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BULK AND THIN LAYER MODELS FOR DRYING
OF PEANUTS IN PODS

by

MANJEET SINGH CHHINNAN

A thesis submitted to the Graduate Faculty of
North Carolina State University at Raleigh
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Doctor of Philosophy

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BIOGRAPHY

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He is a member of Alpha Epsilon, Gamma Sigma Delta, the American Society of Agricultural Engineers and the American Society of Heating, Refrigerating and Air-conditioning Engineers.

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INTRODUCTION

Drying of most farm products is an essential post harvest operation. Drying of peanuts like other crops is necessary for long term storage without product deterioration. Fresh peanuts when harvested may have a moisture content up to 200 percent (dry basis) (Troeger, et al., 1972). Normally peanut plants with peanut pods on vines are removed from the soil and placed in the windrow for several days. The partially dried peanuts are removed from the vine and subjected to forced convection drying until the moisture content is reduced to a safe level. To save time and deterioration due to inclement weather it sometimes becomes necessary to dry the peanuts before they are partially dried in the windrows. It is necessary to know the drying performance of a dryer to carry out the drying operation properly and efficiently whether peanuts are freshly harvested or partially dried in windrows.

Most drying on farms is done in stationery bed dryers, called deep-bed or bulk dryers. Before a bulk drying system can be modeled it is essential to accurately describe the movement of moisture in a single peanut pod exposed to different but constant drying conditions. This is also called development of a thin layer model. Then, the bulk model can be developed based on the thin layer model.

Several investigators have studied the thin layer drying of homogeneous, porous and hygroscopic bodies (Newman, 1931; Henderson, 1955; Crank, 1956; Henderson and Pabis, 1961; Pabis and Henderson, 1961; Young, 1969; Young and Whitaker, 1971a; Whitaker and Young, 1972a; and many others). These models are not adequate for simulating the moisture movement in the kernel and hull of a peanut pod, because they are all applicable to one component system. Peanut pods are two components systems consisting of kernels that are surrounded by hulls with different material properties.

Young and Whitaker (1971b), and Whitaker and Young (1972b) made an attempt to describe the moisture movement in a composite body of two components with differing material properties. Although the pod does not have a simple geometric shape, they modeled it as a two component composite spherical body consisting of an inner spherical core of one component (kernel) and an outer concentric shell of another component (hull). They assumed vapor concentration gradients to be the principal force in the movement of moisture. They also assumed vapor concentration to be a linear function of moisture content within the pod.

Some investigators have considered liquid concentration gradients and others vapor concentration gradients as the driving force in the transfer of moisture in a biological body, but no one has established which is the true driving force. In Manuscript-I an attempt has been made to develop thin layer models based on moisture transfer described by vapor diffusion and liquid diffusion equations separately using finite difference techniques. The comparison between vapor and liquid diffusion thin layer models is made to determine the predominant driving force.

No single diffusion model (neither vapor nor liquid diffusion model) can accurately describe the moisture movement under all drying conditions. The author has found no reports of research considering the simultaneous effects of vapor and liquid moisture transfer in a two component system like a peanut pod. A mathematical model based on numerical techniques was employed in Manuscript-II for depicting moisture transfer in a single peanut pod employing coupled vapor and liquid diffusion equations.

Numerous researchers have reported the work done in the area of bulk drying of hygroscopic solids, Nelson (1961), and Kachru and Matthes (1976) used the dimensional analysis approach. Hamdy and Barre (1970) used analog computer to solve the heat and mass transfer equation, this approach was not followed in this study because the thin layer models developed here applied digital computer techniques. Simmonds, et al., (1953) reported the performance of a grain dr [illegible] by his procedure to be within ± 10 percent over the range of conditions covered in his investigations. Clark, et al., (1968a, 1968b) followed the procedure outlined by Simmonds, et al., (1953). Work reported by Bakker-Arkema, et al., (1967), Myklestad (1968), and Thompson (1968) could not be employed easily because their thin layer models involved explicit type of drying equations (e.g., constant drying rate). Considering the thin layer models developed in this study, the general approach followed by O'Callaghan, et al., (1971) was found most suitable in the development of bulk model.

Manuscript-III consists of the development of bulk model. It computes the change in the moisture content of a thin layer in a deep bed based on the thin layer model. The flow of air is assumed to be constant for a small but finite time interval. From the mass balance, the heat balance and the heat transfer equations, the temperature of the material in the layer after the elapse of a small time interval is computed. Layer to layer computations are done from the bottom to the top of the dryer for a particular time interval. The same procedure is repeated for the next time interval and so on. O'Callaghan, et al., (1971) did not include heat loss to the surroundings but these relations were modified to include this effect.

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MANUSCRIPT - I

A Study of Diffusion Equations Describing Moisture Movement in Peanut Pods - I

Comparison of Vapor and Liquid Diffusion Equations[1]

by

Manjeet S. Chhinnan and James H. Young[2]

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INTRODUCTION

Forced convection drying has developed into an essential operation in modern peanut processing practices. Accurate prediction of drying rates of peanuts under various conditions is of great importance in the design of drying systems and in quality control of the final product. In order to accurately describe the moisture movement in deep bed drying, it is important to understand the movement of moisture in an individual pod based on physical laws represented by a mathematical model.

A great deal of work has been reported on moisture transfer in homogeneous porous, hygroscopic bodies using either vapor diffusion or liquid diffusion equations (Henderson, 1955; Crank, 1956; Young and Whitaker, 1971, Whitaker and Young, 1972a; and many others). As pods consist of two major components (kernels and hulls), differing in material properties, Whitaker and Young (1972b) attempted to describe the moisture movement in a peanut pod modeled as two concentric shells and using the vapor concentration gradient as the driving force for moisture transfer.

It is not known whether a vapor concentration or a liquid concentration gradient is the true driving force in the transfer of moisture. The objectives of this study were (a) to develop two mathematical models, one assuming moisture movement by vapor diffusion and the other by liquid diffusion, (b) to compare the numerical solutions for these two models.

THEORETICAL CONSIDERATIONS

The peanut pod does not have a simple geometric shape, but to simplify the theoretical analysis, it is necessary to model the pod as a perfect geometrically shaped body. Investigations of Whitaker and Young (Young and Whitaker, 1971; Whitaker and Young, 1972a; and Whitaker and Young, 1972b) on moisture movement in peanuts in the hull and shelled peanut kernels suggested that the peanut pod may be considered a composite spherical body of two different materials. The model used in this study for vapor diffusion and for liquid diffusion was a composite spherical body consisting of an inner spherical core of one component (kernel) and an outer concentric shell of another component (hull). Each component was further subdivided into concentric shells of thickness Δr.

Assumptions made in the analysis are:

(a) The mass diffusivities of the kernel and hull are constant.
(b) Shrinkage is negligible.
(c) There are no capillary effects.
(d) There is no change in void space.
(e) Solid and vapor reach equilibrium instantaneously.
(f) Body comes into thermal equilibrium instantaneously with the environment.

(Modified Lewis number, Le_m, defined by Young (1969) is greater than 60 (Young and Whitaker, 1971b), thus the heat transfer equations can be neglected).

In contrast to the work of Whitaker and Young (1972b) the present study (a) had the provision to use non-linear relationships between moisture content and relative humidity, (b) used Crank-Nicholson's method (implicit form) to obtain converging solutions to the diffusion equations for all values of time and space increments (Carnahan, et al., 1969), and (c) allowed different space increments for different materials in the composite body.

In Crank-Nicolson's finite difference method, partial derivatives of a function C with respect to space (r) and time (t) are approximated as follows ('i' and 'n' correspond to space and time step, respectively).

$$\left.\frac{\partial C}{\partial r}\right|_{i,n+\frac{1}{2}} = \frac{1}{2}\left[\frac{C_{i+1,n} - C_{i-1,n}}{2\Delta r} + \frac{C_{i+1,n+1} - C_{i-1,n+1}}{2\Delta r}\right] \qquad (1)$$

$$\left.\frac{\partial^2 C}{\partial r^2}\right|_{i,n+\frac{1}{2}} = \frac{1}{2}\left[\frac{C_{i+1,n} - 2\,C_{i,n} + C_{i-1,n}}{\Delta r^2} + \frac{C_{i+1,n+1} - 2C_{i,n+1} + C_{i-1,n+1}}{\Delta r^2}\right] \qquad (2)$$

$$\left.\frac{\partial C}{\partial t}\right|_{i,n+\frac{1}{2}} = \frac{1}{\Delta t}\,(C_{i,n+1} - C_{i,n}) \qquad (3)$$

where

$C = C(r,t)$

$C_{i+1,n+1} = C(r+\Delta r, t+\Delta t)$

Δr = increment in space

Δt = increment in time

<u>Vapor Diffusion</u>

The equation describing the movement of vapors in jth material along with initial and boundary conditions are:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D_j \frac{\partial C}{\partial r}\right) = f_j \frac{\partial C}{\partial t} + (1-f_j)\, d_{s_j} \frac{\partial M_j}{\partial t} \qquad (4)$$

$$M_1(r,t) = M_{o_1} \qquad t = o,\ o \leq r \leq R_1 \qquad (5)$$

$$M_2(r,t) = M_{o_2} \qquad t = o,\ R_1 \leq r \leq R_2 \qquad (6)$$

$$\frac{\partial C(r,t)}{\partial r} = 0 \qquad t = o,\ r = o \qquad (7)$$

$$C(r,t) = C_e(t) \qquad t > o,\ r = R_2 \qquad (8)$$

$$rh_1(r,t) = rh_2(r,t) \qquad t = o,\ r = R_1 \qquad (9)$$

Where

d_s = density of solid, kg per cu m

f = void fraction

r = distance from center of sphere, m

rh = relative humidity, decimal

t = time, hrs

C = vapor concentration, kg per cu m

D = vapor diffusivity, sq m per hr

M = moisture content, dry basis, decimal, and

Subscript

o = initial value

1 = kernel

2 = hull

e = environment

j = jth material

For a general situation let the moisture content within a material be some function of vapor concentration and temperature.

$$M_j(r,t) = M_j[C(r,t),\ T(r,t)] \qquad (10)$$

[Note: $T(r,t) = T_e(t)$ from assumption (f)]

where

T = absolute temperature, K

$$\frac{\partial M_j}{\partial t} = \frac{\partial M_j}{\partial C} \cdot \frac{\partial C}{\partial t} + \frac{\partial M_j}{\partial T_e} \cdot \frac{\partial T_e}{\partial t} \qquad (11)$$

Substituting (11) in (4) and rearranging the terms we obtain

$$\frac{\partial^2 C}{\partial r^2} + \frac{2}{r}\ \frac{\partial C}{\partial r} = \gamma_j\ \frac{\partial C}{\partial t} + \beta_j \qquad (12)$$

Where

$$\gamma_j = \frac{f_j}{D_j} + (1-f_j)\ \frac{d_{s_j}}{D_j} \cdot \frac{\partial M_j}{\partial C} \qquad (13)$$

$$\beta_j = (1-f_j)\ \frac{d_{s_j}}{D_j} \cdot \frac{\partial M}{\partial T_e} \cdot \frac{\partial T_e}{\partial t} \qquad (14)$$

(a) <u>General Solution</u>

To solve equation (12) using the Crank-Nicolson method, equations (1), (2), and (3) are substituted into (12). After rearranging the terms:

$$\left(\frac{1}{2\Delta r^2_j} - \frac{1}{2r\Delta r_j}\right) C_{i-1,n+1} + \left(-\frac{1}{\Delta r^2_j} - \frac{\gamma_j}{\Delta t}\right) C_{i,n+1} + \left(\frac{1}{2\Delta r^2_j} + \frac{1}{2r\Delta r_j}\right) C_{i+1,n+1} = \left[\left(-\frac{1}{2\Delta r^2_j} + \frac{1}{2r\Delta r_j}\right) C_{i-1,n} + \left(\frac{1}{\Delta r^2_j} - \frac{\gamma_j}{\Delta t}\right) C_{i,n} + \left(-\frac{1}{2\Delta r^2_j} - \frac{1}{2r\Delta r_j}\right) C_{i+1,n} + \beta_j\right] \qquad (15)$$

(b) Solution at Center of Sphere ($r = o$, $i = 1$, $j = 1$)

The diffusion equation represented by (12) is not valid at the center because of the indeterminate quantity $\frac{2}{r}\frac{\partial C}{\partial r}$ at $r = o$.

Now,

$$\lim_{r \to o} \frac{1}{r}\frac{\partial C}{\partial r} = \left.\frac{\partial^2 C}{\partial r^2}\right|_{r = o} \qquad (16)$$

for $i = 1$,

$$\left.\frac{\partial^2 C}{\partial r^2}\right|_{i,n+\frac{1}{2}} = \frac{1}{2\Delta r^2_1}\left[C_{2,n} - 2\,C_{1,n} + C_{o,n} + C_{2,n+1} - 2\,C_{1,n+1} + C_{o,n+1}\right] \qquad (17)$$

Since $C_{o,n}$ is a hypothetical value and also the condition $\left.\frac{\partial C}{\partial r}\right|_{r = o} = o$ must be satisfied, it is necessary that $C_{o,n} = C_{2,n}$.

