Review of solar-energy drying systems, I: An overview of drying principle and theory

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Review of solar-energy drying systems I: an overview of drying principles and theory

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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 analyses. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Drying; Moisture content; Safe storage time; Moisture equilibrium models; Drying rates; Thin layer drying; Deep bed drying; Psychrometric analysis

Nomenclature

A	dryer cross-sectional area (m^2)
A'	constant in Eq. (32)
A_s	crop surface area (m^2)
a	crop shape factor
a'	constant in Eq. (17)
B'	constant in Eq. (32)
b	constant in Eq. (10); dependent on material and its temperature
b'	constant in Eq. (17)
C_a	specific heat capacity of air (J kg^{-1} K^{-1})
c	constant in Eq. (11); related to heat of absorption of water vapour
c'	constant; dependent on material
D	diffusion coefficient

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d	constant in Eq. (12); dependent on material and its temperature
e	constant in Eq. (12); dependent on material and its temperature
F	air flow rate ($m^3 s^{-1}$)
F_m	mass flow rate (kg $m^{-2} s^{-1}$)
f	constant in Eq. (13); dependent on temperature
g	constant in Eq. (13); dependent on temperature
H_o	humidity of inlet air
H_s	humidity of saturated air in dryer
h	heat transfer coefficients (W $K^{-1} m^{-2}$)
K	constant in Eq. (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 Eqs. (25)–(27)
k_{12}, k_{13}, k_{21}, k_{23}, k_{31}, k_{32}	coupling coefficients in Eqs. (25)–(27)
K_f	thermal conductance of air film (W $m^{-2} K^{-1}$)
K_m	mass transfer coefficient of water vapour (kg $s^{-1} m^{-2}$)
L	latent heat of vaporisation (J kg^{-1})
M	moisture content (decimal, dry basis)
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_e	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 Eq. (14); dependent on product
P	pressure (N m^{-2})
P_v	water vapour pressure in product (N m^{-2})
P_{va}	vapour pressure of drying air (N m^{-2})
P_{vs}	saturation vapour pressure (N m^{-2})
p_1–p_5	product constants in Eq. (18)
R_o	universal gas constant (J $mol^{-1} K^{-1}$)
r	distance considered (i.e. within product) (m)
r_o	diameter of 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 internal surfaces are totally covered with 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 product (kg)
W_o	initial weight of undried product (kg)
W_t	weight of product at time, t (kg)
α	angle of contact between moisture and capillary wall
σ	surface tension of moisture (N m^{-1})
ρ_a	air density (kg m^{-3})
ϕ_e	equilibrium relative humidity (decimal)
ϕ_{in}	inlet relative humidity (decimal)
ϕ_{out}	outlet relative humidity (decimal).

1. Introduction

Drying is simply the process of moisture removal from a product. It can be performed 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 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 commonly used for drying agricultural products, involves the vaporisation of moisture within the product by heat and its subsequent evaporation from the product. Thus, thermal drying 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 vaporisation of the moisture now present in the air. Depending on the product, moisture transfer from within the product to the surface (because of the moisture gradient) is as liquid or vapour, while it is as vapour only from the surface.

Conventional drying systems are usually classified (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 into equilibrium usually with the drying air by constant ventilation. These systems enable crops to be dried in bulk or for long term storage. Thus, they are usually called 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 products 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 products 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 is exposed to heated air while descending [1]. Different heat sources are employed for the drying of agricultural products, the most common being fossil fuels, electricity and solar energy. Since the mid 1950 s, 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 is discussed.

2. Basic definitions

2.1. 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 the wet basis is the weight of moisture present in a product per unit weight of the undried material, represented as,

$$M_{\mathrm{wb}} = \frac{W_{\mathrm{o}} - W_{\mathrm{d}}}{W_{\mathrm{o}}} \tag{1}$$

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

$$M_{\mathrm{db}} = \frac{W_{\mathrm{o}} - W_{\mathrm{d}}}{W_{\mathrm{d}}} \tag{2}$$

$$\text{Percentage } M_{\mathrm{wb}} = M_{\mathrm{wb}} \times 100, \tag{3}$$

$$\text{Percentage } M_{\mathrm{db}} = M_{\mathrm{db}} \times 100. \tag{4}$$

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

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

and

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

The relationship between the moisture content on the wet and dry bases is illustrated in Fig. 1. The moisture content on the wet basis is used normally for commercial purposes, while the moisture content on the 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 the weight of water and total crop weight change [1, 4, 5].

