CHAPTER II

REVIEW OF LITERATURE

2-1 The drying rate of thin-layer of grain

The review of literature in this part will deal primarily with the mathematical simulation of thin-layer grain drying. Thin-layer equations are presented because most deep bed grain drying simulations are based on the concept that the deep bed consists of several thin-layers of grains. Thin-layer drying is considered by most researchers to be identical with single kernel drying. The drying process can be divided into two periods :

1) the constant-rate drying period, and

2) the falling-rate drying period. Constant and falling-rate drying periods are illustrated in Figure 2.1

During the initial period of thin-layer drying of most agricultural products, moisture removal from the product is at a constant-rate period which exists as long as the migration of moisture to the surface at which evaporation is occuring is as fast as the evaporation rate taking place at the surface. The rate at which evaporation occurs at the water surface is dependent on two factors : 1) the heat transfer rate from air to the water surface, and 2) the mass transfer rate for moisture moving from the water surface to the air. The constant-rate period terminates when the critical moisture content is reached. The critical moisture content of a product depends on the characteristics of the solid, such as shape, size,

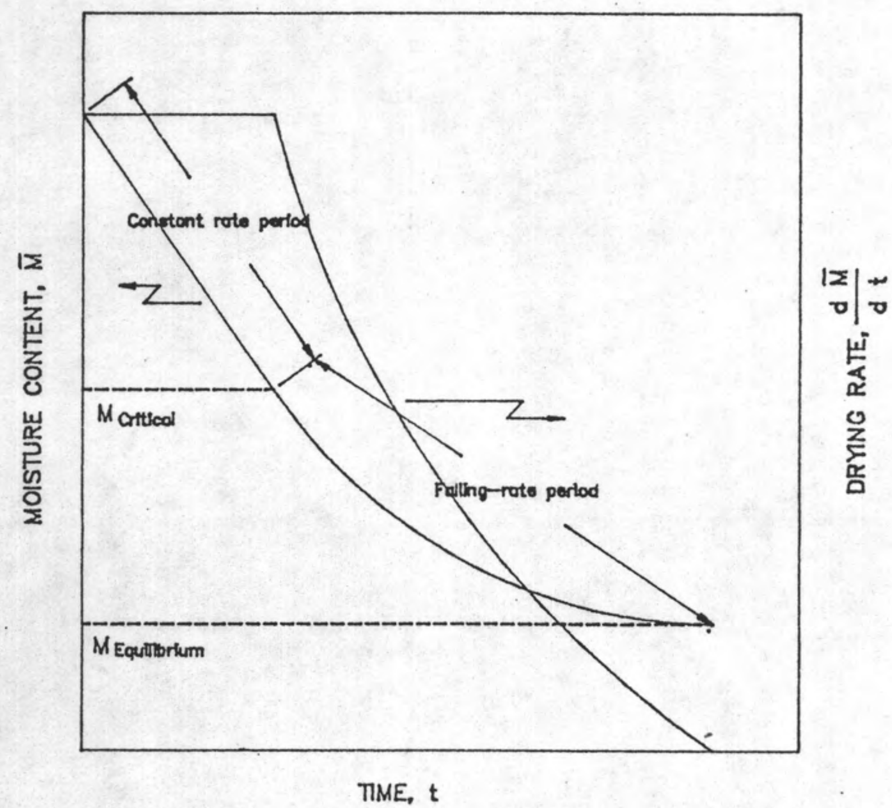

Figure 2.1 Biological product drying during the constant and the falling–rate periods. (Brooker et al.,1981)

the chemical composition and also on the drying conditions.

After the critical moisture content is reached, the drying process proceeds at a decreasing rate. During this period, usually called the falling-rate period, the surface of a drying particle is not covered with a thin-layer of water, as in the case during the constant-rate period, because the internal resistance to moisture transfer has become greater than the external resistance. The driving potential of the drying process decreases along with the drying rate. Cereal grains usually do not exhibit a constant-rate drying period unless they are harvested at a very immature state or have had water condensed or deposited on their surfaces. They dried solely during the falling-rate period. This implies that the drying rate decreases continuously during the period of drying until the equilibrium moisture content is reached.

