.3.5. The method of calculation is described with reference to the grid in Fig. 4.3. Having selected Δz and Δt, drying constant, k, and equilibrium moisture content, M_e, are determined for mean air temperature and relative humidity over the time interval Δt (state 1 to state 2). Moisture content at state 2 is determined from state 1 using either equation 4.31 or equation 4.32. Taking mean air temperature, mean moisture content and mean drying rate over the interval Δt (state 1 to state 2), the grain temperature at state 2 relative to state 1 is calculated using the equation 4.45. Air temperature at state 4 is estimated from equation 4.39 using the conditions at state 2 for values of $\frac{\partial M}{\partial t}$, T_g and H. Air humidity is estimated from state 2 to state 4 using equation 4.28 and the moisture gradient value at state 2. If the relative humidity at state 4 is less than 98%, the moisture content at state 4 is determined in the same way as before from state 3. Grain temperature at state 4 is calculated from state 3 using equation 4.45 taking mean air temperature, mean moisture content and mean drying rate over the time interval Δt (state 3 to state 4).. Air temperature is then recalculated using mean grain temperature and mean humidity over the depth increment Δz (state 2 to state 4) and relative humidity is also recalculated. Relative humidity is again checked and if still below 98% the iteration is complete. When the air temperature gradient is high, Δz is halved until the criterion ($\Delta T_a < 3^{o}C$) on the temperature change is satisfied (a limit of 7 halvings is imposed). The iteration is repeated until the top of the bed is reached and the whole cycle is repeated for each time step.

For each time increment bed depth, z and dry bulk density, ρ_d, are assumed to be constant. At the end of each time increment, the amount of bed shrinkage is calculated from the estimated mean moisture content using equation 2.32 and dry bulk density is recalculated simply considering the volume occupied by the bed and the initial estimate of the weight of dry matter. The amount of shrinkage is used to alter the finite element width Δz for the next time interval. This process is repeated for each time increment.

When the relative humidity exceeds 98%, the condensation routine deposits back the moisture on the previous node. Air and grain temperatures are adjusted for this condensation on the previous node. The condensation procedure used in this model is the same as that described in Section 4.3.6.

4.4.6 Computer Programme

The programme is presented in Appendix 4.2. An exponential approximation similar to Ingram's model and a solution of the set of equations using central difference values updated by an iteration has been incorporated in the programme. This programme adjusts automatically the depth increment Δz by halving when the temperature gradient is high and continues up to 7 halvings if the change criterion is not satisfied. The rest of the additional features are the same as described in the section 4.3.7.

4.5. Preliminary Tests with the Programmes

During the development stage of the model, the programmes for both the models were tested using the equations developed in the earlier chapters 2 and 3, and the input data for a kiln trial obtained from commercial kiln data of Chapman (1982). The input was incomplete, so, the missing data was assumed on the basis of typical conditions during kilning of malt (Chapman, 1982). Initial moisture content (d.b.), initial grain temperature, and dry bulk density were assumed to be 78.50%, 18°C and 392.15 kg/m^3. Both models gave similar predictions. The comparison between the prediction and the kiln trial is presented in the section 5.3.2.

4.5.1 Sensitivity Analysis

A series of tests were conducted to find the effects of the variation of heat transfer coefficient and latent heat of vaporization of moisture. No significant effect was found in the resulting air temperature and mean moisture content predictions. These observations agree with the observations of Nellist (1974). Air temperature in the equation for the drying constant (Eqn. 3.45) was replaced with grain temperature and no significant effect was observed. This confirms the observation of Boyce (1966). The dry bulk density significantly affected the air temperature and mean moisture content variation with time. High dry bulk density caused high mean moisture content and slow passage of the heating front. This indicated that assuming constant dry bulk density for shrinking material would predict rapid passage of the heating front.

The stability of both the models with respect to heat transfer coefficient was partly due to the low specific heat of grain and the relatively high air flow rate. The stability of both the models with respect to latent heat of vaporization of moisture contained in the grain was partly due to the small value of $\frac{\partial M}{\partial t}$ and relatively high air flow rate.