Substituting (3), (16), (17) and $C_{o,k} = C_{2,k}$ into (12) and rearranging the terms, gives

$$-\left(\frac{\gamma_1}{\Delta t} + \frac{3}{\Delta r^2_1}\right) C_{1,n+1} + \frac{3}{\Delta r^2_1} C_{2,n+1} = \left[\left(-\frac{\gamma_1}{\Delta t} + \frac{3}{\Delta r^2_1}\right) C_{1,n} - \frac{3}{\Delta r^2_1} C_{2,n} + \beta_1\right] \qquad (18)$$

(c) <u>Solution at Interface of Two Materials</u> $(i = J)$

It is assumed that the equilibrium conditions at the interface are achieved instantaneously. This means that if $C^-_{J,n}$ and $C^+_{J,n}$ are the vapor concentration at the junction in the inner material and outer material respectively, then

$$C^-_{J,n} = C^+_{J,n} \qquad \text{(implication of (9))} \tag{19}$$

Let Q_1 and Q_2 be the moisture flow from point J-1 to J and J to J+1, respectively (Figure 1).

$$Q_1 = -4\pi\left(r - \frac{\Delta r_j}{2}\right)^2 D_j \left(\frac{\partial C^-}{\partial r}\right)_{J-\frac{1}{2},\, n+\frac{1}{2}} \tag{20}$$

$$Q_2 = -4\pi\left(r + \frac{\Delta r_{j+1}}{2}\right)^2 D_{j+1} \left(\frac{\partial C^+}{\partial r}\right)_{J+\frac{1}{2},\, n+\frac{1}{2}} \tag{21}$$

The differences $(Q_1 - Q_2)$ must be equal to the moisture stored in the shell of thickness $(\Delta r_j + \Delta r_{j+1})/2$ in Figure 1, then

$$Q_1 - Q_2 = 4\pi\frac{r^2\Delta r_j}{2}\left[\gamma_j \left(\frac{\partial C^-}{\partial t}\right)_{J,n+\frac{1}{2}} + \beta_j\right] + 4\pi\frac{r^2\Delta r_{j+1}}{2}\left[\gamma_{j+1}\left(\frac{\partial C^+}{\partial t}\right)_{J,n+\frac{1}{2}} + \beta_{j+1}\right] \tag{22}$$

The Crank-Nicolson finite difference representations of the partial derivatives of C with respect to r involved above are

$$\left(\frac{\partial \bar{C}}{\partial r}\right)_{J-\frac{1}{2},\, n+\frac{1}{2}} = \frac{1}{2}\,\frac{(C^-_{J,n+1} - C_{J-1,n+1})}{\Delta r_j} + \frac{1}{2}\left(\frac{C^-_{J,n} - C_{J-1,n}}{\Delta r_j}\right) \tag{23}$$

$$\left(\frac{\partial C^{+}}{\partial r}\right)_{J+\frac{1}{2},\ n+\frac{1}{2}} = \frac{1}{2}\left(\frac{C_{J+1,n+1} - C^{+}_{J,n+1}}{\Delta r_{j+1}}\right) + \frac{1}{2}\left(\frac{C_{J+1,n} - C^{+}_{J,n}}{\Delta r_{j+1}}\right) \quad (24)$$

Substituting (19) - (21), (23) and (24) in (22) and rearranging the terms

$$K_1\, C_{i-1,n+1} - (K_1+K_2+K_3)\, C_{i,n+1} + K_2 C_{i+1,n+1} = \Big[-K_1 C_{i-1,n} + (K_1+K_2-K_3)\, C_{i,n} - K_2\, C_{i+1,n} + K_4\Big] \quad (25)$$

where

$$K_1 = \frac{D_j}{2\Delta r_j}\left(r - \frac{\Delta r_j}{2}\right)^2 \quad (26)$$

$$K_2 = \frac{D_{j+1}}{2\Delta r_{j+1}}\left(r + \frac{\Delta r_{j+1}}{2}\right)^2 \quad (27)$$

$$K_3 = \frac{r^2}{2\Delta t}\left(\gamma_j D_j \Delta r_j + \gamma_{j+1} D_{j+1} \Delta r_{j+1}\right) \quad (28)$$

$$K_4 = \frac{r}{2}\left(\beta_j \Delta r_j D_j + \beta_{j+1} D_{j+1} \Delta r_{j+1}\right) \quad (29)$$

It is assumed that at time t = o, the outermost surface (i=n+1) is in equilibrium with the environment. If $C_{e,n}$ is the vapor concentration in the environment, then in equation (15)

$$C_{i+1,n+1}\Big|_{i=N} = C_{e,n+1} \quad (30)$$

Where

N = total number of shells in the composite body.

Substituting equation (30) into (15) along with equations (18), (15) and (25) comprise a tridiagonal system of equations and can be solved readily by the Gaussian elimination method (Carnahan, et al., 1969) to obtain vapor concentration values $C_{i,n+1}$ when $C_{i,n}$ values are known. Thus, knowing initial concentration values from initial moisture conditions, along with the history of environmental changes in concentration and temperature, vapor concentration at any point and at any time can be described by solving the above described tridiagonal system of equations for successive time increments.

Moisture distribution at any time in the composite body can be numerically evaluated by using the relationship between moisture content and vapor concentration. There is no restriction concerning whether the relation between moisture content and vapor concentration has to be explicit.

Liquid Diffusion

The partial differential equation describing liquid diffusion is spherical co-ordinates, for jth material is:

$$\frac{\partial^2 C}{\partial r^2} + \frac{2}{r}\frac{\partial C}{\partial r} = \frac{1}{D_j}\frac{\partial C}{\partial t} \qquad (31)$$

where

r = distance from center of sphere, m

C = liquid concentration at r, kg per cu m

D_j = liquid diffusivity of jth material, sq m per hr

t = time, hrs

Initial and boundary conditions are described by equations (5) to (9) except that C corresponds to liquid concentration.

(a) General Solution

Substituting the Crank-Nicholson relations (1) to (3) in equation (31) and simplifying gives:

$$\left(\frac{1}{2\Delta r^2_j} - \frac{1}{2r\Delta r_j}\right) C_{i-1,n+1} - \left(\frac{1}{\Delta r^2_j} + \frac{1}{\Delta t D_j}\right) C_{i,n+1} + \left(\frac{1}{2\Delta r^2_j} + \frac{1}{2r\Delta r_j}\right) X \left(C_{i+1,n+1}\right) = \left[-\left(\frac{1}{2\Delta r^2_j} + \frac{1}{2r\Delta r_j}\right) C_{i-1,n} + \left(\frac{1}{\Delta r^2_j} - \frac{1}{\Delta t D_j}\right) C_{i,n} - \frac{1}{2\Delta r^2_j} + \frac{1}{2r\Delta r_j}) C_{i+1,n}\right] \tag{32}$$

(b) Solution at the Center of the Sphere (r = o, i = 1, j = 1)

Based on arguments parallel to those in vapor diffusion, the solution at the center of the sphere for liquid diffusion is,

$$-\left(\frac{3}{\Delta r^2_1} + \frac{1}{\Delta t D_j}\right) C_{1,n+1} + \frac{3}{\Delta r^2_1} C_{2,n+1} = \left[\left(\frac{3}{\Delta r^2_1} - \frac{1}{\Delta t D_j}\right) C_{1,n} - \frac{\beta_1}{\Delta r_1} C_{2,n}\right] \tag{33}$$

(c) Solution at the Interface of Two Materials (i = J)

If Q_1 and Q_2 are the moisture flows from point J-1 to J and J to J + 1 respectively in Figure 1, then Q_1 and Q_2 are given by relations (20) and (21) except that C is liquid concentration instead of vapor concentration.

Similarly,

$$Q_1 - Q_2 = 4\pi r^2 D_j \frac{\Delta r_j}{2} \left(\frac{\partial C^-}{\partial t}\right)_{J,n+\frac{1}{2}} + \left[4\pi r^2 D_{j+1} \quad X \right.$$

$$\left. \frac{\Delta r_{j+1}}{2} \left(\frac{\partial C^+}{\partial t}\right)_{J,n+\frac{1}{2}}\right] \tag{34}$$

Substitution of equations (20), (21), (23) and (24) into (34) and simplification yields:

$$\frac{D_j}{2} \left(\frac{1}{\Delta r_j} - \frac{1}{r}\right) C_{J-1,n+1} + \left[\frac{D_j}{2} \left(\frac{1}{r} - \frac{1}{\Delta r_j}\right) - \frac{\Delta r_j}{2\Delta t}\right] C^-_{J,n+1} +$$

$$\left[- \frac{D_{j+1}}{2} \left(\frac{1}{r} + \frac{1}{\Delta r_{j+1}}\right) - \frac{\Delta r_{j+1}}{2\Delta t}\right] C^+_{J,n+1} + \frac{D_{j+1}}{2} \left(\frac{1}{r} + \frac{1}{\Delta r_{j+1}}\right) \quad X$$

$$C_{J+1,n+1} = \left[\frac{D_j}{2} \left(\frac{1}{r} - \frac{1}{\Delta r_j}\right) C_{J-1,n} + \left[\frac{D_j}{2} \left(\frac{1}{\Delta r_j} - \frac{1}{r}\right) - \frac{\Delta r_j}{2\Delta t}\right] \quad X \right.$$

$$C^-_{J,n} + \left[\frac{D_{j+1}}{2} \left(\frac{1}{r} + \frac{1}{\Delta r_{j+1}}\right) - \frac{\Delta r_{j+1}}{2\Delta t}\right] C^+_{J,n} - \frac{D_{j+1}}{2} \left(\frac{1}{r} + \frac{1}{\Delta r_{j+1}}\right) \quad X$$

$$\left. C_{J+1,n} \right] \tag{35}$$

The system of equations obtained from the relationships (32), (33), (35) and substituting (30) in (32) does not comprise a tridiagonal system because of 4 unknown concentration terms on the left hand side of equation (35). It may be recalled that in vapor diffusion

$$C^+_{J,n+1} = C^-_{J,n+1} \tag{36}$$

In liquid diffusion, the relative humidity at the junction is in equilibrium but it does not necessarily imply that (36) will hold true. Only if an explicit relation between liquid concentration and relative humidity exists can either C^+ or C^- be eliminated to transform the above mentioned system of equations into a tridiagonal system. This would enable the description of the distribution of liquid concentration at any time in the material, which in turn would enable the description of the moisture distribution by using the following relationship.

Moisture content = Liquid Concentration/density of the material (37)

Equilibrium Moisture Content Equations

The Smith Equation (Smith 1947) and the Young (3-parameter) Equation (Young 1966) describing the equilibrium moisture relations were used in this study. These two relations have been reported (Young 1974) to fit the experimental data better than other commonly used equations for predicting equilibrium moisture content.

The Young (3-parameter) Equation consists of the following set of relations:

$$M = A\ (\theta + \alpha) + B\theta \qquad (38)$$

where

$$A = \rho V_m/W \qquad (39)$$

$$B = \rho V/W \qquad (40)$$

$$\theta = \frac{rh}{rh + (1-rh)\ E} \qquad (41)$$

(θ is fraction of surface of cells covered by a layer of bound water molecules.)

$$\alpha = -\frac{E\,rh}{E-(E-1)rh} + \frac{E^2}{E+1}\ \ln\left(\frac{E-(E-1)rh}{E}\right) - (E+1)\ \ln\ (1-rh) \qquad (42)$$

(total amount of normally condensed moisture measured in molecular layers);

$E = \exp\ [-(q_1-q_L)/kT]$ (43)

$rh = C/C_{sat}$, (relative humidity, decimal) (44)

ρ = density of water, kg per cu m

C_{sat} = saturated vapor concentration, kg per cu m

k = Boltzmann's constant, cal per molecule per °K

M = equilibrium moisture content for a desorption process, decimal (dry basis)

q_1 = heat of adsorption of molecules bound to surface of cells, cal per molecule

q_L = normal heat of vaporization of water molecules, cal per molecule

V_m = volume of moisture in a unimolecular layer of water molecules on the surface of the cells, cu m

V = amount of adsorbed moisture at saturation, cu m

W = mass of dry material, Kg

Parameters A and B defined above vary with temperature, i.e., if,

$$A_o = \frac{V_m}{W}\rho_o$$

and

$$B_o = \frac{V}{W}\rho_o$$

then

$$A = \frac{A_o}{\rho_o}\rho \qquad (45)$$

and

$$B = B_o \rho / \rho_o \tag{46}$$

where A_o, B_o and ρ_o are values of A, B, and ρ at a reference temperature, respectively. To evaluate E at any given temperature it is assumed that $(q_1 - q_L)/q_L$ is constant. Under this assumption,

$$E = E_o^{\delta} \text{ where } \delta = \frac{q_L T_o}{q_{L_o} T} \tag{47}$$

and E_o and q_{L_o} are values of E and q_L at a reference temperature T_o, respectively.

