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**DRYING PRINCIPLES AND THEORY:
AN OVERVIEW**

O.V. Ekechukwu¹
International Centre for Theoretical Physics, Trieste, Italy.

ABSTRACT

A comprehensive review of the fundamental principles and theories governing the drying process is presented. Basic definitions are given. The development of contemporary models of drying of agricultural products are traced from the earliest reported sorption and moisture equilibrium models, through the single kernel of product models to the thin layer and deep bed drying analysis.

MIRAMARE - TRIESTE
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¹Permanent address: Energy Research Centre, University of Nigeria, Nsukka, Nigeria.

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INTRODUCTION

Drying is simply the process of moisture removal from a product. It can be carried out by various methods for a variety of different substances from solids to gases and even liquids [1]. Drying can be achieved chemically by using chemical desiccants or by chemical decomposition of the water in the substance. Freeze drying can be employed for water removal in liquids as well as solids. Water is often removed from gases or solids by absorption as in the removal of water vapour from gases or solids by capillary action. Drying can also be achieved mechanically by compression, centrifugal forces or gravity. Thermal drying, which is the form most used commonly for drying agricultural products, involves the vapourisation of moisture within the product by heat and its subsequent evaporation from the product. Thermal drying thus involves simultaneous heat and mass transfer. The sensible heat of air is reduced as it is utilised for moisture evaporation. The total heat content remains constant, since this loss of sensible heat is regained as latent heat of vapourisation of the moisture now present in the air. Depending on the product, moisture transfer from within the product to the surface (because of moisture gradient) is as liquid or vapour, while as vapour only, from the surface.

Conventional drying systems are classified usually (according to their operating temperature ranges) into low and high temperature dryers. In the low temperature drying systems, the moisture content of the product is brought in equilibrium usually with the drying air, by constant ventilation. These systems enable crops to be dried in bulk or for long term storage. They are thus, referred to usually as bulk or storage dryers [2]. They are most appropriate where preservation of certain nutrients in the product are desired [3] and for crops intended for re-planting. High temperature dryers are used when fast drying is desired and crops require a short exposure to the drying air. Temperatures are such that if the drying air remains in contact with the crop until equilibrium moisture is reached, serious over-drying will occur, thus the product are dried to the desired moisture content and cooled later. High temperature dryers are classified into batch or continuous flow dryers. In the batch systems, the product are dried within a bin and subsequently moved to storage [4]. Continuous flow systems, are heated columns through which the product flows by gravity and exposed to heated air while descending [1]. Different heat sources are employed for the drying of agricultural products, most common being fossil fuels, electricity and solar. Since the mid 1950s, an extensive amount of work has been reported on the basic principles and fundamental theories of crop drying. The development of these drying concepts from earlier models are discussed.

BASIC DEFINITIONS

Moisture Content

The quantity of moisture present in a material can be expressed either on the wet basis or dry basis and expressed either as decimal or percentage.

The moisture content on wet basis is the weight of moisture present in a product per unit

weight of the undried material, represented as,

$$M_{wb} = \frac{W_o - W_d}{W_o} \quad (1)$$

while the moisture content on dry basis is the weight of moisture present in the product per unit weight of dry matter in the product and represented as,

$$M_{db} = \frac{W_o - W_d}{W_d} \quad (2)$$

$$\text{Percentage } M_{wb} = M_{wb} \times 100 \quad (3)$$

$$\text{Percentage } M_{db} = M_{db} \times 100 \quad (4)$$

The moisture content on wet and dry basis are inter-related according to the following equations,

$$M_{wb} = 1 - \left[\frac{1}{(M_{db} + 1)} \right] \quad (5)$$

and

$$M_{db} = \left[\frac{1}{(1 - M_{wb})} \right] - 1 \quad (6)$$

The relationship between moisture content on the wet and dry basis is illustrated in figure 1. The moisture content on wet basis is used normally for commercial purposes while the moisture content on dry basis has tended to be employed for engineering research designation, because the weight change associated with each percentage point of moisture reduction on the dry basis is constant as against the wet basis where the amount of water involved in a moisture content reduction of one percent changes as drying progresses, because weight of water and total crop weight change [1,4,5].

For drying experiments, where weight losses are recorded, the instantaneous moisture contents at any given time can be computed according to the following equations;

$$M_{tdb} = \left[\frac{(M_{odb} + 1)W_o}{W_t} \right] - 1 \quad (7)$$

$$M_{twb} = 1 - \left[\frac{(1 - M_{owb})W_o}{W_t} \right] \quad (8)$$

Equilibrium Moisture Content

A crop has a characteristic water vapour pressure at a particular temperature and moisture content. This determines if the crop will absorb or desorb moisture on exposure to air. The equilibrium moisture content of a hygroscopic product thus refers to the moisture content of the product after it has been exposed to a particular environment for an indefinitely long period of time. At this moisture content, the vapour pressure exerted by the moisture held within the product equals the vapour pressure of the immediate surrounding air. This implies an equilibrium condition, thus the rate of moisture desorption by the product to its immediate surrounding equals its rate of moisture absorption from the environment. The relative humidity of the immediate surrounding air at this condition (which is also in equilibrium with its environment) is referred to as the equilibrium relative humidity. If the surrounding air is replaced continuously by air of lower vapour

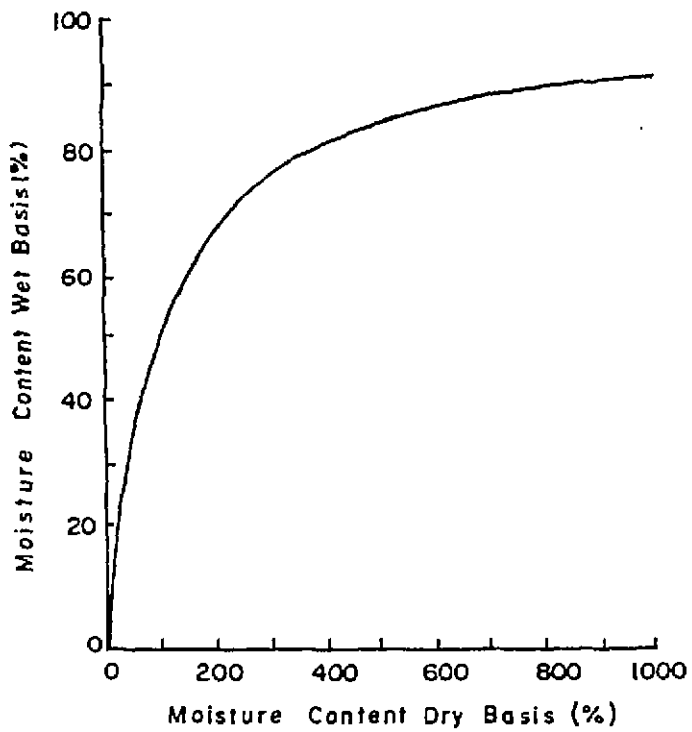


Fig. 1: Relationship Between Moisture Content on (Dry Basis and Wet Basis)

pressure, a vapour deficit is created and the crop will continue to desorb moisture to the air. Equilibrium moisture content is affected by such properties as variety, maturity and crop history (which may significantly change the chemical composition of the crop). Crops with high oil content tend to absorb less moisture from the surrounding air than starchy crops [4].