Chapter 5

DEEP BED DRYING EXPERIMENTS AND COMMERCIAL KILN SIMULATION

The validity of a model should be judged by how well it serves its purpose. A model is sound and defendable if it accomplishes what is expected of it. No model either in physical or social sciences is an exact representation of "reality". Models then should not be judged on an absolute scale but on a relative scale. The model predictions of temperature and moisture content should be judged against the present state of the art and the utility of the models to the biochemists and engineers for quality improvement, energy conservation and efficient use of kilning plant.

Deep bed drying experiments were conducted to test the validity of the two models developed in Sections 4.3 and 4.4. Deep bed drying experiments are costly and laborious and a limited number of experiments were performed in the laboratory, keeping in mind the possible future applications. The variables considered in the deep bed drying experiments are temperature, mass flow rate and relative humidity of the air, weight of bed, moisture content and depth of bed. Inlet temperature, relative humidity, and mass flow rate of air were kept constant and all the variables were monitored during the deep bed tests conducted.

5.1 Apparatus

The experimental set up for the deep bed drying of malt is shown in Fig. 5.1. The drying bin was a rectangular box of 250 mm x 250 mm cross-section and 750 mm deep. The bin was fitted with a plenum chamber and stood on a balance. The fan, heater, moisturising column and air flow measuring equipment were those used for the thin layer drying experiments as described in Section 3.3.

The front of the box was subdivided into seven separately removable sections. When the drying was stopped these could be removed in turn, starting at the top, to enable sampling. The joints between these sections were made air tight with adhesive tape. To minimize the convection and radiation loss, a cottage type insulated cover was placed on top of the bin. The inside of the cottage type cover was covered with aluminium foil. The cover caused the air leaving the grain to flow down through the annular space between the cover and the box.

To measure temperatures at different positions in the bed shielded thermocouples supported by thin horizontal rods running across the box were located at the centre of the cross section (Fig. 5.2). The thermocouples were shielded in a perforated plastic tube. This method proved unsatisfactory due to the formation of channels during the shrinkage of the bed. Subsequently a different technique was used (Nellist, 1983) and the method proved quite satisfactory. In this improved method the thermocouples of required length were suspended from a 'star' shaped support, which was gradually lifted to the desired position step by step, during the filling of the bin with grains layer by layer (Fig. 5.3). This resulted in a malt bed free to contract and slide over the vertically running thermocouples. The thermocouples were not shielded, as it was considered reasonable to assume grain and air temperatures equal and shielding may have impeded shrinkage.

The balance had a capacity of 50 kg and was graduated to 20 g. As the balance was of the beam type fitted with a balance pan for counter weights, the effect of connecting the flexible tube could be eliminated.

The balance gives the correct change of weight as long as the force exerted by the air flow on the bed remains constant.

5.2 Experimental Procedure

Green malt used for deep bed drying experiments was obtained from a maltings at Gainsborough. It was sent directly from the germination chamber and loaded for deep bed drying on arrival. Five experiments were conducted. Three experiments were conducted placing shielded thermocouples at central positions supported by the thin rods across the box and no top cover was used to minimize the effect of air draught and radiation loss. Later, two experiments were conducted employing the suspended thermocouple technique of temperature measurement and with the cottage type cover on the top of the bed.

Before starting any experimental run, the whole of the apparatus and monitoring equipment was operated with a dummy deep grain bed for at least three hours to stabilize the air flow and inlet air conditions. Mass flow rate of air and inlet conditions were adjusted to the values to be used in the deep bed experiment.

The drier bin was filled layer by layer with previously weighed grains which were sealed in plastic bags, one for each layer. For the improved technique, the 'star' support was lifted step by step from the bottom along with the filling of the bin. The weight of the grain bed, including the box was adjusted by counter weights.