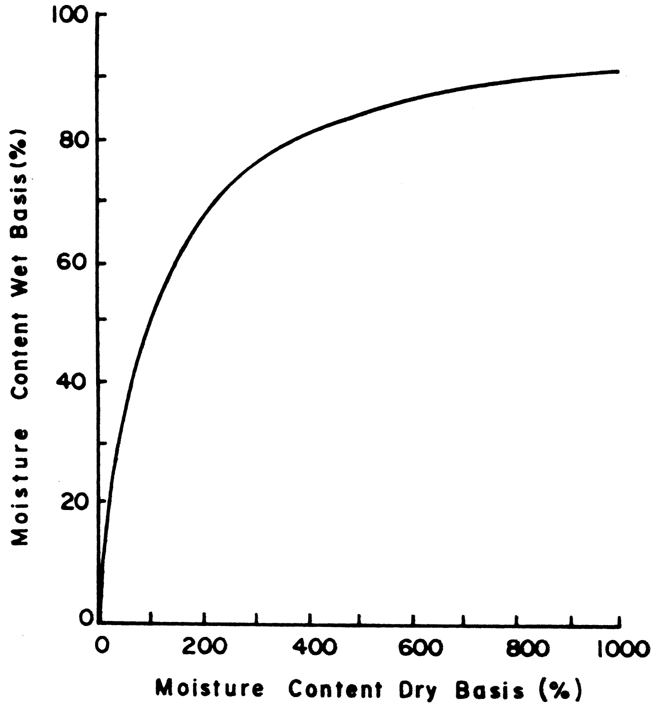

Fig. 1. Relationship between moisture content on dry basis and wet basis.

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

$$M_{\mathrm{tdb}} = \left[\frac{(M_{\mathrm{odb}}+1)W_{\mathrm{o}}}{W_{\mathrm{t}}}\right] - 1 \tag{7}$$

$$M_{\mathrm{twb}} = 1 - \left[\frac{(1-M_{\mathrm{owb}})W_{\mathrm{o}}}{W_{\mathrm{t}}}\right]. \tag{8}$$

2.2. 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. Thus, the equilibrium moisture content of a hygroscopic product 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 known as the equilibrium relative humidity. If the surrounding air is replaced continuously by air of lower vapour 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 which are known as moisture equilibrium isotherms [4].

2.3. Latent heat of vaporisation

This is the amount of energy that must be absorbed by the product to vaporise moisture from it. The latent heat of vaporisation 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 is the heat of vaporisation. The variation of heat of vaporisation of some grains with moisture content and temperature [4, 6] is shown in Fig. 2.

2.4. 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. Fig. 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 Fig. 4 [6].

3. 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 humidities due

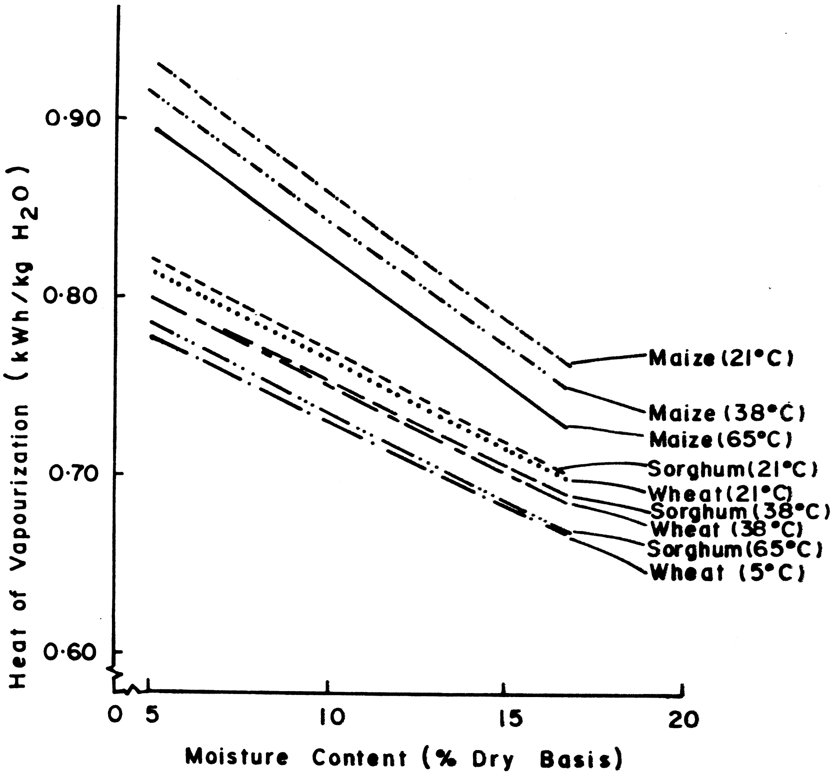

Fig. 2. The variation of heat of vaporization of types of grain with moisture content and temperature.

to over simplification of assumptions in the development of the models. However, they do 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.