Equilibrium moisture content can be determined experimentally by thermostatically controlling the air temperature in an enclosure containing the crop while the vapour pressure of the surrounding air is regulated with either acid or saturated salt solution. A fairly more accurate, though more expensive method of determining equilibrium moisture content is by the use of an evacuated container. The temperature and vapour pressure of the enclosure and the moisture content of the crop are recorded when equilibrium between the crop and its surrounding is reached, i.e. after moisture diffusion from the crop to the vacuum has ceased. Equilibrium moisture content plots against relative humidity at constant temperature result in sigmoid curves referred to as moisture equilibrium isotherms [4].

Latent Heat of Vapourisation

This is the amount of energy that must be absorbed by the product to vapourise moisture from it. The latent heat of vapourisation is absorbed from the surrounding air as it flows past the product. It depends on the product, its moisture content and temperature. The higher the moisture content and temperature, the lower the heat of vapourisation. The variation of heat of vapourisation of some grains with moisture content and temperature [4, 6] is shown in figure 2.

Safe Storage Time

This is the period of exposure of a product at a particular moisture content to a particular relative humidity and temperature below which crop deterioration may occur and beyond which the crop may be impaired. To keep losses low, crops must be dried to the safe storage moisture content (i.e. *moisture content required for long term storage*) within the safe storage time. At high temperatures and high moisture contents, the crop would require a short time to dry. High temperatures should be avoided for crops for re-planting. Figure 3 shows the safe storage period for corn at different temperatures and moisture contents [4, 6] which indicates that for hot and humid climates where crops are harvested at relatively high moisture contents, the safe storage time is short. An illustration of the maximum heating time for some grains at different temperatures and moisture contents that will not impair the grain viability is shown in figure 4 [6].

MOISTURE EQUILIBRIUM MODELS

A number of attempts [7-23] have been made at theoretical, semi-theoretical and empirical modelling of moisture equilibrium in crops, though mainly in cereal grains. Theoretical equilibrium moisture content equations have fallen short of accurately predicting equilibrium moisture content of most crops over wide ranges of temperatures and relative

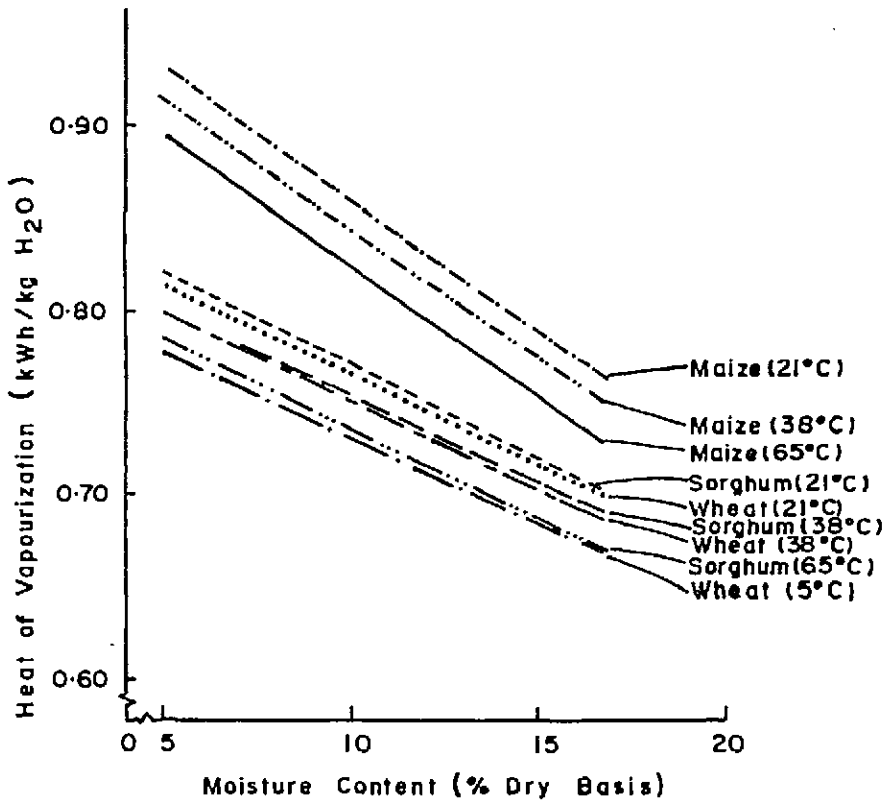


Fig.2: The Variation of Heat of Vapourization of Types of Grain with Moisture Content and Temperature

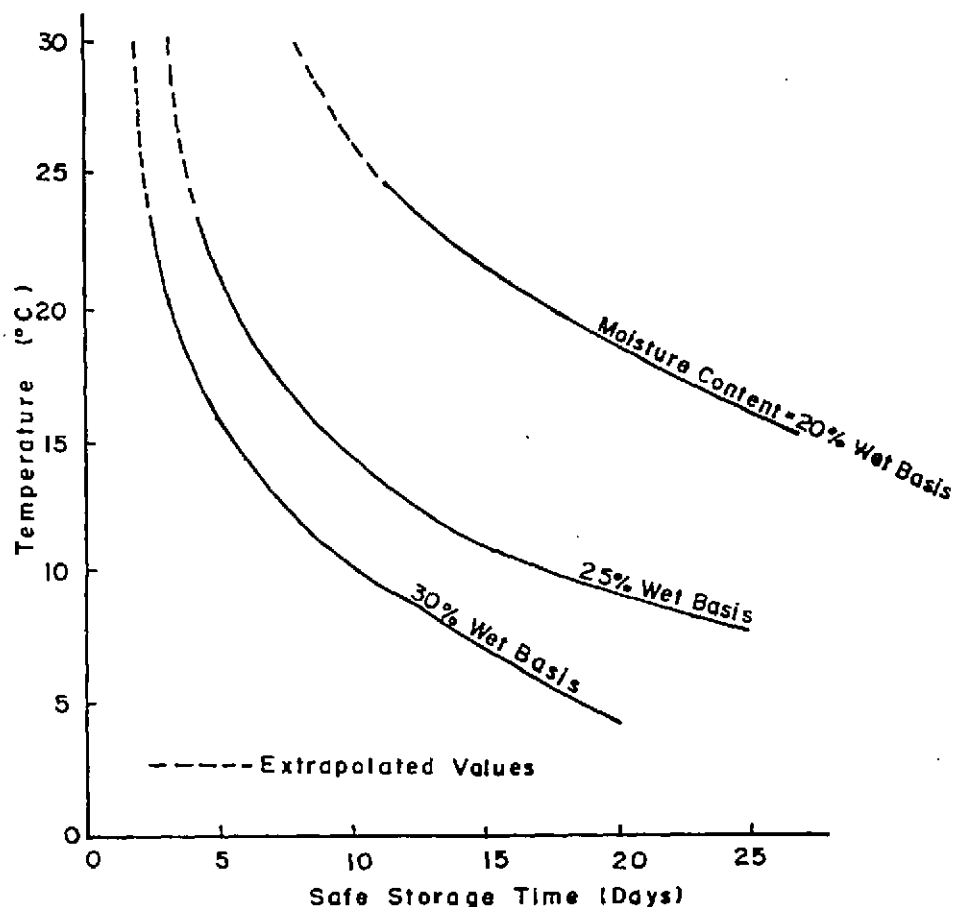


Fig. 3: Safe Storage Period for Corn at Different Temperatures and Moisture Contents