Because the constant-rate drying period is of limited importance, most research, therefore, has been directed towards predicting the drying rate of grains during the falling-rate drying period. Not only do external transfer mechanisms (convective heat and mass transfer) have to be considered in the analysis, but the transfer mechanisms within the product (heat and mass diffusion) must be included. Semitheoretical and empirical relationships have been developed to predict the drying behavior of cereal grains. Some of the proposed mechanisms for describing the transfer of moisture in individual kernels are (Brooker et al., 1981) :

1) Liquid movement due to surface forces (capillary flow) ;

2) Liquid movement due to moisture concentration (liquid diffusion) ;
3) Liquid movement due to diffusion of moisture on the pore surface (surface diffusion) ;
4) Vapor movement due to moisture concentration differences (vapor diffusion) ;
5) Vapor movement due to temperature differences (thermal diffusion) ; and
6) Water and vapor movement due to total pressure differences (hydrodynamic flow).

The word "single kernel" or "thin-layer" refers to a layer of grain is approximately one kernel deep. The following sections are a review of the mathematical models for predicting the thin-layer drying rate. Various mathematical models have been proposed and compared with experimental data.

It has been accepted that drying phenomena of biological product during the falling-rate period is controlled by the mechanism of liquid and/or vapour diffusion. Hamdy et al. (1969) and Whitaker et al. (1972)have been the researchers to apply Fick's diffusion law to the drying of solid materials. Assuming that the drying process is isothermal and the resistance to moisture flow is uniformly distributed throughout the interior of the homogeneous and isotropic material, the kinetics of moisture desorption can be derived; that is

$$\frac{\partial M}{\partial t} = \nabla \cdot (D \cdot \nabla M) \qquad \text{................(2.1)}$$

where :

M = Local moisture content, dry basis (decimal)

D = Diffusion coefficient (m^2/hr)

t = Time, hr

Assuming that the diffusion coefficient, D is independent of local moisture content and the volume shrinkage is negligible. Fick's second law can be derived :

$$\frac{\partial M}{\partial t} = D\left[\frac{\partial^2 M}{\partial r^2} + \frac{C}{r}\frac{\partial M}{\partial r}\right] \quad \text{..............(2.2)}$$

where r is the particle coordinate and C is zero for planar symmetry, unity for a cylindrical body, and 2 for a spherical body. A number of solutions to equation (2.2) for various solid shapes have been used as drying equations for grains. The following initial and boundary conditions are usually assumed in solving equation (2.2)

$$M(r,o) = M_i \quad \text{..................(2.2a)}$$

$$M(R,t) = M_e \quad \text{..................(2.2b)}$$

where :

M_i = initial moisture content,dry basis (decimal)

M_e = equilibrium moisture content,dry basis (decimal)

R = Radius of a sphere

The analytical solutions of equation (2.2) for the average moisture content of various regularly shaped bodies can be obtained directly from books on diffusion, such as Carslaw et al. (1959), Bird et al. (1976) and Crank (1979). Thus, for an infinite plane :

$$\overline{MR}(t) = \frac{8}{\pi^2} \sum_{n=0}^{\alpha} \frac{1}{(2n+1)^2} \exp[-\frac{(2n+1)^2}{4}\pi^2 X^2] \quad ......(2.3)$$

for a sphere :

$$\overline{MR}(t) = \frac{6}{\pi^2} \sum_{n=1}^{\alpha} \frac{1}{n^2} \exp[\frac{-n^2\pi^2 X^2}{9}] \quad ......(2.4)$$

and for an infinite cylinder :

$$\overline{MR}(t) = \sum_{n=1}^{\alpha} \frac{4}{\lambda_n^2} \exp[\frac{-\lambda_n^2}{4} X^2] \quad ......(2.5)$$

which λ_n are the roots of the Bessel function of zero order. For the above equations the average moisture content and the time are expressed as dimensionless quantities, $\overline{MR}$ and X, respectively :

$$\overline{MR}(t) = \frac{\bar{M} - M_e}{M_i - M_e} \quad ......(2.6)$$

and

$$X = \frac{A}{V}(Dt)^{1/2} \quad ......(2.7)$$

where $\overline{MR}$ is average moisture ratio, $\bar{M}$ is average moisture content, dry basis (decimal), A represents the surface area and V the volume of the body. For the plane V/A = half-thickness; for the sphere V/A =

(radius)/3; for the cylinder V/A = (radius)/2

The diffusion equation has been used by many researchers in grain drying to describe thin-layer drying. Most researchers who have used this equation have modeled the grain kernel as a sphere with diffusion in the radial direction.