The Smith equation may be expressed as:

$$M = A - B \ln (1 - rh) \tag{48}$$

The parameter A represents the moisture bound to the surface and B represents the moisture in a unimolecular layer of normally condensed moisture.

Parameters A and B in Smith's equation vary with temperature in a fashion similar to the parameters A and B in Young's equation as described by equations (45) and (46).

Computer Solutions

Two computer programs were written corresponding to two vapor diffusion models, vapor diffusion model - I and II. A third program was written to develop a liquid diffusion model. Vapor diffusion models - I and II involved solving the vapor diffusion equation (4) along with the Young equation (38) and the Smith equation (48) respectively. The liquid diffusion model involved solution of liquid diffusion equation (31) using the Smith equation (48). In solving the liquid diffusion equation it was necessary that an explicit type of relation exist between moisture content, relative humidity and liquid concentration, therefore the Young equation could not be used. Thus the three computer programs were written to solve the following systems of equations:

(a) equations (15), (18), (25), (38) and (41) - (47) for the vapor diffusion model - I,

(b) equations (15), (18), (25) and (48) for the vapor diffusion model - II, and

(c) equations (32), (33), (35), (37) and (48) for the liquid diffusion model.

The program had the provision to:

(i) estimate equilibrium moisture content of each material and the composite body,

(ii) determine moisture content distribution in the spherical model at any time,

(iii) compute average moisture content for each component and the composite body as a function of time,

(iv) compute moisture ratio of the composite body as a function of time,[1]

(v) compute the sum of squares of deviations between the observed and the predicted values of moisture ratio, and

(vi) obtain a best fit for diffusivity values, D_j, by minimizing the sum of squares between the observed and predicted moisture ratio values using the steepest ascent method (Boughton, 1968).

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[1] $$\text{Moisture ratio} = \frac{\text{Moisture content - Equilibrium moisture content}}{\text{Initial moisture content - Equilibrium moisture content}}$$

ANALYSIS OF DATA

Drying data published by Whitaker and Young (1972b), where peanut pods were dried at four dry bulb temperatures (26.7[80], 32.2[90], 37.8[100], and 43.3°C[110°F]) and four dew point temperatures (8.9[48], 13.3[56], 17.8[64], and 22.8°C[73°F]), were used in obtaining numerical solutions of the vapor and liquid diffusion equations for a composite sphere of two materials. The kernel and hull were simulated by the inner and outer core respectively.

Liquid and vapor diffusivity values of kernel and hull were obtained for each drying condition that yielded the best fit to the Whitaker and Young (1972b) drying data. All other input parameters required to obtain the numerical solutions of vapor and liquid diffusion equations were taken from the work reported by Whitaker and Young (1972b) and Young (1974).

DISCUSSION

Values of diffusivities and their associated sum of squares of the deviations that yielded the best fit between the observed and predicted moisture ratio values for each model are given in Table 1. To make a comparison between the experimental and theoretical drying curves, an index called Root Mean Square of deviations 'RMS' was proposed. The RMS for each set of drying conditions was obtained by dividing the sum of squares of deviations by the number of observations in each drying test and then taking the square root.

Figure 2 is a typical plot of theoretical drying curves obtained from the liquid diffusion model and the vapor diffusion model - I along with the experimental curve for peanut pods (drying curve predicted by vapor diffusion model - II is not shown in Figure 2 because the drying curves from vapor diffusion model I and II are coincident during most of the drying period). The theoretical curves and the experimental curve show a close agreement over the whole drying range. Figure 3 is a plot of experimental drying data and theoretical drying curves for the drying model (liquid diffusion) which yielded the largest value of RMS; the drying conditions were 26.7°C [80°F] dry bulb temperature and 22.8°C [73°F] dew point temperature. Even though the curves in Figure 3 produced the largest RMS value, the theoretical curve adequately predicted the drying curve.

Effect of dry bulb temperature on diffusivities is demonstrated in Figure 4. Thermodynamically the diffusivity of a material should decrease exponentially with the increase in reciprocal of absolute temperature.

Thus, liquid diffusivities indicated the theoretically expected trend but due to inexplicable reasons vapor diffusivities obtained from both the vapor diffusion models showed an opposite trend. A similar trend of vapor diffusivities is reported by Whitaker and Young (1972b).

Effect of dew point temperature, indicated by analysis of variance, on liquid and vapor diffusivities of hulls was insignificant. Effect of dew point temperature on liquid and vapor diffusivities of kernels was significant, but this effect was also insignificant when diffusivity values at 22.8°C [73°F] dew point temperature were excluded from the analysis of variance test.

Table 2 compares the fit of experimental drying data obtained by using the three models. Comparisons are made by observing the percent change in the RMS values of the models under consideration.

Vapor diffusion model - I, which uses the Young (3-parameter) equation, fit the experimental data better than the vapor diffusion model - II, which uses the Smith equation, for the most drying conditions (Table 2). This trend was expected because over the considered range of relative humidities the Young equation predicted the equilibrium moisture curve more accurately than the Smith equation (Young 1974).

Comparison of values in col-7 and col-8 of Table 2, corresponding to the percent change of RMS values of vapor diffusion model - I and the liquid diffusion model and percent change of RMS values of vapor diffusion model - II and the liquid diffusion model respectively, indicate almost the same trend of improvement of fit. Thus to compare the vapor diffusion and liquid diffusion models, the percentages in col-7 and col-8 should be observed. Both the columns (7 and *0 indicate that the vapor diffusion models fit the experimental data better than the liquid diffusion model for all drying conditions with only one exception (13.3°C dew point temperature and 43.3°C) (dry bulb temperature) where the liquid diffusion model proved to be better than the vapor diffusion model - II.

Inspection of deviations of observed moisture ratios and moisture ratios predicted from the liquid diffusion model, Δ_ℓ, and deviations of observed moisture ratios and moisture ratios predicted from the vapor diffusion model, Δ_v, revealed that for most drying conditions $|\Delta_\ell|$ was greater than $|\Delta_v|$ during the initial 10 percent of the drying period, whereas for the rest of the drying period $|\Delta_\ell|$ was less than or equal to $|\Delta_v|$. This implies that the vapor diffusion models gave a better fit between the experimental and predicted moisture ratios during the initial stages of drying and the liquid diffusion model gave a better fit during most of the drying period, even though the results in Table 2 indicate that over the whole drying period vapor diffusion models provided a better fit.

Deviations of observed and predicted moisture ratios of vapor and liquid diffusion model suggest that vapor diffusion and liquid diffusion are taking place at the same time in the transfer of moisture. Thus, a model based upon simultaneous diffusion of vapor and liquid would probably predict drying curves more accurately over the whole drying period and for extreme ranges of drying conditions.

SUMMARY AND CONCLUSIONS

Peanut pods were simulated as composite spheres consisting of two concentric shells of different materials where the inner core and the outer shell represented the kernel and hull respectively. Methods to obtain numerical solutions of the vapor and liquid diffusion equations for the moisture movement in the composite sphere were developed. Experimental drying data were used in estimating the liquid and vapor diffusivities which yielded the smallest sum of squares of deviations between the theoretical and experimental drying curves.

Comparison of the liquid and vapor diffusion models indicate the following:

(1) The vapor diffusion model using the Young (3-parameter) equation proved to be better than the vapor diffusion model using the Smith equation.

(2) Over the total drying period, both the vapor diffusion models proved to be better than the liquid diffusion model, but the liquid diffusion model fit the experimental data better than the vapor diffusion model during the later stages of the drying period.

(3) Diffusivities of kernels and hulls for both the models were exponential functions of the reciprocal of absolute dry bulb temperature.

(4) Values of liquid diffusivities increased while the values of vapor diffusivities decreased with the increase of the dry bulb temperature.

(5) Neither vapor nor liquid diffusivities were effected significantly by changes in dew point temperature.

As the trend shown by the liquid diffusivities as a function of dry bulb temperature was expected theoretically and the liquid diffusion model fit the experimental data as good or better than the vapor diffusion model for a large part of the total drying period, the liquid diffusion model probably should be chosen over the vapor diffusion model. However, over the total drying period, the vapor diffusion model gave a lower sum of squares of deviations between observed and predicted values.

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TABLES AND FIGURES

Table 1. Diffusivities and their associated sum of squares of the difference that gave the best fit between the experimental and theoretical moisture ratios for the vapor diffusion and liquid diffusion models.

Diffusion model			Vapor			Liquid			Vapor		
Equilibrium moisture equation			Young's			Smith's			Smith's		
No. of obs.	Dew point °C	Dry bulb °C	a/ $D_1 x10^2$	a/ $D_2 x10^2$	c/ SS	$D_1 x10^6$	$D_2 x10^6$	SS	$D_1 x10^2$	$D_2 x10^2$	SS
109	8.9	26.7	0.241	0.673	.01630	.1881	.2062	.02105	0.243	0.633	.01764
79		32.2	0.237	0.602	.01122	.2706	.2715	.01321	0.223	0.608	.01246
61		37.8	0.228	0.489	.00670	.4197	.3200	.01137	0.213	0.485	.00720
53		43.3	0.207	0.461	.00421	.4534	.4085	.00730	0.200	0.440	.00480
104	13.3	26.7	0.373	0.859	.01213	.2141	.2148	.01978	0.365	0.858	.01265
77		32.2	0.313	0.779	.01119	.2825	.2875	.01435	0.307	0.760	.01215
60		37.8	0.293	0.654	.00727	.3837	.3801	.00803	0.279	0.664	.00746
53		43.3	0.246	0.523	.00672	.4697	.4198	.00682	0.232	0.518	.00709
116	17.8	26.7	0.411	0.850	.01735	.2292	.1691	.03557	0.412	0.840	.01765
84		32.2	0.325	0.629	.01092	.3344	.2301	.02442	0.315	0.622	.01149
70		37.8	0.265	0.499	.00776	.4056	.2741	.01913	0.259	0.490	.00833
55		43.3	0.255	0.399	.00805	.6815	.3235	.01748	0.249	0.392	.00815
111	22.8	26.7	1.131	1.359	.03060	.6627	.1273	.07531	1.134	1.367	.03077
81		32.2	0.549	0.882	.01479	.5277	.2162	.04378	0.549	0.891	.01462
59		37.8	0.439	0.666	.00710	.6568	.2899	.02339	0.427	0.665	.00716
49		43.3	0.354	0.563	.00493	.8499	.3605	.01891	0.341	0.551	.00544

a/ D_1 - Diffusivity of kernel (m^2/hr)

b/ D_2 - Diffusivity of hull (m^2/hr)

c/ SS - Sum of square of deviations

Table 2. Root mean square[a] of the deviations that gave the best fit between the experimental and the theoretical moisture ratio values obtained from the liquid diffusion and vapor diffusion models, along with a measure of improvement of one model over the other.

			Root mean square of deviations			Measure of improvement[b]		
Diffusion model			Vapor	Liquid	Vapor			
Equilibrium moisture equation			Young's	Smith's	Smith's			
Dew point °C [F] Col. 1	Dry bulb °C [F] Col. 2	Rel. hum. percent Col. 3	RMS_1x10 Col. 4	RMS_2x10 Col. 5	RMS_3x10 Col. 6	Q_{21} Col. 7	Q_{23} Col. 8	Q_{31} Col. 9
8.9 [48]	26.7 [80]	32	12.23	13.90	12.72	12.00	8.46	3.87
	32.2 [90]	24	11.92	12.93	12.56	7.84	2.88	5.11
	37.8[100]	18	10.48	13.65	10.88	23.23	20.28	3.68
	43.3[110]	13	8.91	11.74	9.52	24.08	18.90	6.51
13.3 [56]	26.7 [80]	43	10.80	13.79	11.03	21.69	20.03	2.08
	32.2 [90]	31	12.05	13.65	12.56	11.69	7.98	4.03
	37.8[100]	23	11.01	11.57	11.15	4.85	3.62	1.27
	43.3[110]	18	11.26	11.34	11.57	0.75	-1.96	2.65
17.8 [64]	26.7 [80]	58	12.23	17.51	12.33	30.16	29.56	0.85
	32.2 [90]	42	11.40	17.05	11.69	33.13	31.41	2.51
	37.8[100]	31	10.53	16.53	10.91	36.31	34.02	3.47
	43.3[110]	23	12.10	17.83	12.17	32.14	31.70	0.63
22.8 [73]	26.7 [80]	80	16.60	26.05	16.65	36.26	36.08	0.28
	32.2 [90]	58	13.51	23.25	13.43	41.88	42.21	-0.58
	37.8[100]	43	10.97	19.91	11.02	44.90	44.65	0.44
	43.3[110]	32	10.03	19.64	10.54	48.94	46.34	4.85

[a] Root mean square of deviations is obtained by dividing the sum of squares of deviations by the number of observations and then taking the square root.