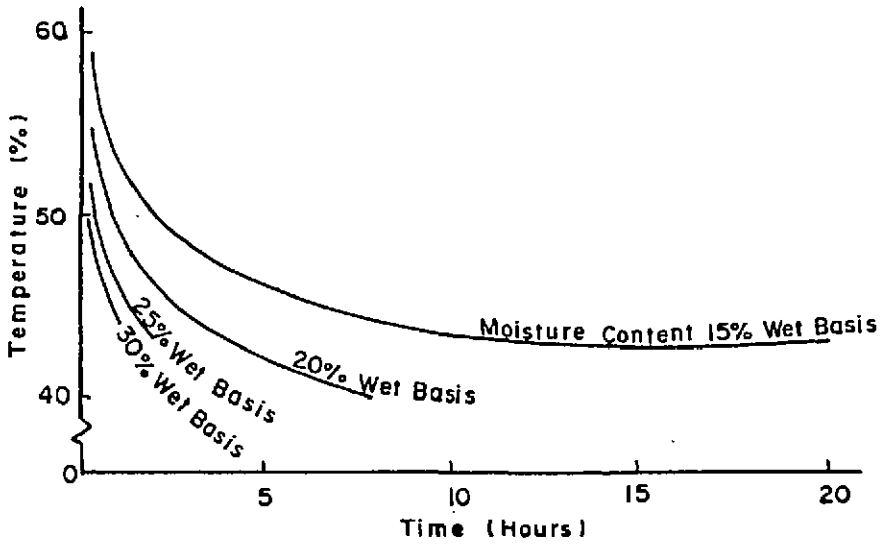


Fig.4: Maximum Heating Time for Grain at Different Temperatures and Moisture Contents in Order not to Destroy Grain Viability

humidities due to over simplification of assumptions in the development of the models. They do however enhance the understanding of the physics of moisture sorption. Purely empirical equations for specific conditions offer better alternatives until fairly accurate theoretical or semi-theoretical models are developed.

Equation (9) describes a model by Kelvin [7] which considers moisture absorption in a solid based on capillary condensation within the pores of the material. The Kelvin equation expresses the relationship between the vapour pressure over a liquid in a capillary and the saturated vapour pressure at same temperature, thus,

$$\ln \left(\frac{P_v}{P_{vs}} \right) = \frac{2\sigma V \cos \alpha}{r' R_g T} \quad (9)$$

The major shortfall of Kelvin's model is its limitation to very high relative humidity range (> 95%) [4] where capillary condensation occurs.

The isothermal moisture equilibrium model by Langmuir [8] is based on the classical kinetic model of balance of evaporation and condensation rates of vapour on a monolayer of water vapour on the internal surface of materials. This gives the volume of water absorbed by a product isothermally at a vapour pressure P_v as,

$$V_v = V_m \left[\frac{b P_v}{(1 + b P_v)} \right] \quad (10)$$

The limitation of this model is that it does not account for multilayer absorption and the interaction between the absorbed water molecules [4]. Brunauer et al [9] modified Langmuir's model to account for multilayer absorption (equation (11)), by assuming the internal surfaces of the material as composed of an array of absorption sites capable of absorbing more than one molecule of water as against Langmuir's assumption of monolayer of moisture absorption.

$$\frac{P_v}{V_v(P_{vs} - P_v)} = \frac{1}{V_m c} + \left(\frac{c-1}{V_m c} \right) \left(\frac{P_v}{P_{vs}} \right) \quad (11)$$

Equation (12) by Harkins and Jura [10] based on the theory of an existence of a potential field above the material surfaces, considers a balance between the work required to absorb or desorb a molecule of water and the sum of work against the potential field in bringing a vapour molecule to the surface and the energy of condensation.

$$\ln(P_v/P_{vs}) = d - e/V_v^2 \quad (12)$$

Equation (13) developed by Smith [11] considers sorbed moisture as made up of bound moisture held by intermolecular forces which are in excess of forces for condensation and unbound (normally condensed) moisture. This model assumes the multilayer concept in Brunauer et al [9] for condensed moisture and uses Langmuir's model [8] for the relationship between the bound moisture and relative humidity.

$$V_v = f - g \ln(1 - P_v/P_{vs}) \quad (13)$$

Henderson's semi-theoretical model [12] which is the most versatile moisture equilibrium model yet, expresses the relationship between the equilibrium moisture content and equilibrium relative humidity at a given temperature as,

$$1 - \phi_e = e^{-kTM_e^2} \quad (14)$$

Figure 5 shows plots of Henderson's predictions for the following crops;

- shelled corn ($k = 1.10 \times 10^{-5}$, $n = 1.90$ at $T = 298K$) [13, 14],
- wheat ($k = 5.59 \times 10^{-7}$, $n = 3.03$ at $T = 305.2K$) [15],
- sorghum ($k = 3.40 \times 10^{-6}$, $n = 2.31$ at $T = 294.1K$) [16],
- soybeans ($k = 3.20 \times 10^{-5}$, $n = 1.52$ at $T = 298K$) [17] and
- cotton ($k = 4.91 \times 10^{-5}$, $n = 1.70$ at $T = 298K$) [18].

Re-arranging equation (14) gives the relationship between equilibrium moisture content and temperature at constant relative humidity, as,

$$\frac{\ln(1 - \phi_e)}{-kT^n} = M_e^n \quad (15)$$

Figure 6 [12] shows that the equilibrium moisture content at a given relative humidity varies little with temperature over a small temperature range, the net effect being a slight decrease in moisture content at that relative humidity.

A number of empirical modifications to Henderson's equation have been made to accurately account for specific cases. Day and Nelson [19] modified Henderson's equation for wheat thus,

$$1 - \phi_e = e^{-j\Delta T^k} \quad (16)$$

where $j = 5.7336 \times 10^{-10} T^{3.3718}$ and $k = 14.863 T^{-0.41733}$

while Thomson's empirical modification [20] for corn was of the form,

$$1 - \phi_e = e^{-a'(T+50)M_e^{b'}} \quad (17)$$

where $a' = -3.8195 \times 10^{-5}$ and $b' = 2$

A purely empirical equation developed by Haynes [21], gave the following relationship for the equilibrium moisture content of seeds.

$$\ln P_v = p_1 + p_2 \ln P_{vs} + p_3 \ln M_e + p_4 \ln P_{vs}^2 + p_5 \ln P_{vs} M_e \quad (18)$$

where $p_1 - p_5$ are product constants.