Morey et al. (1978) report that analytical solutions have been obtained for steady state equlibrium type boundary conditions and constant value of the diffusion coefficient.

Several researchers including Chittenden and Hustrulid (1966) recognized the limitation of the constant diffusivity assumption. Chu and Hustrulid (1968) presented the numerical solution of the diffusion equation for a sphere with concentration dependent diffusivity. The differential equation for such a case is given as

$$\frac{\partial M}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D_m \frac{\partial M}{\partial r}\right] \qquad \text{...............(2.8)}$$

The concentration dependent diffusivity was expressed as

$$D_m = 1.5134 \exp[(0.00045T_A - 0.054857\,M - 2513/T_A] \qquad \text{........(2.8a)}$$

where T_A is the drying air temperature (°F)

Whitaker et al. (1969) developed a method of solution for the case where the diffusion coefficient depended on both position and concentration. They divided the sphere into a number of thin spherical shells and obtained the solution by an analog computer. Husain et al. (1973) allowed the diffusion coefficient to vary with the moisture content of the material and the temperature of the drying air.

Babbit (1949) and the others used the spherical form of analytical solution of diffusion equation to model the rate of adsorption and desorption of wheat and they proposed that the vapor pressure is the driving force for moisture transfer. In such a case, the equation describing the process can be expressed as

$$d_s \frac{\partial M}{\partial t} = \frac{D'}{r^2}[\frac{\partial}{\partial r}(r^2 \frac{\partial P_v}{\partial r}] \quad \text{................(2.9)}$$

where d_s is density of solid material, D' is coefficient of water vapor diffusivity and P_v is vapor pressure.

The equation (2.9) is obviously identical with equation (2.8) if moisture concentration is directly proportional to vapor pressure.

Young and Whitaker (1971) and Whitaker and Young (1972) applied the vapor diffusion equation to the thin-layer drying of peanut pods. The analysis assumed the peanut pod to be a composite sphere with concentric shells.

Chhinnan and Young (1977) found that the vapor diffusion model described the data better than the liquid diffusion model for peanut pods over the entire drying period. Later, the same researchers (Chhinnan and Young, 1977) developed a mathematical model by combining the vapor and liquid diffusion of moisture. The combined model described the thin-layer drying of peanut pods better than either the liquid or vapor diffusion models.

Results have shown that the estimated value of diffusion coefficient, D, depends not only upon the grain but also on the coordinate system of the diffusion equation, whether it is spherical, rectangular or cylindrical.

The diffusion-based modeling approach has become most popular because it is reasonably accurate and it provides a conceptual basis for physically understanding the drying process. The analytical solution of the diffusion model is expressed in the exponential form and is an infinite series. Successive terms in such series converge rapidly for sufficiently large t. The first few terms dominate the series and subsequent terms may often be considered negligible, i.e. if $\overline{MR} = \sum_{i=1}^{\alpha} A_i \exp(-K_i t)$, then for t sufficiently large, a satisfactory approximation may be provided by taking $\overline{MR} = \sum_{i=1}^{n} A_i \exp(-K_i t)$ for finite n.

$$\overline{MR} = A_1 \exp(-K_1 t) + A_2 \exp(-K_2 t) + A_3 \exp(-K_3 t) + \ldots \quad \ldots\ldots\ldots\ldots (2.10)$$

where :

$\overline{MR}$ = Average Moisture ratio

A_i = Constant of the drying object i = 1,2.....

K_i = Drying parameter of the drying object i = 1,2..... (hr^{-1})

If the drying time is long enough or the moisture ratio is less than 0.6, the drying rate can be expressed by the first few terms of the infinite series (Wang et al.1978).

A two-term approximate form of the diffusion equation was suggested by Henderson (1974) in the simulation of thin-layer drying study of corn. He found very good representation of drying rate at 32.5 °C and 28 % relative humidity with drying time up to 7 hours.

$$\overline{MR} = A_o \exp(-K_o t) + A_1 \exp(-K_1 t) \quad ....(2.11)$$

where A_o, K_o, A_1, K_1 are empirical constants.