Eq. (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 the same temperature as

$$\ln\left(\frac{P_{\mathrm{v}}}{P_{\mathrm{vs}}}\right) = \frac{2\sigma V \cos\alpha}{r' R_{\mathrm{o}} T}. \tag{9}$$

The major shortfall of Kelvin's model is its limitation to a 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 for 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,

$$V_{\mathrm{v}} = V_{\mathrm{m}}\left[\frac{bP_{\mathrm{v}}}{(1 + bP_{\mathrm{v}})}\right]. \tag{10}$$

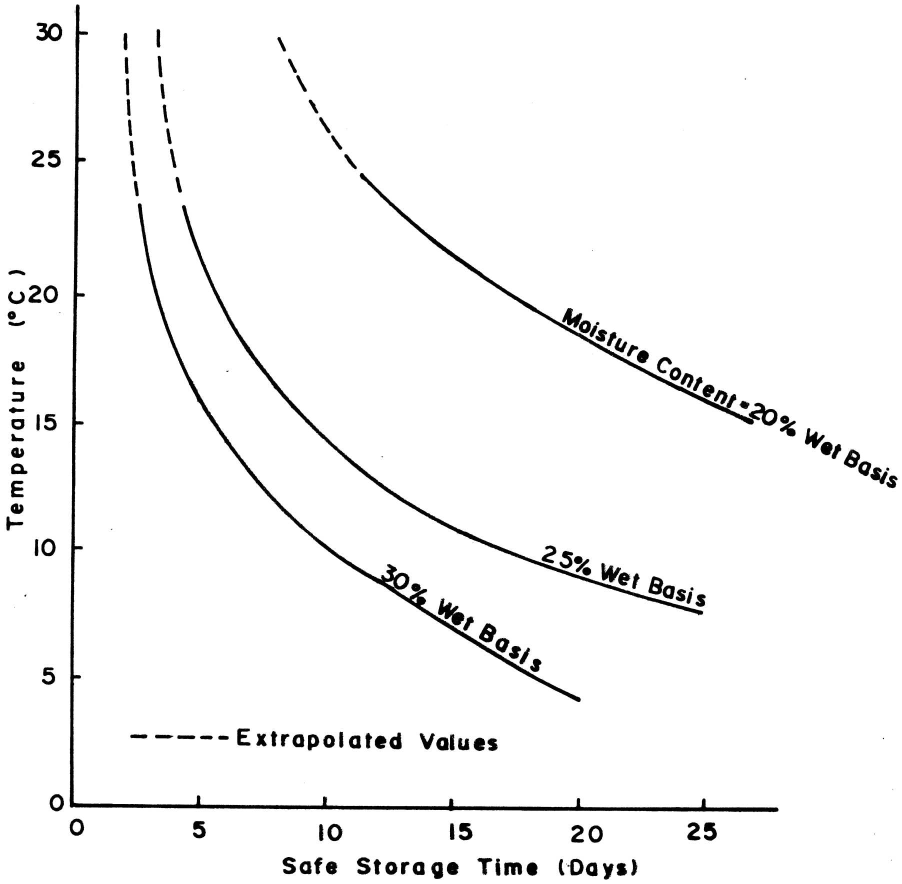

Fig. 3. Safe storage period for corn at different temperatures and moisture contents.