[b] Positive value of the quantity $Q_{ij} = (RMS_i - RMS_j) \times 100/RMS_i$ indicate that model j fit the experimental data under consideration Q_{ij} °/o times better than the model for the same data.

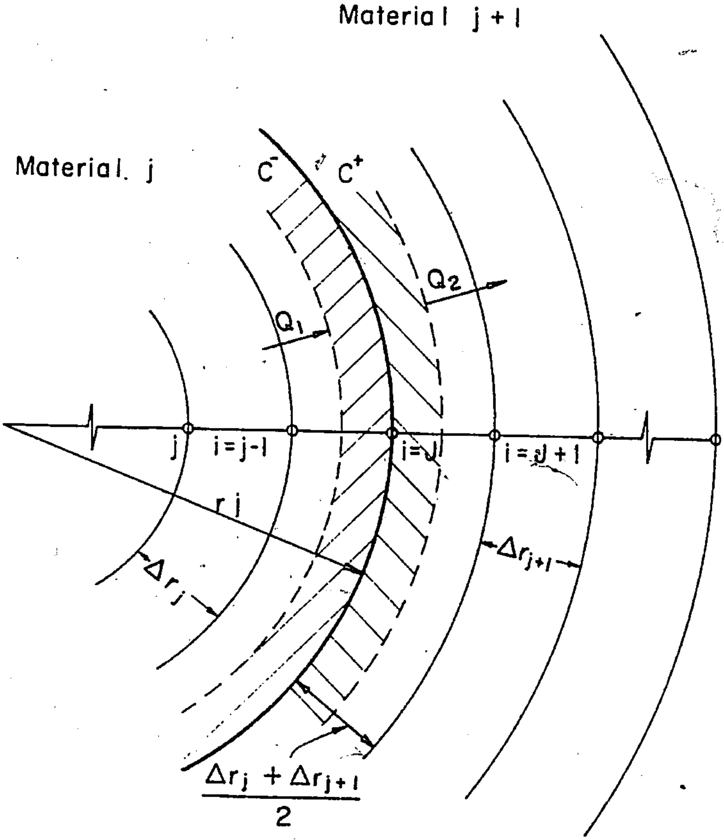

Fig. 1. Schematic diagram of moisture movement at the junction of two materials

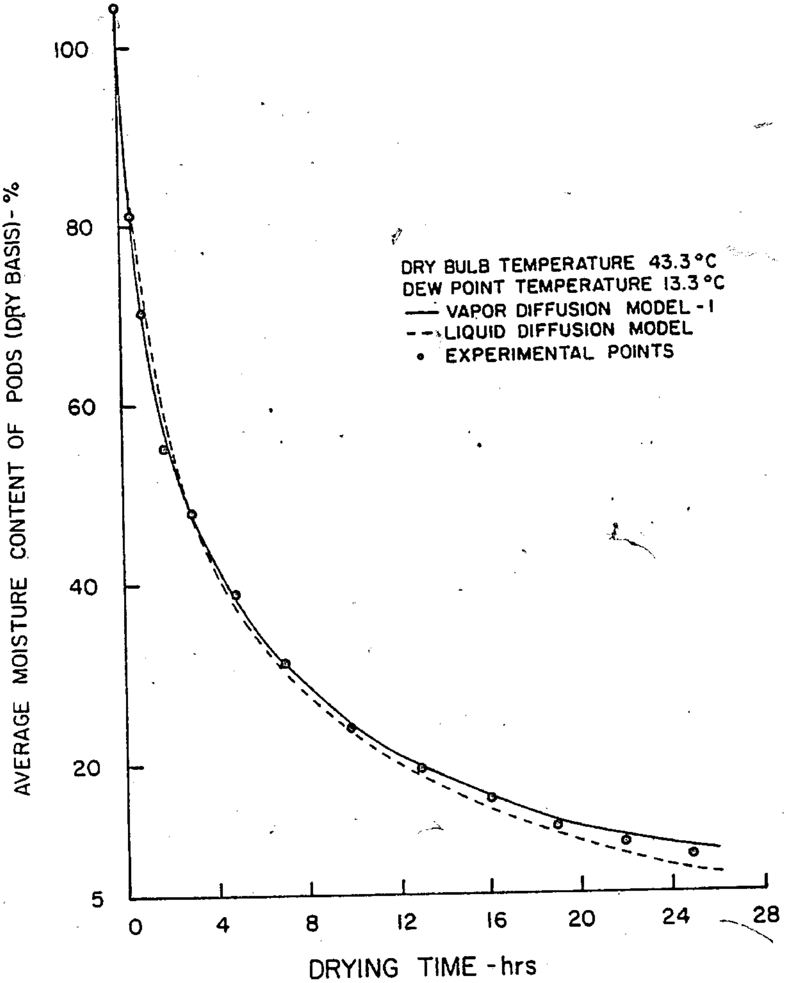

Fig. 2. Comparison of theoretical drying curves for vapor diffusion model-I and liquid diffusion model to experimental values for peanut pods

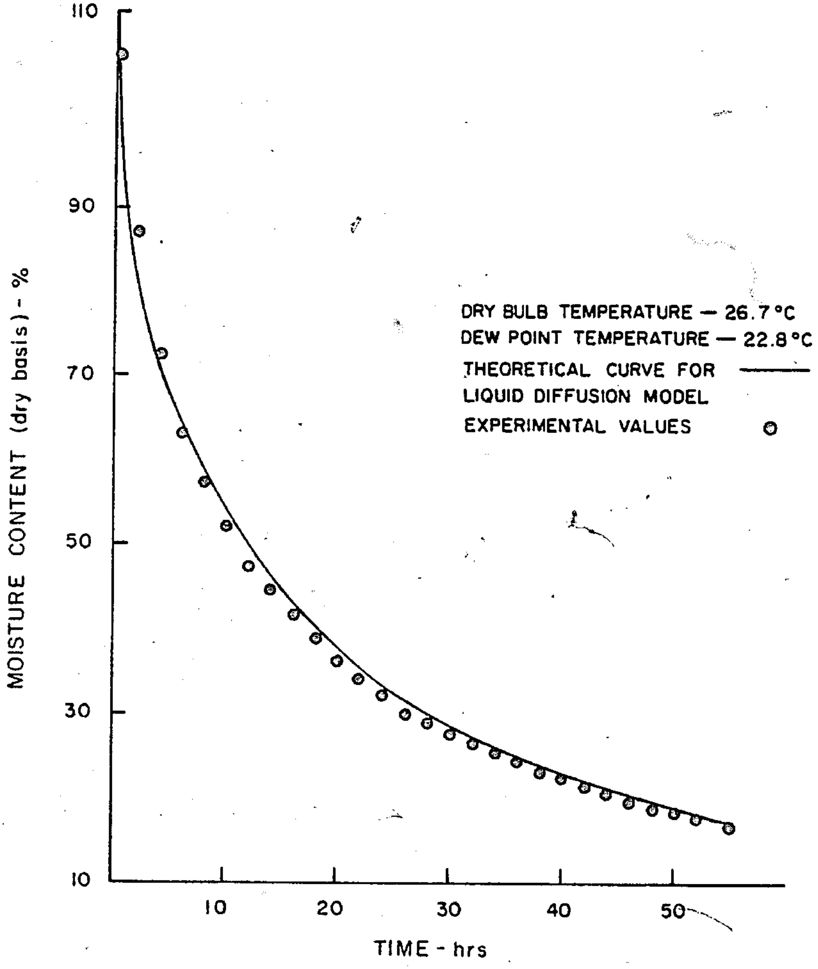

Fig. 3. Comparison of theoretical drying curve with the experimental drying curve which yielded largest sum of squares

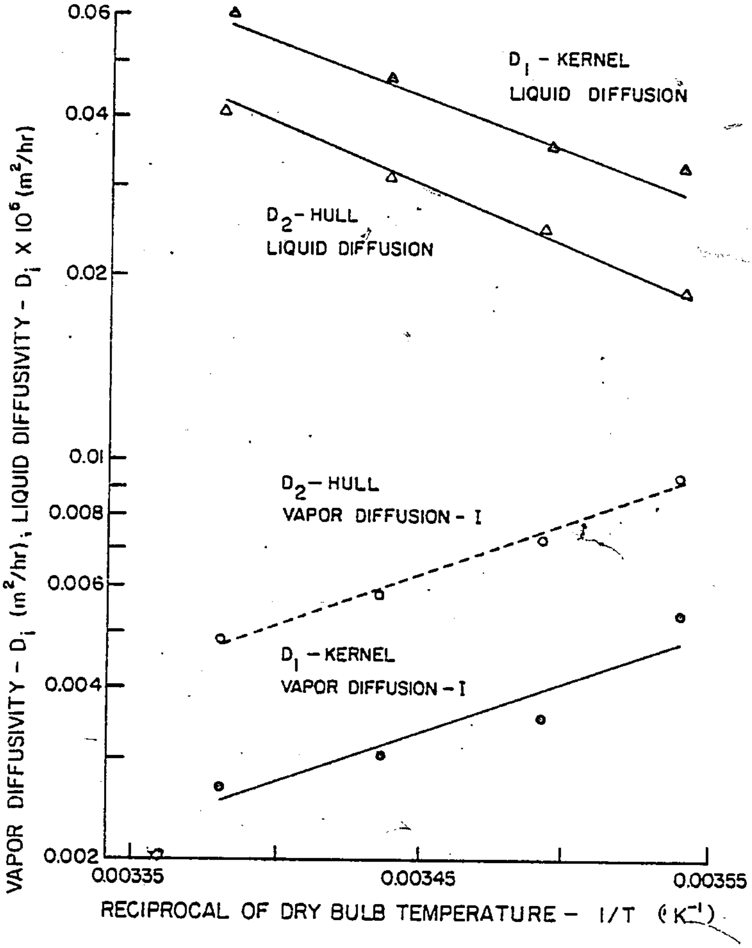

Fig. 4. Effect of dry bulb temperature averaged over dew point temperatures of 8.9, 13.3, 17.8 and 22.8 deg C on the diffusivity of the kernel and hull predicted from liquid diffusion model and vapor diffusion model-I

MANUSCRIPT - II

A Study of Diffusion Equations Describing Moisture Movement in Peanut Pods - II

Simultaneous Vapor and Liquid Diffusion of Moisture[1]

by

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INTRODUCTION

Drying is an important process in maintaining the quality of peanuts after they are harvested. Designing a drying system requires an understanding of the nature of movement of moisture in an individual pod based on physical laws.

Several researchers have investigated the transfer of moisture in homogeneous porous, hygroscopic bodies based on diffusion laws (Newman, 1931; Henderson, 1955; Crank, 1956; Young, 1969; Young and Whitaker, 1971b; and many others). The transfer of moisture in peanuts has been investigated by Young and Whitaker (1971a), Whitaker and Young (1972a), Whitaker and Young (1972b), and Chhinnan and Young (1975).

Some investigators have considered liquid concentration gradients and others vapor concentration gradients as driving forces in the movement of moisture in peanut pods, but which is the true driving force is not established. Also, none of the researchers in their studies have considered simultaneous liquid and vapor diffusion. Chhinnan and Young (1975) developed and compared the numerical solution of two mathematical models in peanut pods, one assuming the vapor concentration gradient and the other liquid concentration gradient to be the driving force. They reported that for a given set of drying conditions, the liquid diffusion model provided a better fit between the experimental and predicted values except in the initial stages of drying. But the vapor diffusion model gave a better fit over the total drying period. This suggests that the driving force for moisture movement is probably a combination of vapor and liquid concentration gradients.

The objectives of this study were: (a) to develop a mathematical model describing the moisture movement in peanut pods based upon simultaneous diffusion of liquid and vapor, (b) to use the method of finite difference to predict the moisture distribution in peanut pods, and (c) to compare the numerical solutions with the results of earlier reported work.

THEORETICAL CONSIDERATIONS

The model developed in this study is a combination of vapor and liquid diffusion equations for a composite sphere consisting of two components, with the kernel as an inner spherical core and the hull as an outer concentric shell. Each component is subdivided into concentric shells of thickness Δr and Crank-Nicolson's approximations for the partial derivatives in the diffusion equation were used to obtain the numerical solution.

The basic approach to the development of a model for coupled vapor and liquid diffusion was similar to that used for vapor or liquid diffusion alone as discussed by Chhinnan and Young (1975). Therefore, in this paper, only the necessary theoretical aspects and assumptions will be discussed.