Nellist (1971, 1976) conducted thin-layer drying tests for two varieties of rye grass seeds. A two-term exponential equation was found to give the best fit among four alternative equations.

Henderson and Henderson (1968), Keener et al. (1978), Glenn (1979) proposed two term and three term exponential models to describe individual drying curves of corn kernels. They indicated that the models could give satisfactory prediction of drying behavior if the parameters and coefficients of these models were related to the conditions of both the product and the drying medium.

Sharaff-Eldeen (1978) developed the following two and three terms exponential equations to represent rough rice drying;

a) $$\overline{MR} = A_o \exp(-Kt)+A_1 \exp(-B_1 Kt)+(1-A_1)\exp(-B_2 Kt) \quad ....(2.12)$$

where : $A_o = 0.31663$, $A_1 = 0.54358$, $B_1 = 0.14420$, $B_2 = 0.03545$,
$K = 4.18643$

b) $$\overline{MR} = A_o \exp(-Kt)+(1-A_o)\exp(-B_1 Kt) \quad ....(2.13)$$

where : $A = 0.44594$, $B = 0.11205$, $K = 2.93634$, t = Time (hr)

In later studies Sharma and Kunze (1982) used the same concept to develop equations with two and three exponential terms for three different drying temperatures.

a) Air temperature 24°C

$$\overline{M} = 15.13+3.60 \exp(-0.310t) \quad ....(2.14)$$

$$\overline{M} = 12.01+3.01 \exp(-0.0006t)+3.97\exp(-0.4t) \quad ......(2.15)$$

b) Air temperature 43°C

$$\overline{M} = 8.23+12.38 \exp(-0.430t) \quad ....(2.16)$$

$$\overline{M} = 4.99+3.54 \exp(-0.0048t)+12.08 \exp(-0.4387t) \quad ...(2.17)$$

c) Air temperature 56°C

$$\overline{M} = 6.18+13.71 \exp(-0.528t) \quad ....(2.18)$$

$$\overline{M} = 3.66+3.73 \exp(-0.0223t)+12.51 \exp(-0.6095t) \quad ...(2.19)$$

where :

$\overline{M}$ = Average moisture content at time t (% D.B.)

t = Time (hr)

A single term approximate form of diffusion equation was of the form :

$$\overline{MR} = A \exp(-K t) \quad ....(2.20)$$

where A and K are empirical constants.

Wang and Singh (1978) presented this exponential approximation of their thin layer data as

$$A = 0.96-0.00008826T+0.02324(RH) \quad .....(2.20a)$$

$$K = 0.002814+0.0001267T-0.00362(RH) \quad ..(2.20b)$$

where T is the drying air temperature (°C)

RH is the drying air relative humidity (decimal)

The simple "lumped" model analogous to Newton's law of cooling in heat transfer is often used to describe the moisture loss in thin-layer grain drying. The drying rate will be proportional to the difference between the average moisture content in solid material and equilibrium moisture content, M_e.

The equation is as follows :

$$\frac{d\overline{M}}{dt} = -K(\overline{M} - M_e) \quad ....(2.21)$$

If the drying constant (k) in equation (2.21) is independent of $\overline{M}$ and M_e, the equation may be integrated to :

$$\overline{MR} = \frac{\overline{M} - M_e}{M_i - M_e} = \exp(-Kt) \quad ......(2.22)$$

The above approach constitutes one means of estimating the drying constant K, which, however, requires the assumption of a particular geometry for the grain kernel. Many workers make use ofan Arrhenius relation of the form

$$K = a \exp(-b/T_a) \qquad \text{..............(2.22a)}$$

or a simple exponential relation of the form

$$K = c \exp(dT) \qquad \text{..............(2.22b)}$$

Nellist (1976) investigated the dependence of k on humidity, H, by fitting expressions of the form

$$K = a \exp(bT + cH) \qquad \text{..............(2.22c)}$$

where a,b,c,d are empirical constants, T_a is absolute product temperature.