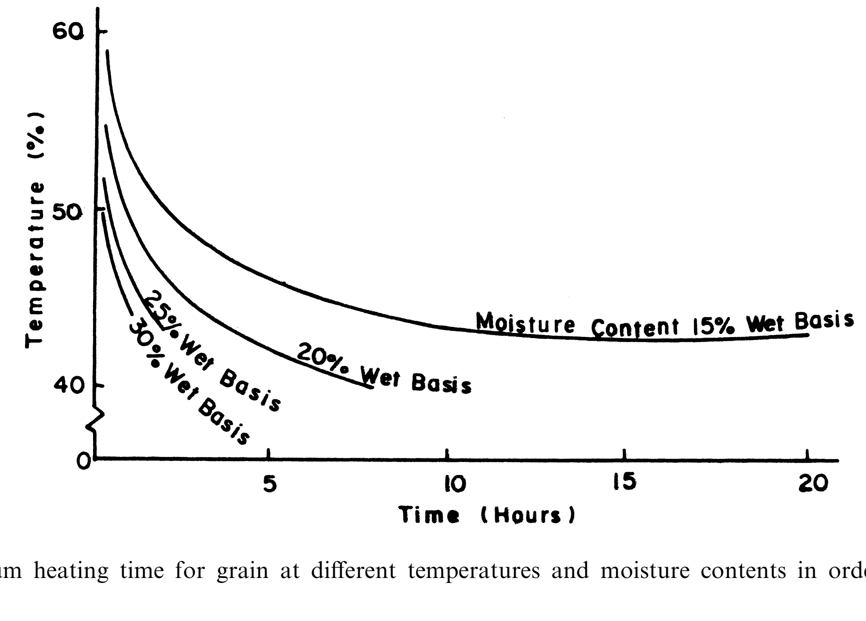

Fig. 4. Maximum heating time for grain at different temperatures and moisture contents in order not to destroy grain viability.

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 (Eq. (11)) by assuming the internal surfaces of the material are composed of an array of absorption sites capable of absorbing more than one molecule of water, as against Langmuir's assumption of a monolayer of moisture absorption.

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

Eq. (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.

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

Eq. (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.

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

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,

$$1 - \phi_e = e^{-kTM_e^n}. \tag{14}$$

Fig. 5 shows plots of Henderson's predictions for the following crops:

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

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

$$\frac{\ln(1 - \phi_e)}{-KT} = M_e^n. \tag{15}$$

Fig. 6 [12] shows that 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.

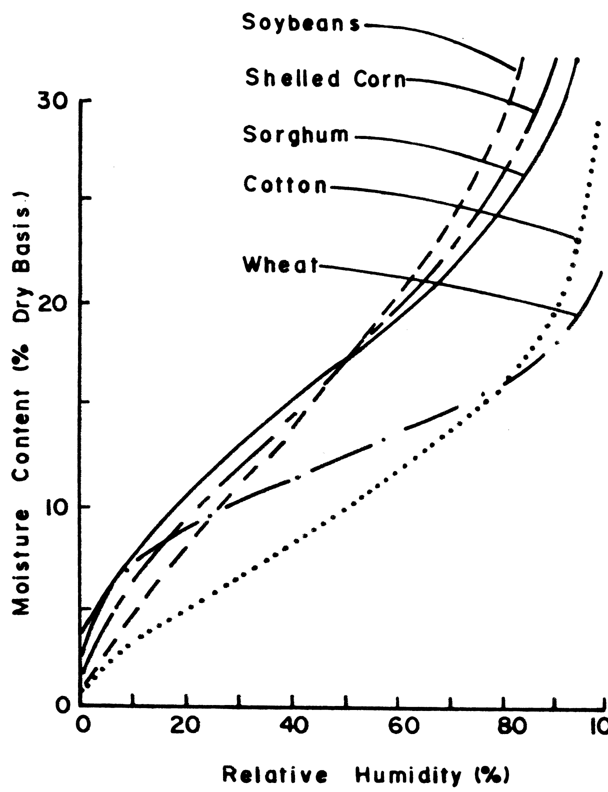

Fig. 5. Henderson's equilibrium moisture predictions for shelled corn, wheat, sorghum soybeans and cotton.

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

$$1 - \phi_e = e^{-jM_e^k} \tag{16}$$

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

While Thompson's empirical modification [20] for corn was of the form,

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

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.

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

where $p_1 - p_5$ are product constants.

Haynes' equation gives good agreement with experimental results within the relative humidity and temperature ranges for which the product constants are determined [4]. Bakker–

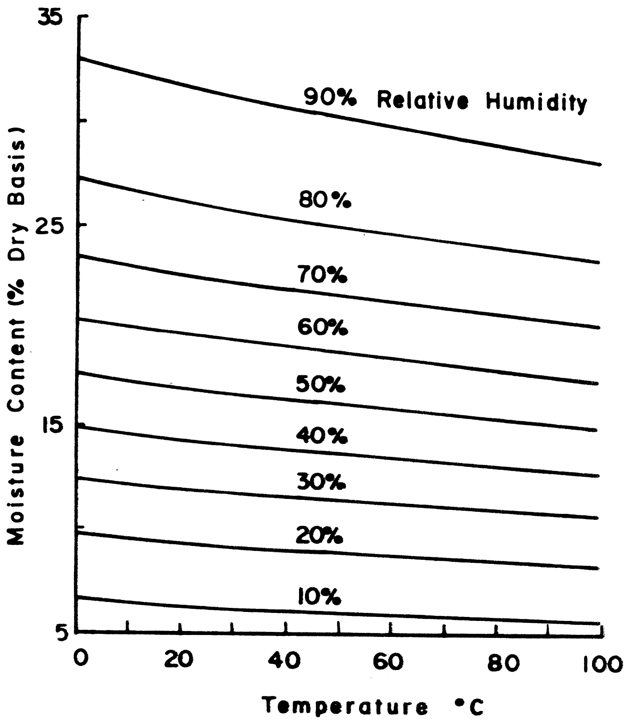

Fig. 6. Effect of temperature on the equilibrium moisture content of shelled corn (from Henderson's model).