Hayne's equation gives a good agreement with experimental results within the relative humidity and temperature ranges the product constants are determined [4]. Bakker-Arkeina et al [22] also developed a set of empirical equations for shelled corn, each corresponding to some short ranges of relative humidity, which gives reasonable agreement with experimental data within temperature ranges of $4^\circ C - 60^\circ C$ [23].

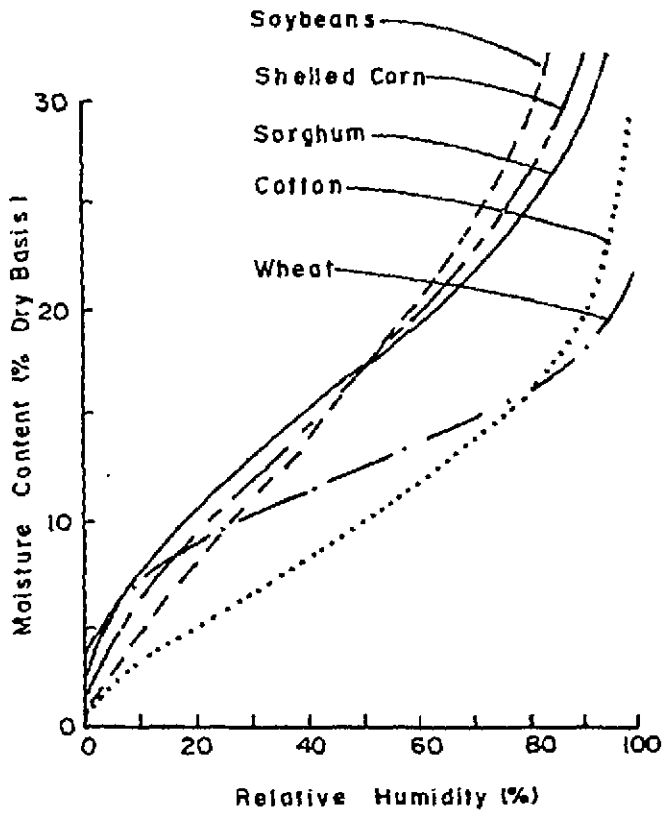


Fig. 5: Henderson's Equilibrium Moisture Predictions for Shelled Corn, Wheat, Sorghum, Soybeans and Cotton

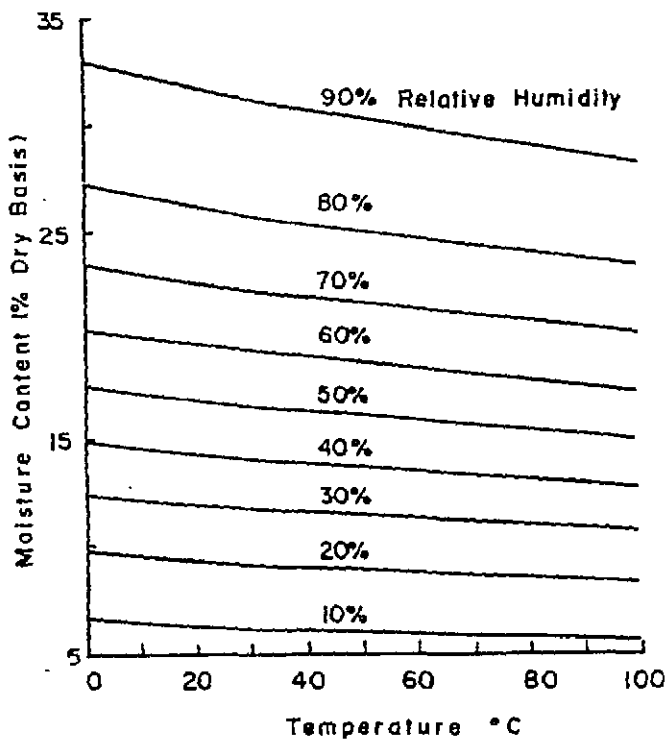


Fig.6: Effect of Temperature on The Equilibrium Moisture Content of Shelled Corn (From Henderson's Model)

DRYING RATES

Agricultural products differ from most other materials dried frequently such as textiles in a laundry, sand, stone, dust or paper. These latter materials are referred to as non-hygroscopic and moisture within them are "loosely" held and regarded as "unbound" [3]. For agricultural products (which are hygroscopic), the moisture held within them are usually "bound" moisture such as moisture trapped in closed capillaries, the water component of juices or water held by surface forces as well as unbound water held within the material by the surface tension of the water itself. For non-hygroscopic materials, drying can be carried out to zero moisture content while for agricultural products, there is always a residual moisture [3].

When a product is heated at constant moisture content, its vapour pressure increases. This results in moisture movement to its environment which is at a lower vapour pressure. The rate of moisture flow is only approximately proportional to its vapour pressure difference with the environment because of the crop resistance to moisture flow. There are two main drying rate regimes for agricultural products, namely the constant drying rate period and the falling drying rate period.

Constant Drying Rate Period

During the constant drying rate period (see figure 7 [1]), drying takes place from the surface of the product and is simply the evaporation of moisture from the free-water surface. Rate of moisture removal during this period is mainly dependent on the surrounding conditions and only affected slightly by the nature of the product. During this period, the product surface is saturated with moisture with its temperature fairly constant and approximately equal to the wet bulb temperature. The end of the constant drying rate period is marked by a decrease in the rate of moisture migration from within the product, below that sufficient to replenish the moisture being evaporated from the surface. At this stage referred to as the **critical moisture content** (see fig. 7), environmental conditions cease to play much role in the rate of drying. For non-hygroscopic materials, all drying takes place within the constant drying rate regime. The environmental factors, namely the vapour pressure difference between the drying air and the wet surface, the surface area of the product exposed to the drying air, the mass transfer coefficient and the drying air velocity are related to the drying rate according to the following [1, 24],

$$\frac{dw}{dt} = \frac{K_m A_s}{R_a T} (P_v - P_{va}) = K_f \frac{A(T_a - T_s)}{L} \quad (19)$$

The thermal conductance of the air film, K_f , is a function of the air velocity.