When it was clear that the air temperature, relative humidity and air flow rate had been stabilized and the drying bin had been filled, the flexible tube was immediately disconnected from the dummy bed and connected to the actual bed. Very quickly the air flow was adjusted if required and the balance was adjusted to zero using lead shot. The data logger was then operated to record air temperatures at intervals of 30 minutes. The time for each 200 g of moisture removal was noted and the balance was re-adjusted to zero using weights. At the same time a careful check was kept on the air flow rate, if necessary a small adjustment was made. The process was repeated during the whole period of the experiment.

At the end of the experiment the final weight of the grains was measured and the grain bed was emptied layer by layer by a flat sampler that could be pushed into the bed. The moisture content of the grains at the desired layers was determined using three samples per layer and according to the method in Appendix 3.1.

5.3 Results and Discussion

Deep bed drying was carried out with the malt variety Triumph. The results of the deep bed drying experiments are shown in Figs. 5.4 to 5.6. The bed depth of all the experiments was sufficient to establish the three drying zones normally observed in deep bed drying. The drying zone was bounded by a dry zone and an undry zone and the drying rate of the bed was constant. When the drying front emerged from the top of the bed, the drying rate of the bed decreased gradually until the bed was fully dried to equilibrium moisture content (Figs. 5.4 and 5.5). In the undry zone the pseudo-wet bulb temperature was approximately equal to the wet-bulb temperature of the air leaving the drying zone.

5.3.1 Comparison of the Simulation with Experimental Results

Laboratory deep bed drying experiments were conducted to assess the accuracy of the predictions of the models. The following three variables were selected to assess the validity of the models.

(1) Mean moisture content variation with time

(2) Moisture content distribution at termination

(3) Air temperature variation with time and position.

5.3.1.1 Mean Moisture Content Variation with Time

Both the models predicted linear variation of mean moisture content until the drying zone emerged and then predicted gradually decreasing drying rate of the bed. The predictions of both the models were very close to each other. The comparison of the predicted mean moisture content with experimental results is shown in Fig. 5.4.

Final mean moisture content calculated from the final experimental moisture content distribution agreed quite well with the predicted final mean moisture content. The difference between the predicted final mean moisture content and the observed final mean moisture content was possibly due to the change in the upward thrust of the air on the balance. Although the mass flow rate of air was almost constant, the upward thrust might have been slightly affected by the change of porosity and bed depth. However, the agreement between the predicted and experimental mean moisture content for all the five experiments was good.

5.3.1.2 Moisture Content Distribution

The drying zone was bounded by a dry zone and an undry zone in experimental run 2, 3 and 5 at the time of termination (Figs. 5.5 (b)

5.5 (c) and 5.5 (e)). The predictions of both models were very close and predicted a slightly higher moisture content in front of the drying zone. An excellent agreement between the predicted and observed moisture content distribution was found when the drying zone has already passed the top of the bed. The agreement between the predicted and observed moisture content distribution for all the five experiments was good (Fig. 5.5).

5.3.1.3 Air Temperature Variation with Time and Position

In the first three tests, air temperature was measured using shielded thermocouples placed centrally and supported by thin rods across the bin at regular intervals. The predictions of both the models were very close to each other and the predicted temperatures did not agree with the experimental results. A comparison of the predicted and experimental results is shown in Figs. 5.6 (a) to 5.6 (c). The experimental temperatures were higher than the predicted ones. The perforated tubes shielding the thermocouples and the thin rods would have affected the shrinkage of the bed. It seems likely that this may have caused some channelling of the air allowing the hot air to proceed more rapidly.

This technique was abandoned. Another two deep bed experiments were conducted using the suspended thermocouple technique. The agreement between the predicted and experimental temperatures was very good. The comparisons of the predicted and observed temperature is shown in Figs. 5.6 (d) to 5.6 (e). However, if the shrinkage is not included in the models, this caused the models to predict a more rapid passage of the heating front (Fig. 5.7). A number of researchers (O'Callaghan et al. 1971, Nellist, 1974, and Chinnan et al. 1978) have not included shrinkage and they also report an over estimate of air temperature rise. The agreement between the predicted and observed pseudo wet bulb temperature was excellent.