Coupled Liquid and Vapor Diffusion Equation

The equation describing the vapor and liquid concentration in a material is:

$$\bar{D}_\ell \Delta^2 \bar{C}_\ell + \bar{D}_v \Delta^2 \bar{C}_v = \frac{\partial \bar{C}_\ell}{\partial t} + \frac{\partial \bar{C}_v}{\partial t} \qquad (1)$$

where

$\bar{D}_\ell$ = liquid diffusivity, m^2hr^{-1}

$\bar{D}_v$ = vapor diffusivity, m^2hr^{-1}

$\bar{C}_\ell$ = liquid concentration based on bulk volume, kg m^{-3}

$\bar{C}_v$ = vapor concentration based on bulk volume, kg m^{-3}

t = time, hrs.

To compare the results of the coupled vapor and liquid diffusion equation with either vapor or liquid alone, the units of concentrations and diffusivities in (1) must be the same as in the individual cases reported by Chhinnan and Young (1975).

The vapor and liquid diffusion equations studied by Chhinnan and Young (1975) are:

$$D_v \Delta^2 C_v = f \frac{\partial C_v}{\partial t} + (1-f) \frac{\partial M}{\partial t} d_s \tag{2}$$

where

d_s = density of solid, kg m^{-3}

f = void fraction, m^3(air)m^{-3}(bulk volume)

C_v = vapor concentration, based on void volume, kg m^{-3}

D_v = vapor diffusivity, $m^2 hr^{-1}$

and

M = moisture content, dry basis, decimal, and

$$D_1 \Delta^2 C_\ell = \frac{\partial C_\ell}{\partial t} \tag{3}$$

where

C_ℓ = liquid concentration, based on volume of solid material, kg m^{-3}

D_ℓ = liquid diffusivity, $m^2 hr^{-1}$

Comparisons of equations (1) through (3) yields the following relationships:

$$\bar{D}_\ell = D_\ell \tag{4}$$

$$\bar{D}_v = D_v/f \tag{5}$$

$$\bar{C}_\ell = C_\ell(1-f) \tag{6}$$

$$\bar{C}_v = C_v f \tag{7}$$

Substitution of equations (4) through (7) in (1) yields:

$$D_\ell(1-f)\Delta^2 C_\ell + D_v\Delta^2 C_v = f\,\frac{\partial C_v}{\partial t} + (1-f)\,\frac{\partial C_\ell}{\partial t} \tag{8}$$

Equation (8) written in spherical co-ordinates for the jth material is:

$$D_{\ell_j}\ (1-f)\ \frac{1}{r^2}\left[\frac{\partial}{\partial r}\left(r^2\frac{\partial C_\ell}{\partial r}\right)\right] + D_{v_j}\ \frac{1}{r^2}\left[\frac{\partial}{\partial r}\ \left(r^2\frac{\partial C_v}{\partial r}\right)\right] = \left[f_j\ \frac{\partial C_v}{\partial t} + (1-f_j)\ \frac{\partial C_\ell}{\partial t}\right] \tag{9a}$$

subject to the following initial and boundary conditions:

$$M(r,t) = M_{o_1} \qquad t = o,\ o \le r \le R_1 \tag{9b}$$

$$M(r,t) = M_{o_2} \qquad t = o,\ R_1 \le r \le R_2 \tag{9c}$$

$$C_v(r,t) = C_{v_e}(r,t) \qquad t > o,\ r = R_2 \tag{9d}$$

$$C_\ell(r,t) = C_{\ell_e}(r,t) \qquad t > o,\ r = R_2 \tag{9e}$$

$$rh_1(r,t) = rh_2(r,t) \qquad t > o,\ r = R_1 \tag{9f}$$

$$\frac{\partial C_\ell(r,t)}{\partial t} = 0 \qquad t = o,\ r = o \tag{9g}$$

$$\frac{\partial C_v(r,t)}{\partial t} = 0 \qquad t = o,\ r = o \tag{9h}$$

where

r = distance from center of sphere, m

rh = relative humidity, decimal, and

R = outer radius of shell, m.

and subscripts are:

0 = initial value

1 = kernel

2 = hull

e = environment

j = jth material

The Smith Equation (Smith 1947) describing the equilibrium moisture relation was used in this study,

$$M = A - B \ln(1-rh) \tag{10}$$

The parameters A and B represent the moisture bound to the surface and the moisture in a unimolecular layer of normally condensed moisture, respectively. Parameters A and B vary with temperature (Young 1974) as shown below:

$$A = \frac{A_o}{\rho_o} \rho \tag{11}$$

$$B = \frac{B_o}{\rho_o} \rho \tag{12}$$

where ρ is density of water, kg m^{-3}, and A_o, B_o and ρ_o are values of A, B, and ρ at a reference temperature, respectively.

Assuming liquid and vapor are always at equilibrium inside the material, the following relationships between moisture content, relative humidity, vapor concentration and liquid concentration are obtained:

$$M = C_\ell / d_s \tag{13}$$

$$rh = C_v / C_{sat} \tag{14}$$

Equations (10), (13), and (14) yield:

$$C_v = C_{sat}\ (1-\exp\ \alpha) \tag{15}$$

where

C_{sat} = saturated vapor concentration, kg m^{-3} and

$$\alpha = \frac{1}{B}\left[A - \frac{C_\ell}{d_s}\right] \tag{16}$$

To solve the system of equation (9) using the Crank-Nicholson method it was necessary to convert either vapor concentration values to liquid concentration values or vice versa. In this study the system of equations (9) was solved in terms of liquid concentration values. To obtain a tridiagonal set of equations from (9), as in work reported by Chhinnan and Young (1975), it was also necessary to have a linear relation between C_v and C_ℓ at the next time step t+Δt. This was approximated as follows:

$$C_v(r,t+\Delta t) = C_v(r,t) + \frac{\partial C_v(r,t)}{\partial C_\ell(r,t)}\ C_\ell(r,t+\Delta t) - C_\ell(r,t)$$

or

$$C_v(r,t+\Delta t) = K_1 + K_2\ C_\ell(r,t+\Delta t) \tag{17a}$$

where

$$K_2 = \frac{C_v(r,t)}{C_\ell(r,t)} \tag{17b}$$

(this is evaluated from (15))

and

$$K_1 = C_v(r,t) - K_2 C_\ell(r,t) \tag{17c}$$

Computer Solutions

A computer program was written to solve the tridiagonal system of equations obtained from (9) through (17) and Crank-Nicholson's approximations to predict $C_{\ell}(r,t)$ in the composite sphere using the same approach as employed by Chhinnan and Young (1975) in solving the liquid diffusion equation. The program also had provisions to:

i) predict the moisture content distribution in the spherical model at any time,

ii) estimate the equilibrium moisture content of each material and the composite body,

iii) compute average moisture content for each component and the composite body as a function of time,

iv) compute moisture ratio (MR) of the composite body as a function of time,

where, $MR = \frac{\text{Moisture content - equilibrium moisture content}}{\text{Initial moisture content - equilibrium moisture content}}$

v) compute the sum of squares of deviations between the observed and the predicted values of moisture ratio, and

vi) obtain best fit of vapor and liquid diffusivity values for the kernel and hull minimizing the sum of squares between the observed and predicted moisture ratio values using the steepest ascent method (Boughton 1968).

ANALYSIS OF DATA

Experimental drying data collected by Whitaker and Young (1972b) for peanut pods for various drying conditions were used in obtaining numerical solutions of the vapor-liquid diffusion equation for a composite sphere consisting of two components with the inner core and the outer shell simulating the kernel and hull respectively. The set of drying conditions consisted of all combinations of four dry bulb temperatures (26.7 [80], 32.2 [90], 37.8 [100], and 43.3°C [110°F] and four dew point temperatures (8.0 [48], 13.3 [56], 17.8 [64], and 22.8°C [73°F]). Data from the above set of drying conditions were also used by Chhinnan and Young (1975) in obtaining the numerical solution of the vapor diffusion and liquid diffusion equations.

Optimum values of liquid and vapor diffusivities reported by Chhinnan and Young (1975) were chosen as initial values of diffusivities to be used to determine the vapor and liquid diffusivity values of kernels and hulls for each set of drying condition that yielded the best fit to the drying data. All other necessary input parameters to the computer model were taken from the work reported by Whitaker and Young (1972b) and Young (1974). The numerical values of these parameters are listed below:

Parameter	Kernel	Hull
$d_s (kg/m^3)$	1102.04	1199.75
f	0.0169	0.419
n	6	6
w	0.76	0.24
A @ 15°C	0.01448	0.07003
B @ 15°C	0.06302	0.08514
R(cm)	0.0558	0.0655

and $\Delta t = 0.1$ hr.

where,

n = number of shells

w = weight fraction

DISCUSSION

Behavior of the computer model was investigated by assuming either vapor diffusivities or liquid diffusivities equal to zero before obtaining the optimum values of diffusivities for each set of drying conditions. Sum of squares of deviations between the experimental and predicted moisture ratios were determined at 43.3°C dry bulb temperature and 8.9°C dew point temperature for vapor (S_v), liquid (S_ℓ) and vapor-liquid ($S_{\ell v}$) diffusion models (Table 1). It is observed (Table 1) that $S_{\ell v}$ (D_v=o) is equal to S_ℓ but $S_{\ell v}(D_\ell$=o) is greater than S_v. Under an ideal situation $S_{\ell v}$(D =o) and S_v must be equal and so must $S_{\ell v}(D_v$=o) and S_ℓ. This discrepancy of $S_{\ell v}$(D =o) not being equal to S_v is probably due to the use of a linear approximation for conversion of vapor concentration values into liquid concentration values in the vapor-liquid diffusion model. It is expected that if the vapor-liquid diffusion equation was solved in terms of vapor concentration values, then $S_{\ell v}$(D =o) and S_v would be equal and probably $S_{\ell v}(D_v$=o) would be greater than S_ℓ.

Another observed behavior of the computer model was that the optimum values of diffusivities obtained were a function of the initial diffusivity values used in the model. This is due to the use of the steepest ascent method (Boughton 1968) which yields only a relative extreme. Thus, to obtain an absolute extreme a wide range of initial values of diffusivities were chosen. Initial vapor diffusivity values for the model were taken as a product of factor, F, and optimum diffusivity values of vapor model - II (Chhinnan and Young 1975). Initial liquid diffusivity values were taken as a product of (1-F) and optimum diffusivity values of the liquid model (Chhinnan and Young 1975). The magnitude of F was varied between zero and one to obtain a wide range of initial values used in the model. It was noted that lower sums of squares between the observed and predicted values were obtained by choosing initial vapor and liquid diffusivity values of 70 percent and 30 percent of optimum vapor and liquid diffusivity values reported by Chhinnan and Young (1975) respectively. This implies vapor diffusion as a predominant phenomenon in moisture movement. Optimum diffusivity values and their associated sums of squares of deviations between the experimental and theoretical moisture ratios are given in Table 2.

Figure 1 depicts the effect of dry bulb temperature on vapor and liquid diffusivities. Diffusivities are exponential functions of the reciprocal of absolute temperature. Liquid diffusivities increased while the vapor diffusivities decreased with an increase in temperature. This is consistent with the previously reported work of Whitaker and Young (1972b), and Chhinnan and Young (1975).

Figure 2 shows the effect of dew point temperature on diffusivities of kernel and hull. Effect of dew point temperature on vapor diffusivity of kernel was found statistically insignificant. Effect of dew point temperature on liquid and vapor diffusivities of hull and liquid diffusivity of kernel was significant. No attempt was made to determine a functional relationship between the diffusivity and the dew point temperature.

An index called Root Mean Square of deviations 'RMS' was used by Chhinnan and Young (1975) to make a meaningful comparison between the experimental and theoretical drying data predicted by various drying models. RMS for a set of drying conditions is evaluated by dividing the sum of squares of deviations by the number of observations in the drying test and then taking the square root. RMS values for each drying test are listed in col-6 of Table 3. Chhinnan and Young (1975) compared RMS values for the liquid diffusion model and vapor diffusion model -II (both the models employed Smith's equilibrium moisture equation (1947)) and found that the vapor diffusion model was better than the liquid diffusion model. In this study vapor diffusion model - II was compared with simultaneous vapor-liquid diffusion model as indicated in col-7 (Table 3). Positive values in col-7 (Table 3) indicate that the vapor-liquid model fits the experimental data better than the vapor diffusion model and the negative values indicate the opposite. In all but 4 cases, the vapor-liquid model was found to fit the observed data better than the vapor model.

SUMMARY AND CONCLUSIONS

Peanut pods were modeled as composite spheres consisting of two components, an inner core and outer shell, of different materials. The kernel and hull were represented by the inner core and outer shell respectively. The Crank-Nicholson method of finite differences was used to develop numerical solutions of the vapor-liquid diffusion equation describing the transfer of moisture in the peanut pod. Liquid and vapor diffusivities of kernels and hulls were estimated that yielded the smallest sum of squares between the theoretical and experimental drying data. Conclusions drawn from this study are:

(1) The vapor-liquid diffusion model gave a better fit of experimental data than either the liquid diffusion or vapor diffusion models studied by Chhinnan and Young (1975).