Falling Drying Rate Period

The critical moisture content of the product which is the minimum moisture content at which the minimum rate of free moisture migration from within the product to the surface equals the maximum rate of moisture evaporation from the surface [1], is thus an equilibrium condition. Beyond the critical moisture content is the falling drying rate period (see fig. 7). This drying rate regime is dependent essentially on the rate of diffusion

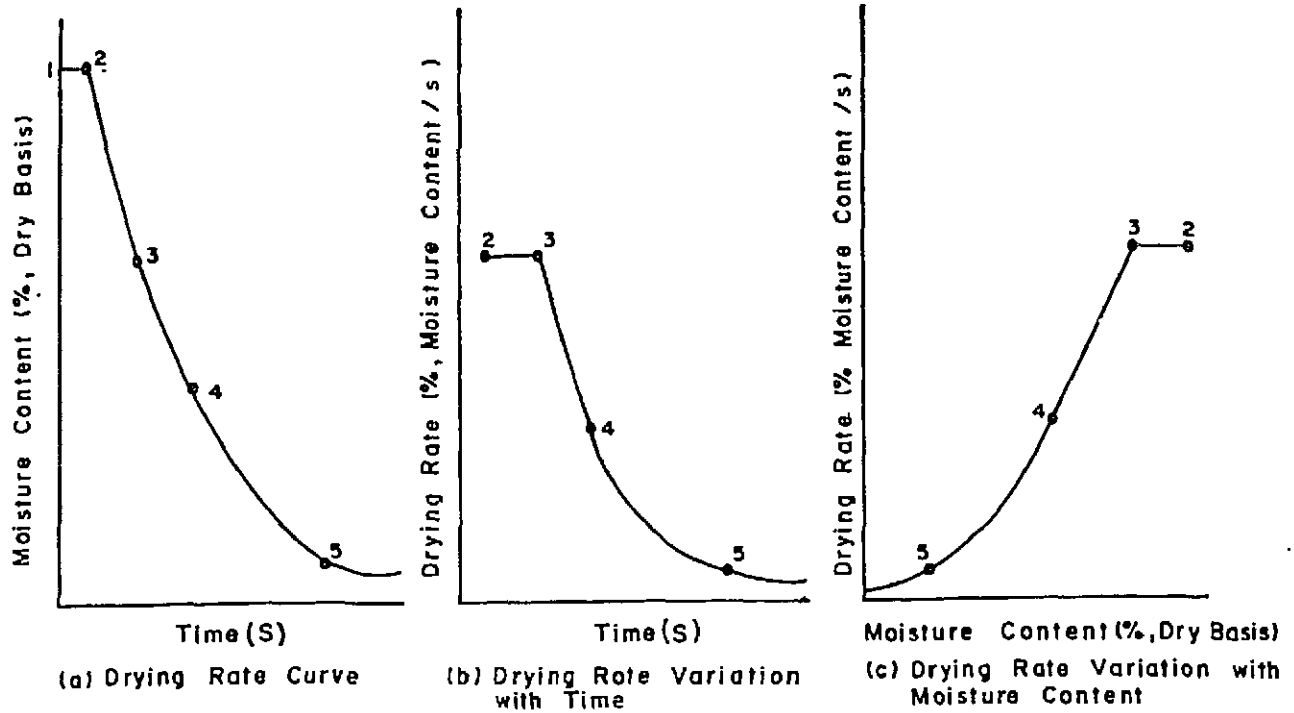


Fig. 7 : Schematic Illustration of Drying Rate Periods

- 1--2 The Heating Period (Constant Moisture Constant)
- 2--3 The Constant Rate Drying Period
- 3 The Critical Moisture Content
- 3--4 The First Falling Rate Period
- 4--5 The Second Falling Rate Period

of moisture from within the product to the surface and also on moisture removal from the surface. It is subdivided usually into two stages, namely [1];

- the first falling drying rate period which involves the unsaturated surface drying and
- the second falling drying rate period where the rate of moisture diffusion to the surface is slow and is the determining factor.

For agricultural products, the duration of each of these drying regimes, depends on the initial moisture content and the safe storage moisture content. For grains, the initial moisture content is below the critical moisture content usually, thus all drying takes place within the falling rate regime. However, for fruits, most vegetables and most tropical tuber crops, the initial moisture content is above the critical moisture content usually, thus the drying of these products would take place within both the constant and falling rate periods. Both the external factors and internal mechanisms controlling the drying processes in the two main rate regimes are important in determining the overall drying rate of products.

THIN LAYER DRYING ANALYSIS

An assumption inherent in the moisture equilibrium models is that the exhaust air is in vapour equilibrium with the moisture in the material. This is a condition of maximum drying rate which is not the situation usually. Drying rate, thus would vary with other parameters which the moisture equilibrium drying analysis neglects.

In the conventional approach to modelling thin layer drying, the assumption is that the ratio of volume of air to crop volume is infinitely large. It thus, defines a characteristic drying rate which is only dependent on seed type and size, moisture content and drying air temperature [5]. The combination of external effects as represented by the driving force of moisture movement and the internal factors of crop resistance to moisture flow can be represented by re-writing equation (19), thus [1],

$$\frac{dM}{dt} = -\frac{P_v - P_{va}}{(1/K_m A_s)R_o T} = -\frac{K_m A_s (P_v - P_{va})}{R_o T} \quad (20)$$

$(P_v - P_{va})$ represents the external driving force due to environmental conditions while $(1/K_m A_s)$ is the crop resistance parameter. A similar equation by Hukill [25], relates the moisture transfer between a material and the drying air to the drying rate as follows,

$$\frac{dM}{dt} = -c'(P_v - P_{va}) \quad (21)$$

where

$P_v > P_{va}$ implies drying taking place

$P_v = P_{va}$ implies an equilibrium condition and no net moisture transfer

$P_v < P_{va}$ implies moisture re-absorption from air by the material.

Assuming a linear relationship between P_v and the moisture content of the material and assuming also that P_{va} is proportional to the equilibrium relative humidity, which is in

turn linear with equilibrium moisture content over the range of values in which drying takes place (see fig. 5), then equation (21) can be re-written as,

$$\frac{dM}{dt} = -K'(M_t - M_e) \quad (22)$$

The negative sign indicates decrease in moisture content with time.

Separating the variables and integrating within time limits 0 and t , and moisture content limits M_o and M_e , the solution to equation (22) becomes,

$$\frac{(M_t - M_e)}{(M_o - M_e)} = e^{-k't} \quad (23)$$

introducing the shape factor of the crop, a [26], equation (23) becomes,

$$\frac{(M_t - M_e)}{(M_o - M_e)} = e^{-ak't} \quad (24)$$

A purely theoretical model developed by Luikov [27] for describing the drying of capillary porous products was based on such physical mechanisms of moisture diffusion, such as vapour migration due to moisture concentration gradient (i.e. vapour diffusion), temperature gradient dependent vapour diffusion (i.e. thermal diffusion), water and vapour migration due to total pressure differences (i.e. hydrodynamic flow), surface forces dependent liquid flow (i.e. capillary flow), moisture gradient dependent liquid migration (i. e. liquid diffusion) and liquid diffusion dependent on diffusion of moisture on the pore surfaces (i.e. surface diffusion). Luikov's model is a set of partial differential equations of the form,

$$\frac{\partial M}{\partial t} = \nabla^2 k_{11}M + \nabla^2 k_{12}T + \nabla^2 k_{13}P \quad (25)$$

$$\frac{\partial T}{\partial t} = \nabla^2 k_{21}M + \nabla^2 k_{22}T + \nabla^2 k_{23}P \quad (26)$$

$$\frac{\partial P}{\partial t} = \nabla^2 k_{31}M + \nabla^2 k_{32}T + \nabla^2 k_{33}P \quad (27)$$

where

k_{11} , k_{22} and k_{33} are specific phenomenological coefficients and k_{12} , k_{13} , k_{21} , k_{23} , k_{31} , and k_{32} are coupling coefficients.