5.3.2 Comparison of the Simulation with Kiln Data

Commercial kiln experimental data was available but the data only contained temperature variation with time and position. The data available is presented in Fig. 5.8. The data on initial grain temperature and initial moisture content had to be assumed and there was a certain anomaly on inlet air temperatures. The anomaly exists between the on-bed air temperatures presented in Figs. 5.8 (a) and 5.8 (c). In order to be consistent with Fig. 5.8 (c), this on-bed temperature was used.

5.3.2.1 Temperature Variation with Time and Position

The predicted temperatures compared with the industrial data is shown in Fig. 5.9. Both the computer programs appeared to be quite adequate during the initial period of drying, but the difference between the predicted and observed results was gradually increasing in the later period. However, the agreement between the predicted and observed pseudo-wet bulb temperature was quite good. It is very difficult to make any definite comment on this disagreement because of insufficient information on the kiln experiment. However, the overall agreement in the early stages is good.

5.4 Computing Time

Computer CPU time required for model-2 was considerably higher than that required for model-1. For example, the CPU time for model-1 for predicting experimental run-4 was 58.34 seconds whereas model-2 required 101.15 CPU seconds.

5.5 Validity of the Models

The validity of the models should be judged against their purposes. Forrester (1968) has mentioned "Model validity is a relative matter. The usefulness of a mathematical simulation model should be judged in comparison with mental image or other abstract model which would be used instead."

No model has been reported to be validated against the experimental data of malt. Although models have been developed for agricultural crops, most of them have been reported to be validated for a shallow depth of bed about 0.3 m. No model has been reported that predicts the temperature changes with a reasonable amount of accuracy for the bed depths encountered in malt drying. Both the models developed can predict moisture content and temperature changes with a reasonable amount of accuracy. There is no difference between the two models for practical purposes. These facts justify the validity of the models.

5.6 Application of Model

The main objectives of this section is to illustrate the use of the programme in the commercial kilning of malt, and the programme was applied to simulate a typical commercial kilning cycle. This cycle was detailed by the technical staff of a malting company.

5.6.1 Operating Procedure

The kiln was simulated so as to satisfy the following requirements of operating procedure as encountered in the commercial kilning of malt:

1. The initial temperature during the first 12 hours rises linearly from 55 to 65°C. The flow rate was adjusted so that the off bed temperature reached 40°C after 12 hours.

2. The temperature then rises linearly from 65 to 75°C over the next 6 hours.
3. The temperature is then set at 80°C for a minimum of 2 hours or until the mean moisture content reaches equilibrium condition.

The programme (model 2) was used to simulate the above operating procedure for gas fired, indirect fired and recirculating conditions. For simulating gas fired conditions, the moisture from combustion was taken as 0.4 g/kg air/10°C increase in temperature. Most of the kilns are gas fired and the recirculation was considered for gas fired conditions only. The recirculation was set at 75% of kiln air through flow and began when the off bed relative humidity dropped to 95%.

The other parameters required for the simulation were set at the following typical values:

Initial moisture content %, (d.b.)	76.3
Grain temperature, °C	18.0
Bulk density, kg/m^3	608.0
Ambient air temperature, °C	10.0
Ambient air humidity, kg/kg	0.0058
Air flow rate, kg/min m^2	23.41
Bed cross sectional area, m^2	55.0
Bed depth, m	1.0

5.6.2 Results

The results of the simulation for gas fired, indirect fired and recirculating conditions are presented under the headings of mean moisture content, moisture content at three levels, temperature at three levels, and energy consumption and drying time.

Mean Moisture Content

During the early stage of drying the mean moisture content for gas fired conditions was slightly higher than that of indirect fired conditions (Fig. 5.10). The major effect was on equilibrium moisture content due to the addition of moisture of combustion. Recirculated gas firing increased mean moisture content further but finally this reached the same equilibrium moisture content as gas firing but required a longer time to reach the equilibrium moisture content (Fig. 5.11).