Arkema et al. [22] also developed a set of empirical equations for shelled corn, each corresponding to some short range of relative humidity, which gives reasonable agreement with experimental data within the temperature range of 4 °C–60 °C [23].

4. 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 known as nonhygroscopic, and moisture within them is "loosely" held and regarded as "unbound" [3]. For agricultural products (which are hygroscopic), the moisture held within them is 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 continued 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.

4.1. Constant drying rate period

During the constant drying rate period (see Fig. 7 [1]), drying takes place from the surface of the product and is simply the evaporation of moisture from the free-water surface. The 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, which defines 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.

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],

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

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

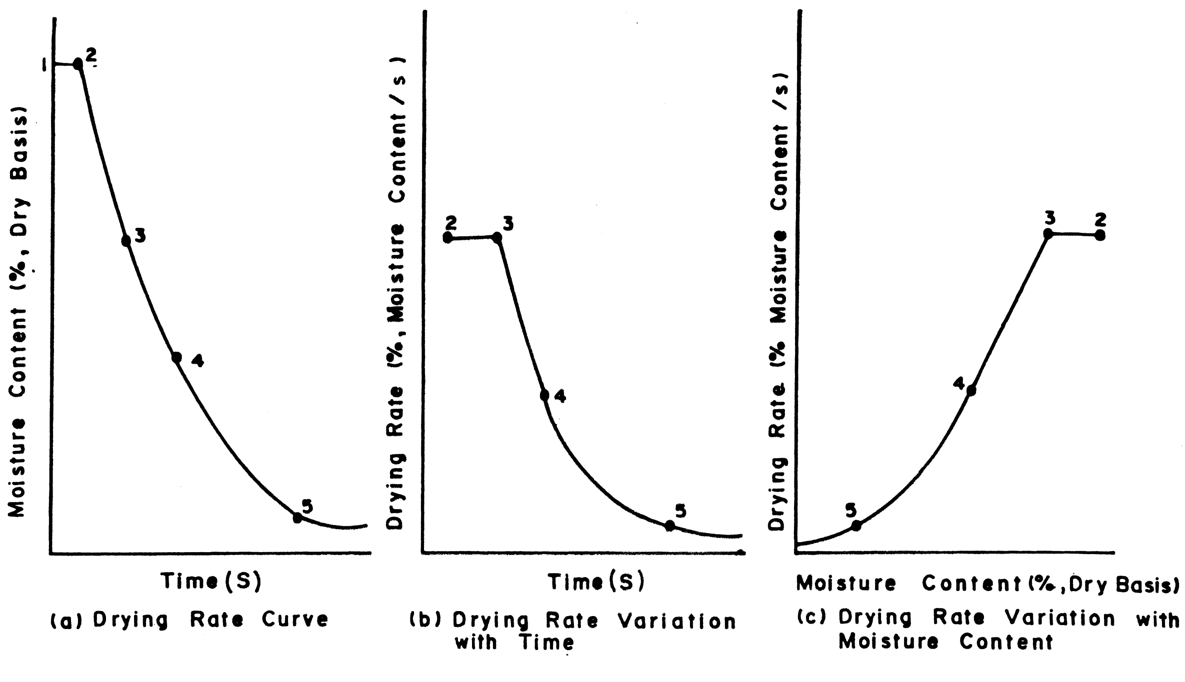

Fig. 7. Schematic illustration of drying rate periods: 1–2 the heating period (constant moisture content); 2–3 the constant rate drying period; 3 the critical moisture content; 3–4 the first falling rate period; 4–5 the second falling rate period.

4.2. 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 an equilibrium condition. Below 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 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]:

1. the first falling drying rate period which involves the unsaturated surface drying; and
2. 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 usually below the critical moisture content , 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 usually above the critical moisture content, 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.

5. 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 usual situation. Thus, the drying rate 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. Thus, it 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 Eq. (19) as [1],

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{P_{\mathrm{v}} - P_{\mathrm{va}}}{(1/K_{\mathrm{m}}A_{\mathrm{s}})R_{\mathrm{o}}T} = -\frac{K_{\mathrm{m}}A_{\mathrm{s}}(P_{\mathrm{v}} - P_{\mathrm{va}})}{R_{\mathrm{o}}T}. \tag{20}$$

$(P_{\mathrm{v}} - P_{\mathrm{va}})$ represents the external driving force due to environmental conditions, while $(1/K_{\mathrm{m}}A_{\mathrm{s}})$ 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,

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

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 Eq. (21) can be re-written as,

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

The negative sign indicates a decrease in moisture content with time.