The application of Luikov's model has been limited because of the lack of knowledge of the phenomenological coefficients for most agricultural products. The coupling coefficients account for the combined effect of moisture, temperature and total pressure gradients on moisture, total mass and energy transfers. However, since total pressure differences are only significant at relatively high temperatures (above drying temperatures usually) and assuming temperature differences within the product are negligible, the pressure and temperature terms in equation (25) can be dropped leading to more simplified form of the model, thus,

$$\frac{\partial M}{\partial t} = \nabla^2 k_{11}M \quad (28)$$

The phenomenological coefficient k_{11} , is referred to as diffusion coefficient, D , since moisture migration within most products is agreed to be by diffusion. For constant values of D , equation (28) can be re-written as,

$$\frac{\partial M}{\partial t} = D \left[\frac{\partial^2 M}{\partial r^2} + \frac{a}{r} \frac{\partial M}{\partial r} \right] \quad (29)$$

where

$a=0$ for planes

$a=1$ for cylindrical shapes and

$a=2$ for spherical shapes [4].

The initial and boundary conditions usually assumed for solving equation (29) are [4],

$$M(r, 0) = M_o \quad (30)$$

and

$$M(r_o, t) = M_e \quad (31)$$

Numerous empirical equations have been proposed for the drying rates of a series of products [4, 20, 28, 29]. Thompson's empirical model [20] for predicting the drying time of shelled corn in the temperature range of $60^\circ\text{C} - 149^\circ\text{C}$ is given as,

$$t = A' \ln \left\{ \frac{(M_t - M_e)}{(M_o - M_e)} \right\} + B' \left\{ \ln \left\{ \frac{(M_t - M_e)}{(M_o - M_e)} \right\} \right\}^2 \quad (32)$$

where

$$A' = 1.86178 + 0.00488T$$

$$B' = 427.3640t^{-0.033017}$$

DEEP BED DRYING ANALYSIS

Consider a schematic illustration of a deep layer drying system as shown in figure 8. The drying air moves from the bottom to the top of the crop bed. Generally, as the drying air moves through the crop mass, it abstracts moisture from the crop assuming it is at a higher temperature and lower humidity. This moisture movement from the crop to the drying air takes place largely in a clearly defined depth of the crop bed regarded as the drying zone. At the commencement of drying, this zone would exist at the bottom of the bed and moves upwards in the direction of the drying air as drying progresses until the zone passes through the entire crop mass. This thus, keeps the entire crop in moisture equilibrium with the drying air.

In figure 8, the established drying zone is midway in the crop bed. The crop mass below this zone has reached moisture equilibrium with the drying air and has a moisture content equal to the equilibrium moisture content, M_e . In the crop mass above the drying zone, drying has not commenced, thus the crop still has the initial moisture content, M_o . Air passing through this zone would still be in equilibrium with the initial crop moisture. As the drying air passes through the crop mass, no further drying takes place below the drying zone which is at moisture equilibrium with the drying air. Drying would only take place within the drying zone where a moisture difference exists until the air gets to

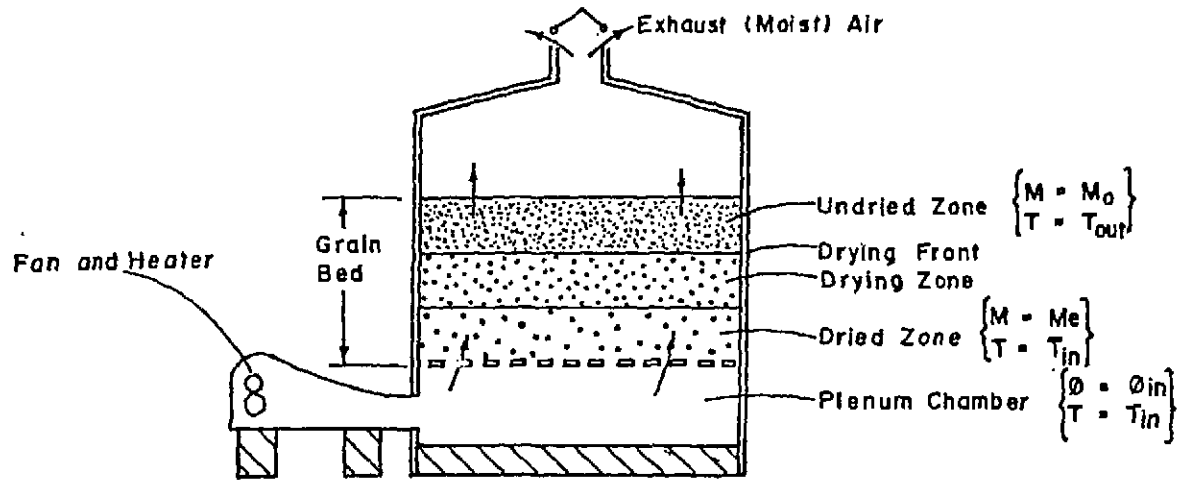


Fig.8 Schematic Illustration of Deep Bed Drying

moisture equilibrium with M_o , above the drying front. Moisture abstraction from the crop is by evaporation resulting in the cooling of the drying air to T_{out} . There is thus a resulting moisture content gradient from M_e to M_o , a temperature gradient from T_{in} to T_{out} and consequently a relative humidity gradient Q_{in} to Q_{out} . It is assumed that the crop temperature along the entire depth is equal to the air temperature at any point. The moisture gradient created is a measure of the drying rate. For fixed bed drying systems, the bed depth, air flow rate and drying temperature are critical factors. For shallow crop beds under high air flow rates, the drying zone may extend completely through the bed and the desired final average moisture content reached before the bottom layer reaches equilibrium with the drying air. This ensures that over-drying does not result. However, for high crop depths, there is a tendency to have over-drying for regions below the drying zone. The temperature and air flow rates should be chosen such that the equilibrium moisture content of the crop for this condition is the desired moisture content. One major difference between the deep layer analysis and the thin layer model is that the air flow rate in the thin layer model is not as critical as in the deep layer model.