Moisture Content at Three Levels

Moisture content variations with time at the bottom layer, 0.5 m and the top layer were compared for all the three cases. Moisture content variation was almost identical for gas and indirect heating except for the final states. Moisture content variations for gas and recirculated gas firing are presented in Fig. 5.12. It is interesting to note that rewetting occurs at the bottom layers where the relative humidity of the drying air is higher than the equilibrium relative humidity of the grain. Moisture content variations for all the three conditions during the final stages, showing the details of the curves as they approach equilibrium moisture content, are shown in Fig. 5.13.

Temperature at Three Levels

Temperature variation with time at the bottom layer 0.5 m and the top layer were compared for all the cases and it was found to be almost identical for gas and indirect firing. Temperature variations for only gas and recirculated gas firing are presented in Fig. 5.14. The rewetting phase during recirculation is reflected by a temperature rise in the air. This is due to the release of the latent heat of adsorption. It would be quite interesting to verify this effect experimentally.

Energy Consumption and Drying Time

The energy consumption for drying is higher for gas firing than that of either indirect firing or recirculated gas and the drying time to reach the same final moisture content is higher for recirculated gas than that of either gas or indirect firing.

The effects of the regimes are summarised as follows:

Item	Gas (direct fired)	Indirect	Recirculated Gas
Eq. moisture content %, (d.b.)	4.46	4.08	4.46
Time to reach the moisture content of 4.5% (d.b.), min	1066	1216	1440
Energy consumption for drying to 4.5% (d.b.), kJ/tonne*	2.58×10^6	2.18×10^6	1.88×10^6

Although the programme can be refined, this section has demonstrated a little of how it might be used and indicated the phenomena the programme is required to simulate.

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* Wet malt (bulk density = 608 kg/m^3)

Chapter 6

DISCUSSION AND CONCLUSION

The objective of this research was to develop a mathematical simulation model for deep bed drying of malt to provide design data and data on temperature and moisture content histories at different depths. The work was carried out under four main headings. The results of each of the sections have been discussed in detail in the relevant section. The essential features of the theoretical and experimental results of each of the main sections are now drawn together and their general implications are discussed. Finally, suggestions are put forward so as to provide possible directions of future research.

6.1 Physical and Thermal Properties of Malt

The physical and thermal properties of physical dimension, 1000 grain weight, bulk density, dry bulk density and specific heat, were determined experimentally in the moisture content range 4.80 - 41.66%, (w.b.) and each of these properties, except bulk density, was found to be linearly dependent on moisture content. The correlation was more effective when moisture content was expressed on a wet basis. There does not appear to be any physical theory to explain this, the correlations are purely empirical.

The ratio of latent heat of malt to latent heat of free water was determined from three isotherms at $5^{o}C$, $25^{o}C$ and $45^{o}C$ covering relative humidities in the range, 11.2 - 97.0%, on the theoretical basis of the Clausius-Clapeyron equation (Othmer, 1940). It was expressed as a function of moisture content (d.b.) in the form proposed by Gallaher (1951). This ratio increases rapidly at very low moisture content. Since Gallaher's form of equation is not based on any physical model, any extrapolation below 5.5% (d.b.) moisture content should be treated with caution. Shrinkage of malt during drying was determined experimentally and found to be a non-linear function of moisture reduction. Although the proposed equation is better than the linear relationship proposed by previous workers, the proposed equation has been supported by only two experimental runs and does not give a very good fit to the experimental data. The volumetric heat transfer coefficient of malt in the temperature range 50.8 - 70.8°C and for air flow rates ranging from 0.35 to 0.62 kg/m^2 sec was determined experimentally and an equation was developed as a function of air flow rates.