Separating the variables and integrating within time limits 0 and t, and moisture content limits M_0 and M_e, the solution to Eq. (22) becomes,

$$\frac{(M_t - M_e)}{(M_o - M_e)} = e^{-K't}. \tag{23}$$

Introducing the shape factor of the crop, a [26], Eq. (23) becomes,

$$\frac{(M_t - M_e)}{(M_o - M_e)} = e^{-aK't}. \tag{24}$$

A purely theoretical model developed by Luikov [27] for describing the drying of capillary porous products was based on several 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,

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

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

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

where k_{11}, k_{22} and k_{23} 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 Eq. (25) can be dropped, leading to a more simplified form of the model, thus,

$$\frac{\partial M}{\partial t} = \nabla^2 k_{11} M. \tag{28}$$

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

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

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 Eq. (29) are [4],

$$M(r, 0) = M_o \tag{30}$$

and

$$M(r_o, t) = M_e. \tag{31}$$

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 °C–140 °C is given as,

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

where $A' = 1.86178 + 0.00488\ T$, $B' = 427.2640e^{-0.03301\ T}$.

6. Deep bed drying analysis

Consider the schematic illustration of a deep layer drying system shown in Fig. 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 extracts 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

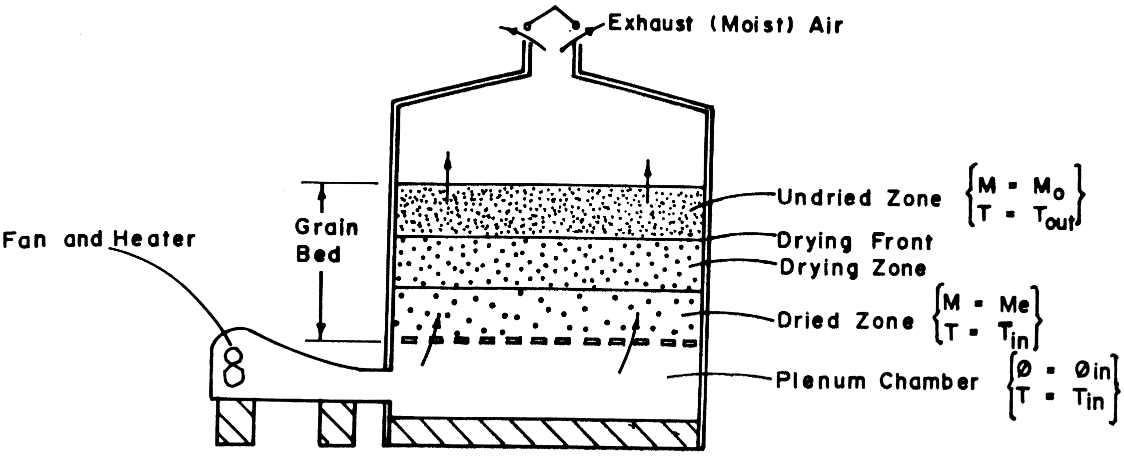

Fig. 8. Schematic illustration of deep bed drying.

the entire crop mass. Thus, this keeps the entire crop in moisture equilibrium with the drying air.

In Fig. 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 exits until the air gets to moisture equilibrium with M_o, above the drying front. Moisture extraction from the crop is by evaporation, resulting in cooling of the drying air to T_{out}. Thus, there is 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 ϕ_{in} to ϕ_{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 vaporisation 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,

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

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,

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

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

$$\frac{dw}{dt} = hA\frac{(T_{in} - T_{out})}{L} = \frac{hAdT}{L}. \quad (35)$$

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 drying to when the drying front reaches the top of the bed and is represented by the following equation [1],

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

Thus,

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

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 after the drying front reaches the top of the bed, as represented thus [1],

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

Given $K' = 2.3\,K''$ [1],

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

and

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

7. 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 Ref. [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 downward to the right, while the corresponding steeper lines represent the constant volume lines. The process of heating or cooling at constant absolute humidity are along 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 vaporisation.

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 vaporisation 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 Fig. 10.