Rodriguez-Arias (1956) used equation (2.22) to describe the thin-layer drying data of corn. The drying constant (k) was found to vary in a step-wise manner at various intervals throughout the drying period. These equations were also used by O'Callaghan et al. (1971) for the drying rate of fully exposed corn kernels, and by Ross and White (1973) for white and yellow corn. Westerman et al. (1973) applied these models to study effects of relative humidity on high temperature drying of corn. It was called a logarithmic model by Sabbah et al. (1977). White et al. (1981) also used it to study drying behavior of fully exposed popcorn. In general, the model (equation 2.22) has been found to be inadequate in describing the thin-layer drying data. Thompson et al. (1968) point out the inadequancy of this model and had to establish an empirical model to explain their experimental data. Whitaker and Young (1972) and

Henderson (1974) showed the inadequancy of this model in the early stage of drying.

Several empirical drying models have been developed for cereal grains.

Page (1949) found that the drying of shelled corn in thin-layer could be represented by the equation

$$\overline{MR} = \exp(-pt^{Q}) \quad \text{.................(2.23)}$$

where P and Q are experimental constants
Page recognized that Q depended on the relative humidity of the drying air.

White et al. (1973) employed equation (2.23) to describe the effect of ambient dew-point variations on thin-layer drying characteristics of white shelled corn. This equation was also used by Overhults et al. (1973), by Misra and Brooker (1980) to describe the thin-layer drying and rewetting rate of shelled corn.

Agrawal and Singh (1977) conducted the thin layer drying experiments on short grain rough rice. They employed equation (2.23) to describe thin layer drying rate. From their analysis of the experimental data the following thin layer drying equation was obtained :

$$P = 0.02958-0.44565RH+0.01215T \quad \text{.......(2.23a)}$$

$$Q = 0.13365+1.93653RH+1.77431(RH)^2+0.009468T \quad \text{..(2.23b)}$$

Where T is the drying air temperature (°C), RH is the relative humidity (decimal) and t is the drying time (hours)

Equation (2.23a) and (2.23b) were obtained from a limited number of initial moisture content from one initial moisture content, 24 % W.B. The temperature and relative humidity of drying air were 32 to 51 °C and 18.75 to 85 percent respectively.

Sabbah (1968) used drying air temperature ranging from 2.30 to 21.10 °C and relative humidities ranging from 22 to 80 percent in his experimental work. From this work he developed the following equation :

$$\overline{MR} = \exp(-Kt^{0.664}) \qquad \text{..............(2.24)}$$

where : $K = \exp(-xt^{y})$

The constant X and Y were related to the drying temperature and relative humidity as follows :

$$X = [6.0142+1.453\times10^{-4}(RH)^2]^{0.5} - T[3.35\times10^{-4}+3.0\times10^{-8}(RH)^2]^5 \qquad \text{.......(2.25)}$$

$$Y = 0.1245-2.197\times10^{-3}(RH)+2.3\times10^{-5}(RH)(T)-5.8\times10^{-5}(T)$$

del Giudice (1959) conducted his experimental work using air temperatures ranging from 60 to 105°F,relaxtive humidities ranging from 60 to 100 percent and air velocity of approximately 10 feet per minute. From this experimental work he arrived at the following equation for rewetting :

$$\overline{MR} = \exp[-0.625(P_s)^{0.466(RH)}(RH)^{3.0}t] \quad ..(2.26)$$

Thompson (1968) proposed the following empirical equation for calculating the drying rate of shelled corn.

$$t = A \ln(\overline{MR}) + B[\ln(\overline{MR})]^2 \quad ....(2.27)$$

He conducted drying tests using corn having initial moisture contents of 19, 23, and 33 percent wet basis; air flow rates ranging from 0.1016 to 0.3048 $m^3/sec/m^2$; and drying air temperature ranging from 60 to 150°C. He determined values of the constants A and B from his experimental data using a least squares technique. The values he obtained were :

$$A = -102.32894 + 0.5275T$$

$$B = 8916.5136 \exp(-0.059418T)$$

T = Drying air temperature (°C)

t = Time, min.

They found this developed equation was better than the logarithmic model in predicting the drying rate of grain.