(2) Diffusivities were exponential functions of the reciprocal of absolute dry bulb temperature.

(3) Liquid diffusivity values increased with the increase in dry bulb temperature while the vapor diffusivity values decreased with the increase in dry bulb temperature.

(4) Vapor and liquid diffusivities of hull and liquid diffusivity of kernel and vapor diffusivity of kernel was effected significantly by changes in dew point temperature.

It is recommended that vapor-liquid diffusion model be chosen over either liquid or vapor diffusion model in developing a bulk drying model.

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TABLES AND FIGURES

Table 1. Comparison of sum of squares deviations between the experimental and predicted values at 43.3°C dry bulb temperature and 8.9°C dew point temperature, obtained from vapor-II, liquid diffusion models (Chhinnan and Young 1975) and vapor-liquid diffusion model.

Diffusion model	Diffusivity[a/] (m^2/hr)				Sum of Squares
	Liquid		Vapor		
	Kernel	Hull	Kernel	Hull	
Liquid	0.4534×10^{-6}	0.4085×10^{-6}	-	-	$S_\ell = 0.00730$
Vapor-liquid	0.4534×10^{-6}	0.4085×10^{-6}	0.0	0.0	$S_{\ell v}(D_v = o) = 0.00730$
Vapor-II	-	-	0.0020	0.0044	$S_v = 0.00480$
Vapor-liquid	0.0	0.0	0.0020	0.0044	$S_{\ell v}(D = o) = 0.01029$

[a/] Diffusivity values are taken from Table I of Chhinnan and Young, 1975.

Table 2. Diffusivities and their associated sum of squares of the difference that gave the best fit between the experimental and theoretical moisture ratios for the simultaneous vapor and liquid diffusion model.

No. of obs.	Dew point °C[°F]	Dry bulb °C[°F]	Diffusivity (m^2/hr)				Sum of square of deviations
			Vapor x 10^2		Liquid x 10^7		
			Kernel	Hull	Kernel	Hull	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
109	8.9 [48]	26.7 [80]	.1455	.3503	.4808	.7005	.01045
79		32.2 [90]	.1741	.3098	.5182	.9624	.00689
61		37.8[100]	.1525	.3017	.6957	.7605	.00527
53		43.3[100]	.1323	.2834	.8277	.9745	.00390
104	13.3 [56]	26.7 [80]	.2729	.6240	.3069	.3658	.01085
77		32.2 [90]	.2110	.4866	.5171	.7048	.00891
60		37.8[100]	.1746	.3717	.8509	1.1622	.00588
53		43.3[110]	.1441	.2947	1.1086	1.2697	.00553
116	17.8 [64]	26.7 [80]	.1831	.5827	.4284	.3307	.01595
84		32.2 [90]	.1972	.4344	.6075	.4494	.01078
70		37.8[100]	.1313	.3476	.8853	.4914	.00875
55		43.3[110]	.1204	.3060	1.2012	.3567	.00894
111	22.8 [73]	26.7 [80]	.1911	1.1922	.7877	.0157	.02820
81		32.2 [90]	.1530	.7641	1.1520	.0601	.01381
59		37.8[100]	.1737	.5344	1.2885	.2561	.00848
49		43.3[110]	.0967	.4535	1.9026	.2272	.00547

Table 3. Root mean square of the deviations that gave the best fit between the experimental and theoretical moisture ratios for the simultaneous vapor and liquid diffusion model, along with the measure of improvement over the vapor diffusion model - I (Chhinnan and Young, 1975).[a]

# of obs. Col. 1	Dew point °C[°F] Col. 2	Dry bulb °C[°F] Col. 3	Rel. hum. % Col. 4	Root mean square of deviations $R_{v\ell} \times 10^3$ Col. 6	$\frac{(R_v - R_{v\ell})}{R_v} \times 100$ [b] Col. 7
109	8.9 [48]	26.7 [80]	32	9.79	23.7
79		32.2 [90]	24	9.34	25.6
61		32.8[100]	18	9.29	14.6
53		43.3[110]	13	8.58	9.9
104	13.3 [56]	26.7 [80]	43	10.21	7.4
77		32.2 [90]	31	10.75	14.4
60		37.8[100]	23	9.90	11.2
53		43.3[110]	18	10.21	11.7
116	17.8 [64]	26.7 [80]	58	11.72	4.9
84		32.2 [90]	42	11.33	3.1
70		37.8[100]	31	11.18	-2.5
55		43.3[110]	23	12.75	-4.7
111	22.8 [73]	26.7 [80]	80	15.93	4.3
81		32.2 [90]	58	13.06	2.8
59		37.8[100]	43	11.99	-8.8
49		43.3[110]	32	10.56	-0.2

[a] Root mean square of deviations is obtained by dividing the sum of squares of deviations by the number of observations and then taking the square root.

[b] R_v is root mean square of deviations obtained from vapor diffusion model - I, see Table 2, Col. 4 (Chhinnan and Young, 1975).

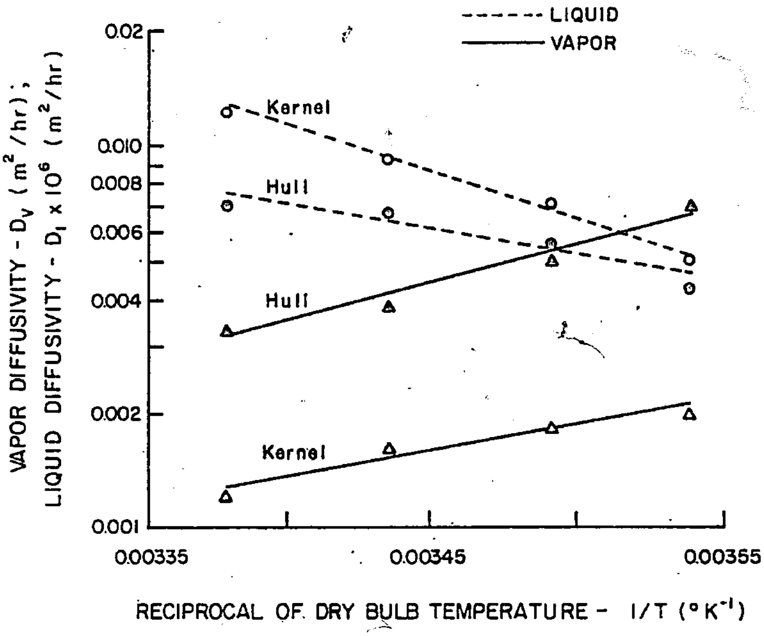

Fig. 1. Effect of dry bulb temperatures averaged over dew point temperatures of 8.9, 13.3, 17.8 and 22.8°C on kernel and hull diffusivities predicted from vapor-liquid diffusion model

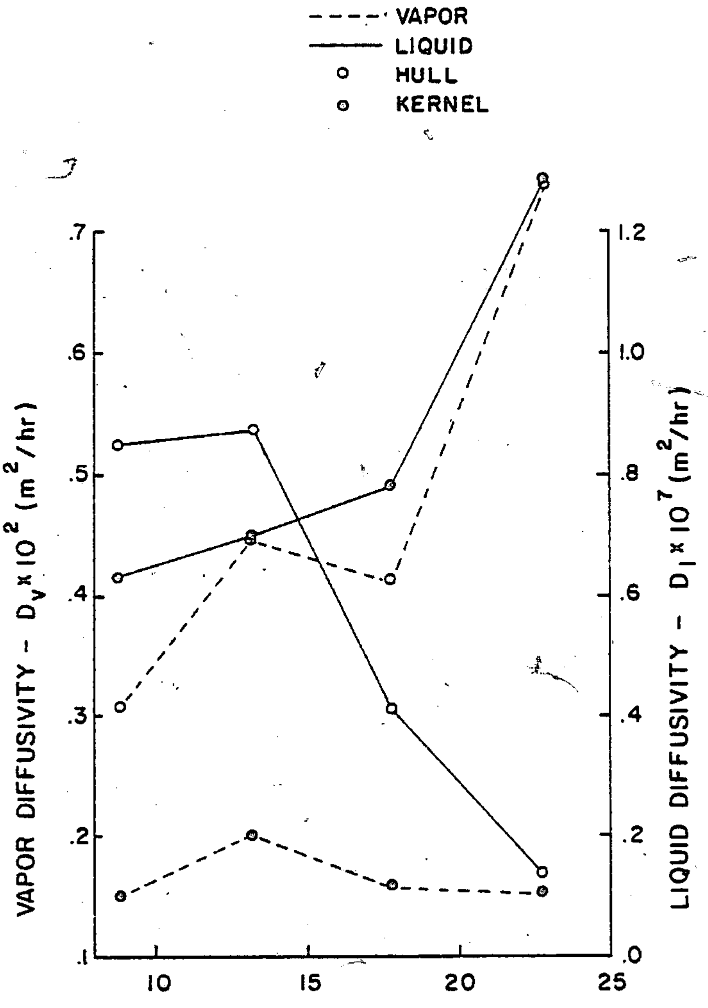

Fig. 2. Effect of dew point temperature averaged over dry bulb temperatures of 26.7, 32.2, 37.8 and 43.3 deg C on kernel and hull diffusivities predicted from vapor-liquid diffusion model

MANUSCRIPT - III

Computer Simulation of Bulk Drying of Peanut Pods[1]

by

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INTRODUCTION

Peanuts, an excellent food source of high protein and energy, have taken an important place among major crops. Like many other farm crops peanuts contain excess moisture when harvested. The excess moisture is usually removed from peanuts on the farms in stationary bed drying trailers. In order to design more efficient and practical driers or to predict the performance of a drier, there is a need to develop an algorithm by which the performance of full scale units may be analyzed in terms of the results of laboratory experiments on thin layers.

Numerous researchers have studied the drying of hygroscopic solids in deep beds (Bakker-Arkema, et al., 1967; Boyce, 1965; Hamdy and Barre, 1970; Henderson, et al. 1968; Kachru, et al., 1971; Myklestad, 1968; Parti, et al., 1974; Thompson, et al., 1968; Simmonds, et al., 1953; Spencer, 1969; and many others). They proposed analytical or computer models for predicting the moisture and temperature of the drying material and the drying medium at any time and position in a bulk drier. The development of these models considered two basic steps. It was first necessary to develop a thin layer model to characterize the change in moisture content and temperature of the individual particle under constant drying conditions. The second step involved the development of a bulk model from the thin layer model which involved the study of simultaneous changes in moisture and temperature in both the drying material and the drying medium.

OBJECTIVES

All the reported literature on drying of biological materials represent the thin layer model as a one component system consisting of the material being dried while the bulk drying model is represented as a two component system consisting of the drying material and the drying medium. The peanut pods consist of two major components (kernels and hulls), differing in material properties. Thus, in drying of peanut pods the thin layer models must consider pods as a two component system, the kernel and the hull, and the bulk drying model as a three component system, the kernel, the hull and the drying medium. This indicates that the existing thin layer or bulk drying models may not have the necessary accuracy to describe a reliable and consistent drying system for peanut pods.

Specifically, the objectives of this study were:

(1) Develop a bulk drying model for peanut pods based on the thin layer models for peanuts developed by the authors (Chhinnan and Young, 1975 and 1976).

(2) Obtain experimental drying data in a deep bed drying simulator for different inlet conditions of air.

(3) Check the validity of the computer bulk model with the experimental drying data.

THEORY

In a bulk drying system it is required to know the occurrence of the simultaneous changes in four quantities, the moisture and the temperature of both the drying material and the drying medium. Equations describing the exchange of heat and mass between the material and the drying air may be solved numerically by assuming the deep bed of material to be composed of a number of thin layers of finite thickness ΔZ. Knowing the state of the air flowing into the layer and assuming the conditions of the entering air do not change for a small but finite time, Δt, the change in moisture of the product in time Δt can be determined from a thin layer drying model. Then, solving the mass balance, the heat balance and the heat transfer equations, the temperature of the air and the material and the relative humidity of the air can be determined at the end of the time Δt. These computations give the condition of the air leaving the current layer, which is also the condition of the air entering the next layer. These computations also give the temperature and moisture content of the current layer for computations of the next time step. Thus, the solution of the four independent equations discussed below for a layer of thickness ΔZ and time increment Δt can describe the condition of the air and the material at any time and position in a bulk dryer by performing step by step (time step) and layer by layer computations.

Thin Layer Drying

It is necessary that a thin layer drying model is available that predicts a change in moisture distribution $M(r,t)$ in the peanut pod at a spatial position $\bar{r}$ and time t, and moisture distribution $M(r, t + \Delta t)$ after an elapse of time Δt corresponding to the drying air at temperature T and relative humidity rh.

$$M(r, t + \Delta t) = f(M(r,t), T, rh) \qquad (1)$$

where f is a function representing the thin layer model.

Mass Balance

Let $\bar{M}(t)$ and $\bar{M}(t + \Delta t)$ be the average moisture content (dry basis, expressed in decimal) of the product in layer ΔZ evaluated from $M(r,t)$ and $M(r, t + \Delta t)$ respectively.