Assuming that the sensible heat loss by the drying air to the crop is equal to the latent heat of vapourisation for the crop and neglecting temperature changes in the crop, and condensation which may occur at the upper layers of the crop mass at the start of the drying process, a heat balance for the drying process can be written as,

$$\rho_a F C_a (T_{in} - T_{out}) t = W_d (M_o - M_e) L \quad (33)$$

Introducing the heat transfer coefficient, h , from the air to the wet surface of the crop, (which is proportional to the air flow rate), as,

$$h = \frac{\rho_a F C_a}{A} \quad (34)$$

and including the cross-sectional area of the drying bed, A (in contact with the drying air at any instance), equation (33) becomes,

$$\frac{dw}{dt} = h A \frac{(T_{in} - T_{out})}{L} = \frac{h A dT}{L} \quad (35)$$

Deep layer drying is usually associated with two drying rate periods, namely, the maximum drying rate period and the decreasing drying rate period. The maximum drying rate period is from the commencement of the drying to when the drying front reaches the top of the bed and is represented by the following equation [1],

$$\frac{M_o - M_1}{t_1} = \frac{d\bar{M}}{dt} = A F_m \frac{(H_s - H_o)}{W_d} \quad (36)$$

thus

$$t_1 = \frac{W_d (M_o - M_1)}{A F_m (H_s - H_o)} \quad (37)$$

The rate of drying during this period is dependent solely on the moisture carrying capability of the drying air.

The decreasing rate period commences immediately the drying front reaches the top of the bed as represented thus [1],

$$\frac{dM}{dt} = K' (\bar{M} - M_e) \quad (38)$$

given $K' = 2.3K^n$ [1]

$$t_2 = \frac{1}{K^n} \log \frac{(M_1 - M_e)}{(M_2 - M_e)} \quad (39)$$

and

$$t_t = t_1 + t_2 \quad (40)$$

PSYCHROMETRIC ANALYSIS OF CROP DRYING

The drying process depends largely on the changes which occur in the properties of moist air (i.e. dry air and water vapour) which constitutes the drying air. Psychrometrics is an organised presentation of these properties. Consider a simple psychrometric chart (fig. 9) reproduced from [3]. The ordinate represents absolute humidity with the dry bulb temperature as the abscissa. The dew point temperatures are located on the uppermost curve which is the saturation line corresponding to 100% relative humidity. The constant relative humidity curves are the subsequent curves below the saturation line. The constant wet bulb lines are the straight lines sloping gently downwards to the right while the corresponding steeper lines represent the constant specific volume lines. The process of heating or cooling at constant absolute humidity are along the horizontal lines. Relative humidity decreases with heating along this line and increases with cooling. The wet bulb lines correspond to adiabatic cooling lines (lines of constant enthalpy) resulting from evaporative cooling of air flowing over a wet surface and gaining latent heat of vapourisation.

A drying process may employ unheated or preheated air. As the air flows past the product, heat is transferred to the product from the air. This results in vapourisation of moisture from the product to the air (simultaneous heat and mass transfer process) and subsequent increase in the air relative humidity since the process occurs with a decrease in the dry bulb temperature at constant wet bulb temperature. A schematic illustration of the psychrometrics of a typical drying process is shown in figure 10.

Consider an unsaturated ambient air at dry bulb temperature, T_1 and wet bulb temperature, T_{w1} and at relative humidity, ϕ_1 , with absolute humidity of H_1 . The moisture carrying capacity of this air depends on if it is heated or not. Assuming the air were to be used in drying without preheating, the process will progress along the constant wet bulb T_{w1} adiabatic cooling line AB (in fig. 10). The sensible heat loss from the air evaporates moisture from the crop. If the process were to continue to saturation, it would correspond to a final absolute humidity of H_2 . This would imply a maximum moisture carrying capacity of $H_2 - H_1$. If however, the same ambient air were to be preheated (before using it for drying), at a constant absolute humidity of H_1 , to a dry bulb temperature of T_2 , corresponding to a lower relative humidity, ϕ_2 (line AC in fig. 10), the drying process would now follow the adiabatic cooling line corresponding to the new wet bulb temperature, T_{w2} (line CD in fig. 10). At saturation, it would have a new absolute humidity of H_3 . This corresponds to a maximum moisture carrying capacity of $H_3 - H_1$. Within the temperature range that crop drying occurs, the moisture carrying capacity of 1kg of unsaturated moist air is increased by $3.6 \times 10^{-4} kg$ per $^{\circ}C$ increase in its temperature [1]. The minimum volume of air required to hold a certain quantity of moisture can be calculated, assuming the dryer exhaust air is at 100% relative humidity. A relatively small amount of heating can greatly enhance the moisture carrying capability of air. Heating