Troeger (1971) developed an empirical thin-layer drying model for corn in which they divided the time required to dry a thin-layer of grain from M_i to M_e into three stages. He conducted drying tests using corn having initial moisture contents of 21,31,36 and 42 percent dry basis, drying air temperature ranging from 90 to 160°F; dry air relative humidity ranging from 0 - 80 percent and air velocity ranging from 20 to 160 ft per min. They assumed that the following three equations could be used to describe the rate of drying each stage :

$$\frac{d\bar{M}}{dt} = -A_1(\bar{M}-M_e)^{B_1} \quad M_i \geq \bar{M} \geq M_{x1} \quad \text{............(2.28)}$$

$$\frac{d\bar{M}}{dt} = -A_2(\bar{M}-M_e)^{B_2} \quad M_{X1} \geq \bar{M} \geq M_{X2} \quad \text{............(2.29)}$$

$$\frac{d\bar{M}}{dt} = -A_3(\bar{M}-M_e)^{B_3} \quad M_{X2} \geq \bar{M} \geq M_e \quad \text{............(2.30)}$$

Troeger's equation includes the air velocity effect. The equations are as follows :

$$t = [P_1(\bar{M}-M_e)^{q_1}-P_1(M_i-M_e)^{q_1}] \quad M_i > \bar{M} > M_{x1} \quad \text{.......(2.31)}$$

$$t = [P_2(\bar{M}-M_e)^{q_2}-P_2(M_{x1}-M_e)^{q_2}+t_{x1}] \quad M_{x1} > \bar{M} > M_{x2} \quad \text{.......(2.32)}$$

$$t = [P_3(\bar{M}-M_e)^{q_3}-P_3(M_{x2}-M_e)^{q_3}+t_{x2}] \quad M_{x2} > \bar{M} > M_e \quad \text{.......(2.33)}$$

$$M_{x1} = 0.40(M_i-M_e) + M_e \quad \text{............(2.34)}$$

$$M_{x2} = 0.12(M_i-M_e) + M_e \quad \text{............(2.35)}$$

$$t_{x1} = P_1(M_{x1}-M_e)^{q_1}-P_1(M_i-M_e)^{q_1} \quad \text{............(2.36)}$$

$$t_{x2} = P_2(M_{x2}-M_e)^{q_2}-P_2(M_{x1}-M_e)^{q_2}+t_{x1} \quad \text{............(2.37)}$$

$$P_1 = \exp[-2.45+6.42M_i^{1.25}-3.15RH+9.62M_i\sqrt{RH}+0.03T-0.002V] \quad \text{..(2.38)}$$

$$P_2 = \exp[2.82+7.49(RH+0.01)^{0.67}-0.0179T] \qquad \text{.............(2.39)}$$

$$P_3 = 0.12(M_i-M_e)^{q_2+1}(-P_2q_2) \qquad \text{.............(2.40)}$$

$$q_1 = -3.98+2.87M_i-[0.019/(RH+0.015)]+0.016T \qquad \text{.............(2.41)}$$

$$q_2 = -\exp(0.810-3.11RH) \qquad \text{.............(2.42)}$$

$$q_3 = -1 \qquad \text{.............(2.43)}$$

where : T is the drying air temperature (°F); RH is the drying air relative humidity (decimal), M_i is the initial moisture content of corn (percent, dry basis) and V is the velocity of drying air (ft per min).

A regression analysis for a quadratic equation model was developed by Wang and Singh (1979) on their single layer drying data for rice to facilitate numerical techniques. That is;

$$\overline{MR} = 1+At+Bt^2 \quad \text{......................(2.44)}$$

where :

$A = -0.001208T^{0.4687}\ RH^{-0.3187}$

$B = -0.00006625T^{0.03408}\ RH^{-0.4872}$

t = Time (min)

T = Drying air temperature (°C)

RH = Relative humidity of drying air (decimal)

All the equations reviewed often give the best results in predicting the drying behavior of grain, if they are employed within the temperature, relative humidity, airflow rates, and moisture content range for which they are derived.

2-2 Equilibrium moisture content

The equilibrium moisture content refers to the quantity of moisture in the product when it is at equilibrium with the surrounding environment. A product is in moisture equilibrium with its environment when the rate of moisture loss from the product to the surrounding atmosphere is equal to the rate of gain of the product from the surrounding atmosphere. The equilibrium moisture content of grain depends on the air temperature and relative humidity, the grain variety, and previous history (Steffe et al.,1980). The equilibrium moisture content depends on whether the grain adsorbs or desorbs moisture in reaching equilibrium. The desorption equilibrium moisture contents are higher than the adsorption equilibrium moisture contents. This phenomenon is referred to as the hysteresis effect.