6.2 Thin Layer Drying of Malt

Thin layer drying experiments for the malt variety Triumph were conducted with air temperatures ranging from 30.3°C to 90.2°C and relative humidity ranging from 2.4% to 79.2%. An iterative least squares procedure was developed to fit the single exponential equation, the double exponential equation and the Page equation to the thin layer drying data. The double exponential equation always gave the best fit, but the double exponential equation could not be fitted to all experimental runs. The programme failed to converge to all the experimental runs mainly due to the fact that the programme finds a local unconstrained minimum. In the case of fitting the double exponential equation there was more than one minimum and the starting values caused convergence to a minimum which was physically unrealistic but mathematically possible. In addition, the drying constants and the proportion of the two components of the double exponential equation were found to vary randomly. The Page equation was better than the single exponential equation. However, the difference between the standard error of estimate of these two equations was small. The single exponential equation is physically more justified since it is of the mathematical form of the first term of the solution to the diffusion equation. The single exponential equation was found to describe the thin layer drying of malt adequately and this was probably due to the degradation in the endosperm and cell walls of the germinated barley, causing the resistance to the drying to be mainly concentrated at the testa and pericarp, i.e. at the outer surface of the kernel.

The drying constant was expressed as a function of air temperature by an Arrhenius type equation for the normal drying range of the malt kilning process and the extrapolation of the drying constant above $90^{\circ}C$ for production of dark malt should be treated with caution. Dynamic equilibrium moisture content was expressed as a function of air temperature and relative humidity. The modified Smith equation and the Chung and Pfost equation were fitted to the derived dynamic equilibrium moisture content data. The Chung and Pfost equation gave the correct overall shape over the entire practical range, but it showed small temperature effect. An examination of the plots of the logarithm of the change in free energy Vs. moisture content of the isotherms for corn (Chung and Pfost, 1967) reveals that these plots are almost parallel to one another. On the basis of this observation, the Chung and Pfost equation was modified to include a further temperature effect and this improved the fit to the data. This equation gave the correct overall shape over the entire practical range and this equation might be expected to give more realistic values as it included the temperature effect.

6.3 Simulation of Deep Bed Drying

Two mathematical models were developed to describe the moisture content and temperature changes with position and time during the deep bed drying of malt. Model 1 is similar to the Newcastle Model described by Nellist and Model 2 is similar to the Michigan State University Model described by Ingram. The shrinkage of the malt bed, variation of the dry bulk density and a modified condensation procedure have been incorporated in both models. Both the models have been programmed in FORTRAN. Both the programmes can be adapted easily for the use of alternative thin layer equations and fluctuating inlet conditions.

Model 2 takes considerably more computing time in comparison with Model 1. Model 2 has been formulated in terms of the governing differential equations. A solution procedure using an exponential approximation similar to the Ingram's model and the use of central difference values updated by an iteration to the solution of the set of equations makes the second model better suited to more extreme conditions.

The modified condensation routine finds the balance between air and freely available water by three simple steps. The difference between the predicted and maximum permissible relative humidity has been expressed as a function of moisture loss. A small interval containing the root of the function is found by incremental search. An approximate root is determined by the method of bisection and finally a more accurate root is determined by the secant method.

A series of tests were conducted to find the effects of the variation of heat transfer coefficient and latent heat of vaporization of moisture. No significant effect was observed in the resulting air temperature and mean moisture content. The variation of dry bulk density considerably affected the mean moisture content and temperature variation with time. High dry bulk density caused high mean moisture content and slow passage of the heating front.

6.4 Deep Bed Drying Experiments and Commercial Kiln Simulation

Five deep bed experiments were conducted in the laboratory to assess the accuracy of the model predictions. Bed depth was 0.75 m and inlet air conditions were maintained almost constant. Drying times varied from 260 min to 615 min and initial moisture content varied from 62.5 to 76.3%, (d.b.). Shielded thermocouples supported by thin rods were used to measure air temperatures during the first three experiments but this technique proved unsatisfactory, possibly due to the channelling of air. The last two experiments were conducted using the suspended thermocouple technique of temperature measurement and were found to be quite satisfactory.