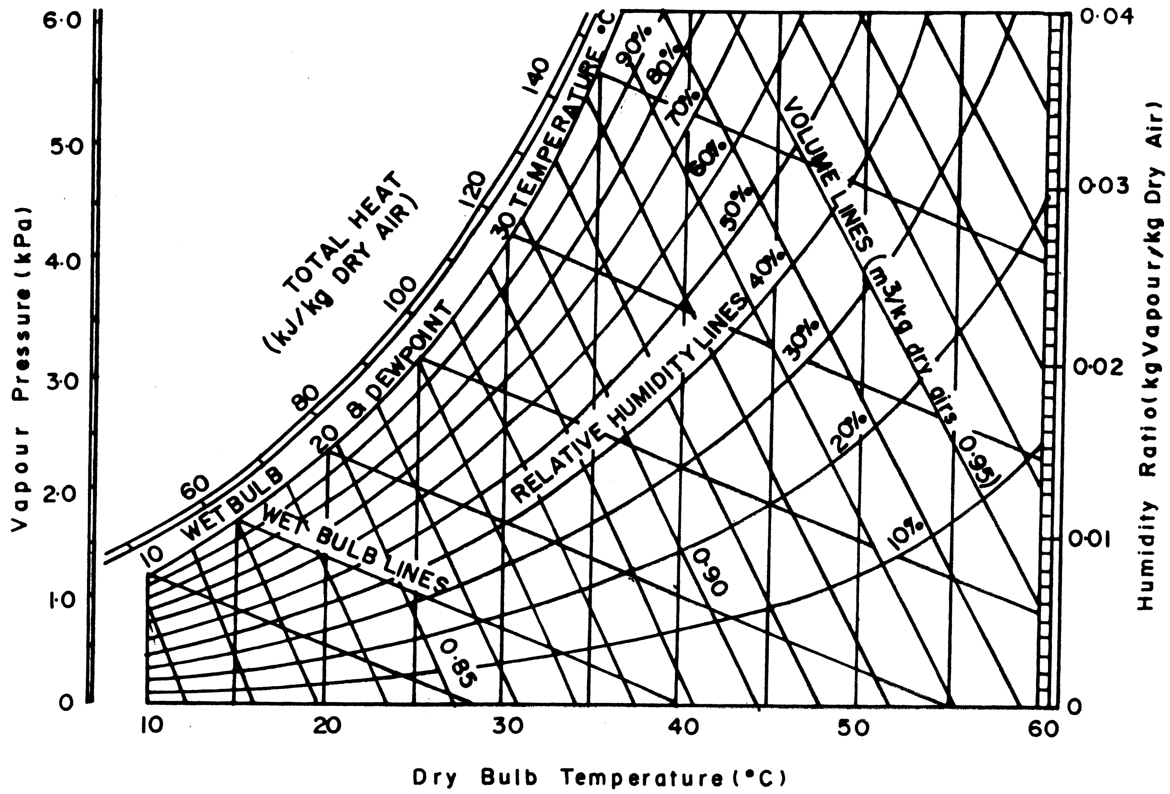

Fig. 9. Psychrometric chart for barometric pressure of 101.325 kPa.

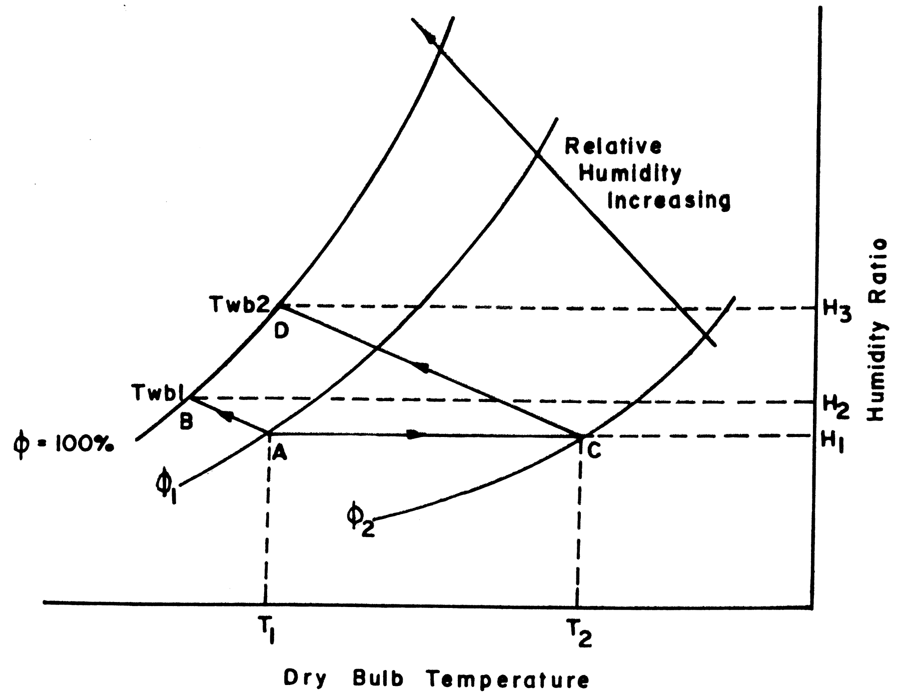

Fig. 10. Schematic illustration of the psychrometrics of drying process.