The concept of equilibrium moisture content is important in the study of grain drying because equilibrium moisture content determines the minimum moisture content to which grain can be dried under a given set of drying conditions when there is no radiative or conductive heat transfer.

The equilibrium moisture content value is usually considered to be dependent upon the temperature and the humidity of the ambient air. Equilibrium moisture content values may be determined in an air stream and identified as dynamic equilibrium moisture content or in a closed container and identified as static equilibrium moisture content. The static equilibrium moisture content is obtained when the product is kept under constant air temperature and humidity environment for a very long period. Traditional methods of obtaining static equilibrium moisture data by the static method use saturated solutions of certain salts and acids. These methods are time consuming. Equilibrium moisture content equations for rough rice have been determined by several researchers.

Henderson (1952) presented an equilibrium moisture content equation which was modified by Thompson (1972). The Henderson-Thompson equation for rough rice as presented by Pfost et al. (1976) is :

$$M_e = (0.01)(A/B)^{0.409} \quad ....(2.45)$$

where : $A = \ln(1-RH)$

$B = (-0.000019187)(T+51.161)$

M_e is the equilibrium moisture content (decimal, dry basis), T is the product temperature (°C), and RH is the relative humidity (decimal)

Chung and Pfost (1967) presented an equilibrium moisture content equation which was modified by Pfost et al. (1976). The Chung-Pfost equation for rough rice as presented by Pfost et al. (1976) is :

$$M_e = 0.325535-(0.046015)(\ln A) \quad ....(2.46)$$

where : $A = (-1.987)(T+35.703)(\ln RH)$

T and RH have been defined in Equation (2.45)

Equation (2.46) is a more general equation because it was developed with data from several sources and includes both desorption and adsorption information.

Kachru and Mattes (1976) presented adsorption and desorption equilibrium moisture content for rough rice at different temperatures in the range of 19° to 38°C and different relative humidities in the range of 5 to 95 percent.

Zuritz and Singh (1978) reviewed various methods used in the literature to evaluate equilibrium moisture contents. They experimentally determined the equilibrium moisture contents of medium grain rough rice with static method and compared different prediction equations.

Steffe et al. (1982) analyzed drying and tempering of short grain rough rice by using the equilibrium moisture content models presented by Zuritz et al. (1978). This equilibrium moisture content was developed from desorption isotherms using a static method for medium grain rough rice for temperatures less than 42.5°C.

$$M_e = (0.001)[(A/B)^C] \quad \text{................(2.47)}$$

where :

$$A = -\ln(1.0-RH)(T_a)$$
$$B = (1-T_a/641.7)^{-23.438}(2.667\text{x}10^{-7})$$
$$C = 1/(4\text{x}10)(T_a)^{-2.1166}$$

T_a is the absolute temperature of product (K).

For temperatures greater than 42.5°C, the equation (2.48) is recommended :

$$M_e = (A-B)/C \quad \text{...................(2.48)}$$

where : $A = \ln(-\ln RH)$

$B = \ln[2.387 \times 10^{9} \times T^{-3.444}]$

$C = (-0.02118)(T^{1.1852})$

M_e, T_a, and RH have been defined in Equation (2.47)

Vemuganti et al. (1980) presented coefficients for the Henderson-Thompson and Chung-Pfost equations for equilibrium relative humidity and equilibrium moisture content of 20 food grains including medium grain rough rice.

C.Laithong (1987) determined desorption isotherms of long grain rough rice of RD 7 and RD 23 varieties at temperature 30 to 60°C in the relative humidity range of 10 to 90 percent by using the static method. The mathematical models based on the equation of Henderson and Chung & Pfost were developed to fit the experimental data. The equations are as follows :

Henderson equation; RD 7 variety :

$$\text{Desorption} : 1-RH = \exp[-4.723\times10^{-6} \times T_a (100M_e)^{2.386}] \quad ....(2.49)$$

$$\text{Adsorption} : 1-RH = \exp[-7.147\times10^{-6} \times T_a (100M_e)^{2.287}] \quad ....(2.50)$$

Henderson equation; RD 23 Variety :

$$\text{Desorption} : 1-RH = \exp[-3.146\times10^{-6} \times T_a (100M_e)^{2.464}] \quad ....(2.51)$$

$$\text{Adsorption} : 1-RH = \exp[-4.584\times10^{-6} \times T_a (100M_e)^{2.397}] \quad ....(2.52)$$