The mass balance for the moisture of the layer and the drying medium over the time interval Δt is:

Moisture gained by air = Moisture lost by material

$$\dot{Q}(H'-H)\ \Delta t = -\Delta Z\ P\ A\ (\bar{M}(t+\Delta t) - \bar{M}(t))$$

or

$$\dot{Q}(H'-H)\ \Delta t = W\Delta\bar{M} = W(\bar{M}(t+\Delta t) - \bar{M}(t)) \qquad (2)$$

where[1]

$\dot{Q}$ = mass flow rate of air, kg/hr

ρ = density of dry matter, kg/m^3

A = cross-sectional area of the dryer, m^2

ΔZ = thickness of layer, m

$\Delta\bar{M}$ = change in pod moisture content (dry basis), decimal

W = mass of pods in the layer, kg, and

H = absolute humidity of air, kg of water/kg of dry air

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[1] Parameter with a suffix prime (') refer to the value after time increment Δt.

whence, the change in absolute humidity of air

$$\Delta H = H' - H = -\frac{W}{\dot{Q}}\frac{\Delta \bar{M}}{\Delta t} \qquad (3)$$

Heat Balance

Taking a heat balance for the layer over the time interval Δt:

Energy lost by air = Energy absorbed by the material +
Energy absorbed by the walls of the dryer +
Energy lost to the surrounding through the walls
(4)

$$\text{Energy lost by air} = \dot{Q}\,\Delta t(h - h') \qquad (5)$$

where

h = enthalpy of air-vapor mixture, J/kg dry air

h is expressed in terms of enthalpy of air, h_a, and enthalpy of vapors, h_v, as:

$$h = h_a + Hh_v$$

$$= C_a(T - T_o) + H(C_v(T - T_o) + h_{g,o}) \qquad (6)$$

where

C_a = specific heat of air, J/(kg · K)

C_v = specific heat of vapor, J/(kg · K)

T = temperature of air, K

T_o = reference temperature, K

$h_{g,o}$ = heat of vaporization at T_o, J/kg

Energy gained by the material (pods)

$$= W(C_p + \bar{M} C_\ell)(T_p' - T_p) + W \bar{M} C T_p' \qquad (7)$$

where

C_p = specific heat of dry pods, J/(kg · K)

C_ℓ = specific heat of liquid water, J/(kg · K)

T_p = temperature of pods, K.

Energy gained by the walls of the dryer

$$= W_w C_w (T_w' - T_w) \qquad (8)$$

where

W_w = weight of walls per layer, kg

C_w = specific heat of walls, J/(kg · K)

T_w = temperature of wall, K.

Energy lost to the surroundings

$$= 3600\ h_c A_w (T_w - T_s)\ \Delta t \qquad (9)$$

where

h_c = heat transfer coefficient, W/(m^2 . k)

A_s = surface area of walls exposed to the surroundings per layer, m^2

T_s = temperature of the surroundings, k.

Heat Transfer Equations

Heat transfer equations as expressed below describe the transfer of heat from the air to the pods and the walls.

Heat transfer between the air and the pod is:

$$Q_v A \Delta Z \Delta t \left[\frac{T + T'}{2} - \frac{T_P + T_P'}{2} \right] = W[(C_P + \bar{M}C_\ell)(T_P' - T_P) + \Delta\bar{M}C_\ell T_P' - \Delta\bar{M}h_v'] \qquad (10)$$

where

Q_v = overall volumetric heat transfer coefficient, $W/(m^3 \cdot K)$.

Heat transfer between the air and the walls of the dryer is:

$$h_c A_w \left[\frac{T + T'}{2} - \frac{T_w + T_w'}{2} \right] = W_w\, C_w (T_w' - T_w) \qquad (11)$$

There are three unknown temperatures, T', T_w', T_P', the temperature of air, walls and pod respectively in equations (4) to (11) which can be evaluated by solving three independent simultaneous linear equations obtained from heat balance and heat transfer equations (4) to (11) for a given layer and time increment.

EXPERIMENTAL METHODS

Deep Bed Dryer

The deep bed drying simulator designed by Vedak and Young (1974) was used to obtain experimental data on bulk drying. The simulator had provision for measuring the moisture content of the pods, temperature and relative humidity of the air at different levels in the bed without disturbing the drying material. The dryer was divided into ten layers. Each layer consisted of a 15.2 cm deep basket made of sheet metal with a perforated bottom placed in an aluminum frame hung at the end of a steel cantilever bar. Teflon sheets were used to connect one frame to the next. The same material was used to cover the side and the back of the frames and an aluminum plate was used to seal the front of each frame. This arrangement let the air pass from one frame to the next without leakage. A relative humidity element and a thermocouple were placed in the inter-frame gap to monitor the temperature and relative humidity of the air leaving the layer below and entering the layer above. Four strain gages in a wheat stone bridge configuration were installed on the cantilever bars from which the baskets and the frames were hung. These strain gages monitored the change in weight of basket filled with pods. Knowing the weight of the baskets, the weight of the pods and finally the moisture content can be computed.

A schematic diagram of the simulator with the air conditioning unit is shown in Figure 1. Air was conditioned to the desired dew point temperature and dry bulb temperature in the air conditioning unit. The conditioned air entered the simulator from the bottom and passed through successive baskets filled with pods and left the pods at the top. The volumetric flow rate of air was measured by the pressure differential across the Meriam[2] laminar flow unit and the absolute pressure of air.

Figure 2 shows the schematic diagram of the automatic recording system to monitor the weight of each basket, and the temperature and relative humidity of the air entering and leaving each basket.

Experimental Procedure

Six drying experiments were conducted in the simulator for various inlet conditions of the air as given in Table 1. The first four tests were conducted to check the validity of the computer model with the experimental data under constant drying conditions. Test-5 was conducted to check the behavior of the model under wetting conditions. A temperature of 10°C[50°F] was chosen for this test to maintain a reduced level of bacterial activity. After 3 days it was noticed that the rate of increase in moisture content was very low, so the dry bulb temperature was increased to 34.4°C[90°C] to accelerate the moisture absorption process.

Test 6 was conducted for varying drying conditions where the dew point temperature was kept constant but the dry bulb temperature was varied between 21.1 and 26.7°C[70 and 80°F] every 12 hours in steps of 2.8°C[5°F]. No attempt was made to change the dew point temperature during this test.

Freshly harvested peanuts were used in all the drying tests, that is for Test-1 to 4 and Test 6. Test-5 was a wetting test, thus low

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[2] The use of trade names in this publication does not imply endorsement by the North Carolina Experiment Station of the products named, nor criticism of similar ones not mentioned.

moisture peanuts taken from storage were used. Peanuts for Test-1 and 2 were dug from muddy fields, they were washed with water, left overnight in plastic bags in a cold room and loaded in the dryer the next morning. For other tests, freshly dug peanuts were stored in the cold room for a maximum of 4 days before loading in the dryer. In all tests the air conditioning unit was set at the desired conditions and run overnight to stablize it, and was switched off before loading the dryer. The dryer was loaded in the morning and the air conditioning unit was switched on again. Once the dryer was switched back on, the desired conditions of the air was quickly obtained. The weight of each basket and the temperature and relative humidity of air entering and leaving each layer was recorded every ten minutes for at least the first six hours of drying, and every one half hour for the rest of the 3 to 5 day drying period.

Samples were taken from each basket before and after completing each test to determine initial and final moisture content of kernels, hulls and pods.

Differential and absolute pressure gage readings were recorded periodically to calculate the volumetric air flow rate. Temperature of the water reservoir, which corresponded to the dew point temperature of the air was also recorded periodically.

COMPUTER SIMULATIONS

Thin Layer Drying

Chhinnan and Young (1976) recommended that the vapor-liquid diffusion thin layer model may be chosen over either liquid or vapor diffusion models in developing a bulk drying model. The liquid-vapor diffusion thin layer model was written in the form of a subroutine called 'THINLR' to be included in the main program of the bulk drying model. THINLR evaluated the moisture content of kernels and hulls at the end of a time increment for a known temperature, T, and relative humidity, rh, of air.

Diffusivities of kernels and hulls used in THINLR corresponding to dry bulb temperature, T, and dew point temperature, T_d, were interpolated from values estimated by Chhinnan and Young (1976). Vapor and liquid diffusivities of kernels and hulls were estimated by Chhinnan and Young (1976) for four dry bulb temperatures (26.7, 32.2, 37.8, 43.3°C) and four dew point temperatures (8.0, 13.3, 17.8, 22.8°C). An exponential function of the reciprocal of absolute dry bulb temperature was used to estimate diffusivities for T and T_d values which fell outside the range of the above mentioned four dry bulb and dew point temperatures.

Diffusivity as an exponential function of absolute dry bulb temperature, T(K), is expressed as

$$D = \exp[D_o + A/T]$$

where, D_o and A_o are constants estimated by a regression analysis. These values are tabulated in Table 2.

THINLR could also be easily used as a liquid diffusion model by providing liquid diffusivities from the liquid diffusion model (Chhinnan and Young, 1975) and forcing vapor diffusivity values equal to zero. Exponential function parameters D_o and A for the liquid diffusion model are also given in Table 1.

The Smith Equation (Smith, 1947) describing the equilibrium relation was used in computing equilibrium relative humidity or equilibrium moisture content values.

$$M = A - B \ln (1 - rh)$$

Parameters A and B vary with density of water (Young, 1974).

@ 15°C

A (kernel) = 0.01448	A (Hull) = 0.07003
B (kernel) = 0.06302	B (Hull) = 0.08514

Development of the Bulk Model

The computer program was written based on the theory discussed in the preceding sections. In the first version of the bulk model, both sorption and desorption processes involved in deep bed drying were taken into account but for simplicity heat losses through walls and temperature drop of the air due to change in sensible heat of the pods were neglected.

When the computer program was tested for a bulk drying simulation it appeared to be adequate during the initial period of drying, but became unstable as the drying in the lower layers and wetting in the upper layers continued. A reasonable amount of agreement was observed between the experimental and the observed values of moisture contents in the layers where drying was taking place. The instability was caused by the sorption taking place in the saturated air zone. It was found that an excessive amount of wetting of the pods was predicted in a layer exposed to highly saturated air. This moisture had to be removed from the air. Thus, the moisture content of the air dropped significantly resulting in excessive drying of the succeeding layer in which the air became saturated again. Continued wetting and drying of alternate layers caused premature termination of the computer program. The probable reason for the high rate of absorption under wetting conditions is discussed in the next section.

Inspection of the experimental data for moisture content of the layers exposed to saturated or nearly saturated air revealed that the increase in the moisture content of these layers was of very small magnitude. It was true for all the tests (Test 1-4), where the initial moisture content of the pods was very high and the lower layers were always exposed to drying conditions. The bulk model was modified so that it did not take into account the sorption process. This modification eliminated the instability problem but the model was no longer usable for conditions of air where wetting occurred. Thus, computer simulation was not completed for Test-5 and 6.

A trial run of the bulk model for Test-1 indicated estimation of faster rates of drying than observed. The deviations between the predicted and observed moisture ratios for the upper layers were higher than for the lower layers. It was felt that the heat losses and the sensible heat of the pods should not be neglected. The bulk model was modified to include the heat losses and sensible heat gain as discussed in THEORY. A flow-chart of the final modified bulk model is given in the Appendix.

Physical and Thermodynamic Properties

Dew point temperature T_d(K) of air was calculated corresponding to T and rh of air using the following relation (ASHRAE 1972):

$$T_d = 299.26 + 16.988\alpha + 1.0496\,\alpha^2$$

where

$\alpha = \log_e (3376.85\ P_w)$, and

P_w = vapor pressure of water, Pa

Relation between relative humidity, rh, and absolute humidity, H, is given by the equation below (Henderson and Perry, 1966):

$$rh = 1.608\ P_{at}\ H/(1.608\ P_{sat}\ H + P_{sat})$$

where

P_{at} = pressure exerted by the atmosphere, Pa

P_{sat} = saturation vapor pressure at the same temperature, Pa.

Density of moist air (gm/ℓ) was taken from Weast (1970),

$$D_{air} = 3.48512 \times 10^{-6}\ (P_{at} - 0.3783\ P_w)/T$$

Heat of vaporization, saturation pressure, specific volume of air and density of water were taken from steam tables (Keenan and Keys, 1936). Volumetric heat transfer coefficient used in equation (10) was taken from O'Callaghan, et al., (1971)

$$Q_v = 850.06\ [GT/P_{at}]^{0.6011} \qquad W/(M^3 \cdot k)$$

where

G = mass flow rate of air per unit area of bed, kg/hr/m^2.