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 whether 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 1 kg of unsaturated moist air is increased by 3.6×10^{-4} kg per °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 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.

8. 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.

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References

[1] Hall CW. Drying and storage of agricultural products. Avi, Westport, 1980.
[2] McLean KA. Drying and storage of combinable crops. Farm Press, Suffolk, 1980.
[3] Howe ED. Principles of drying and evaporating. Sunworld 1980;4 (6):182–6.
[4] Brooker DB, Bakker-Arkema FW, Hall CW. Drying cereal grains. Avi, Westport, 1974.
[5] Foster GH. Drying cereal grains. In: Christensen CM, editors. Storage of cereal grains and their products. Am Ass Cereal Chem, 1982. p. 79–116.
[6] Gustafson G. Solar assisted grain drying in hot and humid areas. Rapport, Sveriges Lantbruksuniversitet, 1982;20.
[7] Kelvin WT. (1871), cited by Gregg SJ, Sing SW, Adsorption surface area and porosity. New York: Academic Press, 1967.
[8] Langmuir I. The adsorption of gases on plane surfaces of glass and mica and platinum. J. Am Chem Soc 1918;40:1361–5.
[9] Brunauer S, Emmett PH, Teller E. Adsoprtion in multi-molecular layers. J Am Chem Soc 1938;60:309–19.
[10] Harkins WD, Jura G. A vapour adsorption method for the determination of the area of a solid. J Am Chem Soc 1944;66:1366–71.
[11] Smith JE. The sorption of water vapour by high polymers. J. Am Chem Soc 1947;69:646–51.
[12] Henderson SM. A basic concept of equilibrium moisture. Agric Engng 1952;33 (1):29–32.
[13] Bailey CH. Respiration of shelled corn. Minn Agric Exp Station Tech Bull, 1921;3.
[14] Brokington SF, Dorin HC, Howerton HK. Hygroscopic equilibrium of whole kernel corn. Cereal Chem 1949;26:166–73.
[15] Gay FJ. Effects of temperature on moisture content equilibrium of wheat. J Council Sci Ind Res 1946;19:187–9.
[16] Fenton FC. Storage of grain sorghum. Agric Engng 1941;22:185–8.

[17] Lamour RK, Sallans HR, Craig BM. Hygroscopic equilibrium of sunflower seed, flaxseed and soybeans. Can J Res 1944;22:(F1–8).
[18] International critical tables listed, vol. II. McGraw-Hill, 1927. 321–5.
[19] Day DL, Nelson GL. Desorption for wheat. Trans ASAE 1965;8:293–7.
[20] Thompson TL. Predicted performances and optimal designs of convection grain dryers. PhD thesis. Purdue University, Lafayette, Ind., U.S.A., 1967.
[21] Haynes BC. Vapour pressure determination of seed hygroscopicity. In: Tech Bull. ARS, USDA, Washington D.C., U.S.A., 1961;1229.
[22] Bakker-Arkema FW, Lerew LE, DeBoer SF. Corn drying simulation. In: Agric Exp Station Res Bull. Michigan State Univ, East Lansing, Mich, U.S.A., 1974.
[23] Rodreiguez-Arias JH. Desorption isothermals and drying rates of shelled corn in the temperature range of 40–140 °F. Ph.D thesis. Michigan State Univ, East Lansing, Mich, U.S.A., 1956.
[24] Henderson SM, Perry RL. Agricultural process engineering. New York: Wiley, 1955.
[25] Hukill WV. Grain drying. In: Storage of cereal grains. Am Soc Cereal Chem, 1955; also in Christensen CM, editor., 2nd ed. ed. Storage of cereal grain and their products, 1974.
[26] Henderson SM, Pabis S. Grain drying theory. J Agric Engng Res 1961;6:169–74.
[27] Luikov AV. Heat and mass transfer in capillary–porous bodies. London: Pergamon Press, 1966.
[28] Troeger JM, Hukill WV. Mathematical description of the drying rate of fully exposed corn. Trans ASAE 1962;14:1153–56.
[29] Schumann TEW. Heat transfer: a liquid flowing through a porous prism. J Franklin Inst 1929;208:305–14.