Chung-Pfost equation; RD 7 variety :

Desorption : $\ln(RH) = \frac{-19021.05}{RT_a} \exp[-0.186(100\ M_e)]$ ....(2.53)

Adsorption : $\ln(RH) = \frac{-16530.48}{RT_a} \exp[-0.187(100\ M_e)]$ ....(2.54)

Chung-Pfost equation; RD 23 variety :

Desorption : $\ln(RH) = \frac{-21803.46}{RT_a} \exp[-0.187(100\ M_e)]$ ....(2.55)

Adsorption : $\ln(RH) = \frac{-20030.57}{RT_a} \exp[-0.189(100\ M_e)]$ ....(2.56)

where T_a is absolute drying air temperature (K) and RH is relative humidity of the drying air (decimal).

2-3 Physical and Thermal properties of rough rice

The following equations representing rough rice properties were used in the development of the model.

2-3.1 Specific heat of rough rice

C.Laithong (1987) determined the specific heat of long grain rough rice (RD7) to be :

$$C_p = 1.292 + 0.042\,\overline{M} \quad \text{...............} (2.57)$$

where

C_p = Specific heat of rough rice, kJ/Kg °C

$\overline{M}$ = Average moisture content of rough rice, % (D.B.)

2-3.2 Bulk density of rough rice

C.Laithong also found the following equation to express the bulk density of rough rice (RD 7) :

$$BD = 552.10 + 2.82\,\overline{M} \quad \text{.............} (2.58)$$

where

BD = Bulk density of rough rice, kg/m^3

$\overline{M}$ = Average moisture content of rough rice, % (D.B.)

2-3.3 Latent heat of vaporization in rough rice

The latent heat of water in rough rice was developed by Wang (1978).

$$L = (1795.44-0.811T)(\overline{M})^{-0.346} \qquad ....(2.59)$$

where

L = Heat of vaporization of water in rice, kJ/kg

T = Air temperature, K, and

$\overline{M}$ = Average moisture content of rough rice, %(D.B.)

2-4 Deep bed drying simulation

The drying behavior of grain can be predicted accurately by the thin-layer equations and most of the published works have dealt with this type of semi-theoretical and empirical equations. Many researchers have based their analysis on the heat and mass transfer in a thin-layer. The conditions of the exhaust air from a thin-layer are treated as the input conditions to the layer immediately above it.

Hukill (1954) suggested that after the airflow is started several factors may affect the instantaneous moisture content at any certain time. He assumed that the sensible heat of grain is negligible and the drying air temperature decreases exponentially as it rises through the deep bed. Considering these assumptions he developed a simple model which is the first attempt in deep-bed drying studies (Bakker-Arkema et al., 1974).

Thompson (1968) appears to present the empirical deep bed analysis that has been developed for a digital computer solution for corn drying. He first calculated an equilibrium drying temperature based on the sensible heat balance between air and grain. The equilibrium moisture content and the drying rate of the grain were then estimated using this temperature.

Bakker-Arkema et al. (1970, 1971, 1974) developed a series of theoretical fixed bed, concurrent, crossflow and counter-current dryer models. (MICHIGAN STATE MODELS OR MSU MODELS). The models were developed by considering enthalpy and mass balance on a differential volume.

Chan (1976) used the MSU fixed bed model to simulate the drying of rice in a bin. Several researchers (Evan et al.,1970; Lerew et al.,1972 ; Brook et al.,(1978) have simulated drying of other agricultural products with the aid of other models developed by Bakker-Arkema et al., (1974).

Spencer's (1969) model of wheat drying predicts drying rates well at both high and low moisture contents. However, the theoretical temperature curve deviate considerable from the experimental curve in the early period of the drying process.

Ingram (1976) developed deep bed dryer models for wheat and corn similar to Bakker-Arkema et al., 1969). Both models were based on intra-particle diffusion. Only one of the dryer models mentioned so far has been applied to rice drying (Chan, 1976).

Several other researchers introduced analytical and dimensional analysis in deep-bed studies. Nevertheless, over simplifications and assumptions limited the insight into the batch type drying. In recent years, the access to computers has permitted the development of more elaborate and sophisticated models with considerably less questionable assumptions.