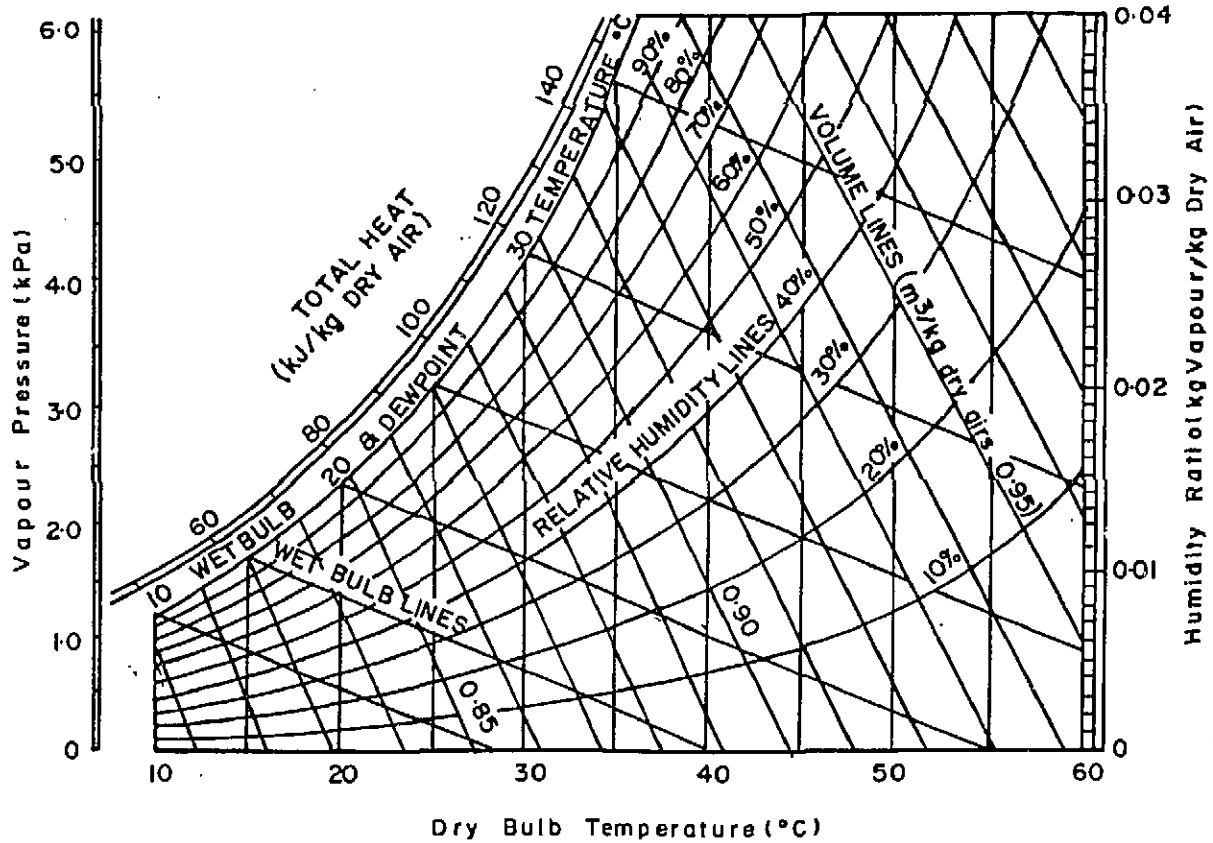


Fig.9 Psychrometric Chart for Barometric Pressure of 101-325 kPa

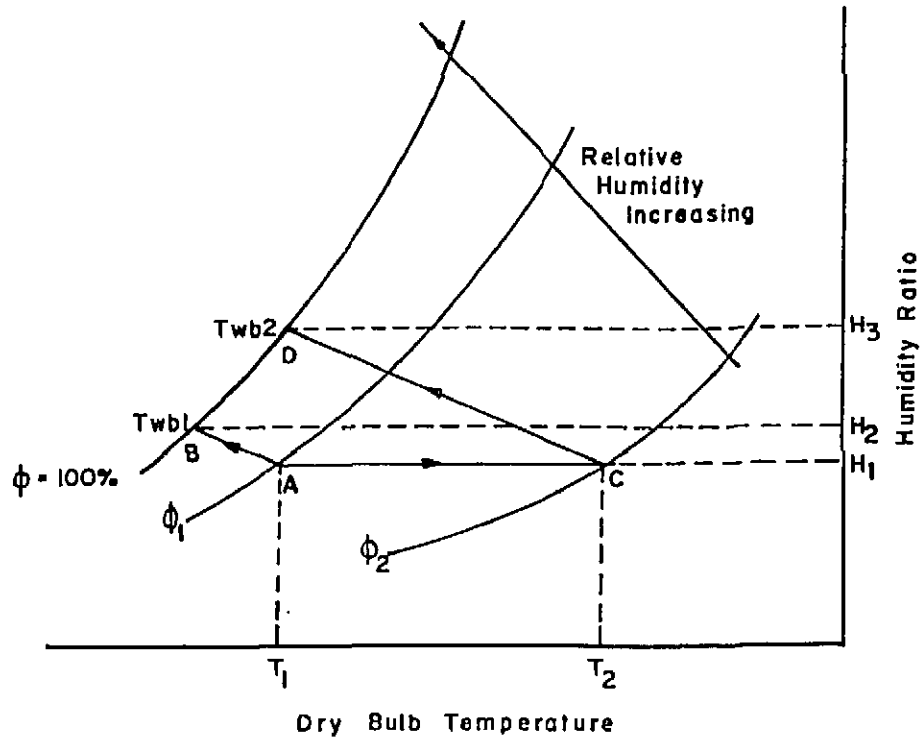


Fig.10: Schematic Illustration of the Psychrometrics of Drying Process

air say from a temperature of 20°C at 59% relative humidity to a temperature of 35°C at 25% relative humidity, increases its moisture holding capability three times [3]. This illustrates the enormous advantage of preheating air in the drying process.

CONCLUSION

A comprehensive review of the fundamental principles and theories governing the drying of agricultural products has been presented. A chronological development of the purely theoretical, semi-theoretical and empirical models has been outlined. Theoretical models have fallen short of predicting accurately the exact processes involved in drying, due to over simplification of assumptions. Empirical models for specific products and conditions, offer better predictions.

NOMENCLATURE

A	Dryer cross-sectional area (m^2)
A_s	Crop surface area (m^2)
a	Crop shape factor
b	Constant in equation (10); dependent on material and its temperature
C_a	Specific heat capacity of air ($Jkg^{-1}K^{-1}$)
c	Constant in equation (11); related to heat of absorption of water vapour
c'	Constant; dependent on material
D	Diffusion coefficient
d	Constant in equation (12); dependent on material and its temperature
e	Constant in equation (12); dependent on material and its temperature
F	Air flow rate (m^3s^{-1})
F_m	Mass flow rate ($kgm^{-2}s^{-1}$)
f	Constant in equation (13); dependent on temperature
g	Constant in equation (13); dependent on temperature
H_o	Humidity of inlet air
H_s	Humidity of saturated air in dryer
h	Heat transfer coefficient ($WK^{-1}m^{-2}$)
K	Constant in equation (14); dependent on product
K'	Drying constant (s^{-1})
K''	Deep bed drying constant (s^{-1})
K_{11}, K_{22}, K_{33}	Specific phenomenological coefficients in equations (25)–(27)
$K_{12}, K_{13}, K_{21},$ K_{23}, K_{31}, K_{32}	Coupling coefficients in equations (25)–(27)
K_f	Thermal conductance of air film ($Wm^{-2}K^{-1}$)
K_m	Mass transfer coefficient of water vapour ($kg s^{-1}m^{-2}$)
L	Latent heat of vapourisation (Jkg^{-1})
M	Moisture content (decimal, dry basis)
\bar{M}	Average moisture content of crop bed (decimal, dry basis)
M_1	Moisture content at end of maximum rate period in deep bed drying (decimal, dry basis)
M_2	Final moisture content in deep bed drying (decimal, dry basis)

M_c	Equilibrium moisture content (decimal, dry basis)
M_o	Initial moisture content (decimal, dry basis)
M_t	Moisture content at time, t (decimal, dry basis)
n	Constant in equation (14); dependent on product
P	Pressure (Nm^{-2})
P_v	Water vapour pressure in a product (Nm^{-2})
P_{va}	Vapour pressure of drying air (Nm^{-2})
P_{vs}	Saturation vapour pressure (Nm^{-2})
$p_1 - p_5$	Product constants in equation (18)
R_o	Universal gas constant ($Jmol^{-1}K^{-1}$)
r	Distance considered (i.e. within the product) (m)
r_o	Diameter of the considered particle (m)
r'	Cylindrical capillary radius (m)
T	Absolute temperature (K)
T_a	Drying air temperature (K)
T_{in}	Dryer inlet temperature (K)
T_{out}	Dryer outlet temperature (K)
T_s	Crop surface temperature (K)
t	Time (s)
t_1	Time for maximum drying rate period in deep bed drying (s)
t_2	Time for decreasing drying rate period in deep bed drying (s)
t_t	Total time of drying in deep bed drying (s)
V	Volume of liquid moisture (m^3)
V_m	Volume of water absorbed when the internal surfaces are totally covered with a monolayer of water molecule (m^3)
V_v	Volume of water absorbed by product isothermally at vapour pressure P_v , (m^3)
W	Weight of water removed (kg)
W_d	Weight of dry matter in the product (kg)
W_o	Initial weight of undried product (kg)
W_t	Weight of product at time, t (kg)
α	Angle of contact between the moisture and capillary wall
σ	Surface tension of moisture (Nm^{-1})
ρ_a	Air density (kgm^{-3})
ϕ_c	Equilibrium relative humidity (decimal)
ϕ_{in}	Inlet relative humidity (decimal)
ϕ_{out}	Outlet relative humidity (decimal)

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