Both the models were validated by comparing the model predictions with the experimental data. The mean moisture content and moisture content profile predictions of both the models were found to be in good agreement with experimental results for all the deep bed experiments. The predicted air temperature for the first three experiments did not agree with the experimental results possibly due to the channelling of air. The predicted air temperature for the last two experiments were in very good agreement with the experimental results. Both the models predicted the initial period of drying for commercial kiln data adequately, but later the difference between the predicted and observed results increased gradually. This might be due to insufficient data, a discrepancy in the data and possibly recirculation in the latter period of the drying.

In general both the models can predict the temperature and moisture content changes with time and position with reasonable accuracy for the conditions tested. There is a need for further testing over a wider range of variables. Practically there is no difference between the predictions of the two models, Model 1 takes less computing time than Model 2.

Model 2 was used to simulate a typical commercial kilning cycle detailed by the technical staff of a malting company. The effects of gas fired, indirect fired and recirculated gas fired conditions were considered. Final equilibrium moisture content for gas fired conditions is higher than that of indirect fired conditions. Final equilibrium moisture content for the recirculating condition was the same as that of the gas fired condition but required a longer time to reach. Rewetting and increase of air temperature due to the release of heat of adsorption during the early phase of recirculation were predicted. Energy consumption for kilning of malt with recirculation was lowest and the highest was for the direct fired condition.

6.5 Future Work

A limited number of experiments have been conducted on the shrinkage of a malt bed and the effects of loading and compaction have not been considered in terms of dry bulk density and shrinkage. Further work on dry bulk density and shrinkage considering the effect of loading and compaction would be quite useful for the simulation of the deep bed drying of malt. Specific heat and heat transfer coefficients have little effect on the variation of temperature and mean moisture content, and the expressions for these properties have been developed for the whole range of malting process. Further work on these two variables does not seem to be justified. Although the latent heat of malt appeared to have little effect on the distribution of temperature and mean moisture content, the value of this property increases rapidly at very low moisture content. Since malt is dried to 2.4 - 4% moisture content (d.b.) and the use of the expression for latent heat needs extrapolation below 5.5% moisture content (d.b.), the data below this moisture content would be quite useful.

The drying constant was determined for a temperature range $30.3^{o}C$ to $90.2^{o}C$. The prediction and experimental data (Fig. 3.12) show that an extrapolation above $90^{o}C$ might cause serious error in the use of the equation for drying constant. No thin layer drying was conducted above 80% relative humidity. So, further work on thin layer drying for low relative humidity and high temperature (above $90^{o}C$) and high relative humidity (above 80%) and low temperature would be quite useful for simulation over a wider range. The air flow resistance of a malt bed changes during drying and affects the air flow depending on the fan characteristics, which in turn affects temperature and moisture content distribution in the bed. Further work on air flow resistance considering the effect of loading and compaction would be quite useful in the model prediction and economy of the malting plant.

Model 2 takes considerably more computing time. Further theoretical work to improve the numerical technique using the exponential approximation and central difference scheme without iteration is needed. Further experimental work on deep bed drying in the laboratory and commercial kiln for similar conditions would be useful to assess the limitations and indicate where development is required.

Simulation of a commercial kilning shows a rewetting and an increase of temperature due to release of heat of adsorption during the early stage of recirculation. Further work on rewetting and its effect on temperature variation during kilning of malt would be quite useful in the simulation of kilning of malt with recirculation. Once the programme has been refined, further theoretical work should be conducted to investigate the effects of different rates of recirculation after the break within one kiln and the effects of reuse of post break air from one kiln for pre-break drying on another kiln. It should be emphasised that before any further development the benefits of the model should be realized by the malsters and biochemists and should be applied to the malting industry.

Finally, the value of the programme depends on its application in the industry. This will require more precise specifications by the malsters and biochemists of their requirements. The simulation can then help achieve the quality requirements whilst minimising energy use.

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