Heat transfer coefficients in equation (9) and (11) were taken as (Krieth, 1969)

$$h_c = 11.356\ \mathrm{W/(m^2 \cdot k)}\ [2.0\ \mathrm{Btu/(hr \cdot ft^2 \cdot {}^\circ F)}]$$

Relations for the specific heat of kernels and hulls at moisture content $\bar{M}$ (dry basis, expressed in decimal) were developed by Young and Whitaker (1973).

$$C_{Pk} = -522.5 + 6.98T$$

$$C_{Ph} = 710.6$$

where C_{Pk} and C_{Ph} are specific heats of dry kernels and hulls respectively in J/(kg · K).

$$C_w = 4.604 \times 10^2$$

$$C_a = 1.004 \times 10^2$$

$$C_v = 1.842 \times 10^2$$

$$C_\ell = 4.186 \times 10^2$$

All of the above specific heats are in J/(kg · K)

RESULTS AND DISCUSSION

Three quantities, temperature and relative humidity of the air leaving each layer and the moisture ratio of each layer, were computed at intervals of one-tenth of an hour for Tests 1-4. The deviations between the observed and predicted values over the drying period for layer was measured by computing 'RMS' values. RMS implies the root mean square of deviations, which is computed by taking the mean of sum of squares of deviations between the observed and predicted values and then taking the square root of the mean.

RMS values obtained from deviations of observed and predicted moisture ratios for each of the tests (Tests 1-4) and each of the layers (layers 1-10) are given in Table 3.

The bulk model was also run employing the liquid diffusion thin layer model, which used liquid diffusivities estimated by Chhinnan and Young (1975). The vapor-liquid diffusion model provided a better fit than the liquid diffusion model for the thin layer drying data. As expected bulk model using the vapor-liquid diffusion thin layer model gave smaller RMS values than did the liquid diffusion model. RMS values of the moisture ratios using the liquid diffusion thin layer model for Test-1 are tabulated in Table 3.

Computer simulations were also made which neglected heat loss through the walls and the sensible heat of pods. Neglecting the heat loss and the sensible heat gain of pods produced larger RMS values indicating the importance of these quantities (for example see Test-1, Table 2).

Estimated and observed values of moisture ratios at three typical depths in the dryer such as layer #2, 5 and 8 were plotted for Tests-1 to 4 (Figures 3 to 6). The deep bed in the simulator was divided into ten layers and were numberd 1 to 10 starting from the bottom. There is good agreement between the observed and predicted values of moisture ratios for the bottom layers as shown by the moisture ratio curves for layer #2 in Figures 3 to 6. The deviations between the observed and predicted values increased in the middle and upper sections of the dryer.

Even though the agreement between the observed and the predicted values of moisture ratios may seem reasonable for a particular layer, any deviation between the predicted and actual conditions of the air leaving the layer will result in errors in the prediction of the moisture removal from the next layer. This affect is compounded as we move to upper layers of the dryer, as is clearly demonstrated in the plots of relative humidity and temperature of the air leaving layers #2, 5, and 8 for a typical drying test (Figures 7 and 8). The deviations of predicted values of relative humidity and temperature from observed values affect the correct prediction of moisture ratios and vice versa.

It is very important that the thin layer model predict the removal of moisture from the pods quite accurately at high relative humidities. Thus, prediction of the parameters controlling the moisture removal, the diffusivities of kernels and hulls, should be good at high relative humidities. In all the layers except a bottom few drying takes place for a considerable length of time under high humidity conditions of the air. The period of exposure to high relative humidities become longer and longer as we move to the upper layers.

Thin layer models of Chhinnan and Young (1975, 1976) and Whitaker and Young (1972) were less accurate for high than low dew point temperatures. It should be noted in this study that RMS values of moisture ratios (Table 3) are smaller for drying conditions corresponding to lower dew point temperatures than the higher dew point temperatures. It is probably due to availability of better estimate of diffusivities of kernels and hulls for dew point temperatures lower than 22.8°C. For dew point temperatures greater than 22.8°C diffusivities were considered as an exponential function of dry bulb temperature only, as no simple relation was suggested for the affect of dew point temperatures (Chhinnan and Young, 1976).

Considering the fact that so many parameters are involved in a bulk model and that a good estimation of some of the controlling parameters are not available (for example diffusivities at high dew point temperatures), the prediction of moisture ratios are quite reasonable.

In an earlier section, Development of Bulk Model, it was indicated that the bulk model became highly unstable when the layers were exposed to saturated air, because of high rates of sorption of moisture by the hull. Diffusivities of kernels and hulls are the parameters controlling the rate of removal or addition of water in the pods. Excessive sorption predicted in the layers exposed to saturated air is attributed to the values of diffusivities used in predicting the process. Unfortunately the values of diffusivities for the sorption process were not known so the values corresponding to the desorption process estimated by Chhinnan and Young (1976) were used and apparently were insufficient during sorption.

Another factor contributing to high sorption rate is the assumption that the outermost shell is in equilibrium with the surrounding air. If the diffusivities estimated from the drying data is to be used in a wetting process an appropriate value of surface resistance should be taken into account, or an independent estimate of diffusivities should be made from sorption data.

The desorption data used in obtaining the values of diffusivities was available for whole pods and not for kernels and hulls separately. Though the estimated values of diffusivities provided a reasonable fit for the whole pod, it has not been established that the same diffusivity values would predict an accurate flow of moisture in kernels and hulls separately. This indicates the need to get estimates of diffusivities of kernels and hulls from experimental data for kernels and hulls separately.

When the dryer was unloaded after the completion of each test, growth of fungi was observed in the upper layers of the dryer. The growth was visible in layers 7, 8 and 9 in Tests-1 and 2, layers 6 to 9 in Test-3 and layers 5 to 9 in Test-4 and 6. In all tests layer #10 did not show an excessive growth of fungi compared to layers below it, as it was open to the room environment. The wetting test, Test-5, produced an excessive fungal growth in all the layers from top to bottom. The effect of fungal growth on drying is not known, thus, not included in the bulk model.

SUMMARY AND CONCLUSIONS

A deep bed drying computer model was developed based on the vapor-liquid diffusion thin layer model. The bed was divided into several layers of finite thickness. The model was written to predict moisture content in each layer at any time. The model originally took into account a desorption as well as a sorption process, but due to unavailability of diffusivities for sorption, the model was modified to neglect sorption effects caused by high relative humidity air in the upper zones of the dryer. This modified model seemed to work well for the drying tests subjected to constant inlet drying conditions.

Tests were conducted by monitoring the moisture content of pods, and the relative humidity and temperature of the air at various depths in the deep bed drying simulator for various inlet air conditions. A good estimate of diffusivities from the thin layer drying models was not available for air at high dew point temperatures causing inaccurate predictions where they occurred.

Bulk model predictions were also obtained employing the liquid diffusion thin layer model. In most cases, as expected, the bulk model with the vapor-liquid diffusion thin layer model gave a better estimate of change in condition of the pods in the layers and the condition of the air leaving the layer than the liquid diffusion model. Inclusion of heat loss effects in the model produced a significant effect in correctly predicting the moisture ratios of the layers, especially with high dry bulb temperature inlet air conditions. In spite of the compounding effect of errors involved in calculating the drying profile of a layer, a reasonably good estimate of these profiles was produced by the bulk model.

COMMENTS AND RECOMMENDATIONS

The bulk model originally developed had to be modified to drop the sorption effect at high relative humidities in upper layers of the dryer due to high rate of sorption predicted by the currently available estimates of diffusivities of kernels and hulls. Following are the probable reasons for high rates of sorption of water by the hulls under wetting conditions and the deviations between the predicted and observed quantities:

i) the diffusivities were estimated by the thin layer models from thin layers desorption data,

ii) surface resistance to the flow of moisture is assumed to be negligible,

iii) desorption data available for estimating the diffusivities was for the whole pods and not separately for the kernel and the hull in a pod,

iv) non-availability of good estimates of diffusivities at high dew point temperatures.

New estimate of diffusivities should be obtained considering the four factors stated above by obtaining new sorption and desorption thin layer data for a wide range of drying conditions.

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TABLES AND FIGURES

Table 1. Inlet conditions of the air for the drying experiments

Test	Dew point temperature °C[°F]	Dry bulb temperature °C[°F]	Relative humidity %
1	22.8 [73.0]	34.4 [94.0]	50.0
2	18.0 [64.5]	32.2 [90.0]	43.0
3	17.2 [63.0]	27.2 [81.0]	55.0
4	20.0 [68.0]	26.7 [80.0]	65.0
5	9.2-31.5 [48.5-88.7][a]	10.0-34.4 [50.0-90.0][a]	95.0
6	16.7 [62.0]	21.1-26.7 [70.0-80.0][a]	55.0-75.0

[a] Lower and upper limit of temperature range

Table 2. Coefficients evaluated from regression analysis expressing diffusivities as an exponential function of dry bulb temperature

Thin layer model	Diffusivity	Pod Component	Intercept D_o (m^2/hr)	Coefficient A_o (m^2-°C/hr)
Vapor-liquid	Vapor	Kernel	-10.7668	2591.344
		Hull	-16.4951	3674.266
	Liquid	Kernel	0.5885	-5228.412
		Hull	3.5353	-6341.678
Liquid	Liquid	Kernel	-0.6956	-4320.815
		Hull	-1.1877	-4292.973

Table 3. RMS values of predicted and observed moisture ratios

Test #	1			2	3	4
Dry bulb °C	34.4			32.2	27.2	26.7
Dew point °C	22.8			18.0	17.2	20.0
Thin layer model	Vapor-liquid	Liquid	Vapor-liquid	Vapor-liquid	Vapor-liquid	Vapor-liquid
Heat loss and sensible heat terms included	Yes	Yes	No	Yes	Yes	Yes
Layer # 1	.0236	.0281	.0266	.0212	.0313	.0302
2	.0297	.0410	.0297	.0235	.0200	.0443
3	.0484	.0586	.0620	.0560	.0273	.0467
4	.0644	.0713	.0919	.0398	.0400	.0588
5	.0718	.0728	.1085	.0428	.0448	.0659
6	.0647	.0750	.1224	.0543	.0718	.0781
7	.0837	.0890	.1685	.0551	.0668	.0787
8	.0670	.0730	.1820	.0519	.0595	.0794
9	.0830	.1083	.2235	.0495	.0730	.0779
10	.1137	.1311	.1821	.0548	.0633	.0881
Mean	.0650	.0748	.1197	.0449	.0498	.0648

[a/] RMS means square root of the mean of the sum of squares of deviations between the observed and predicted values.

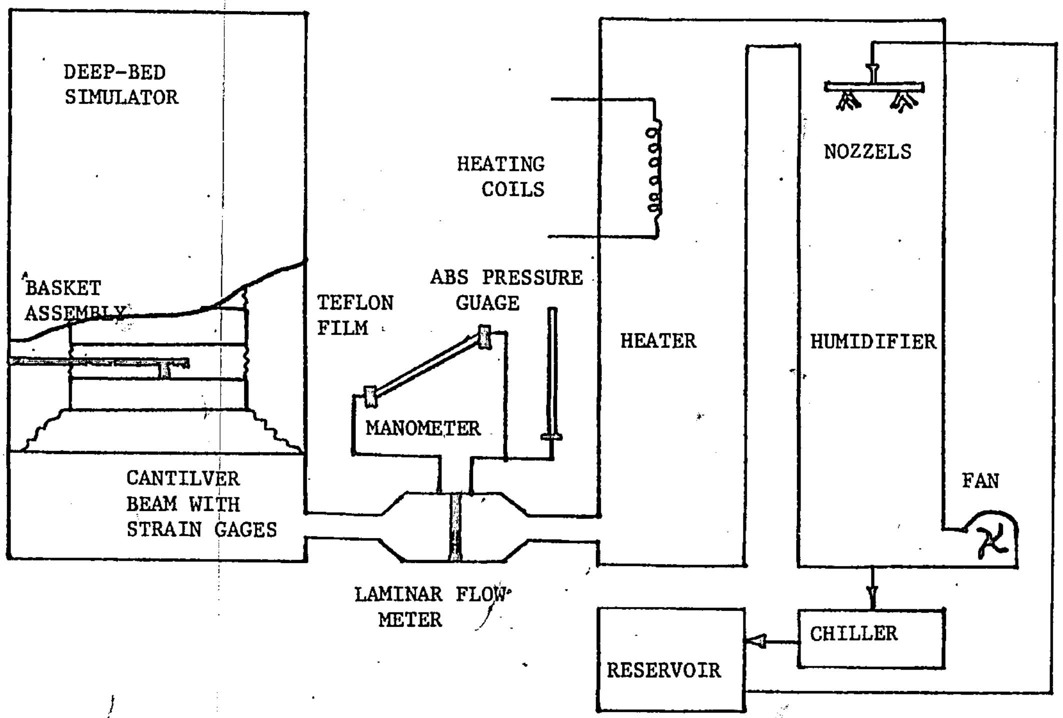


Fig. 1. Schematic diagram of the deep-bed simulator and the air-conditioning unit

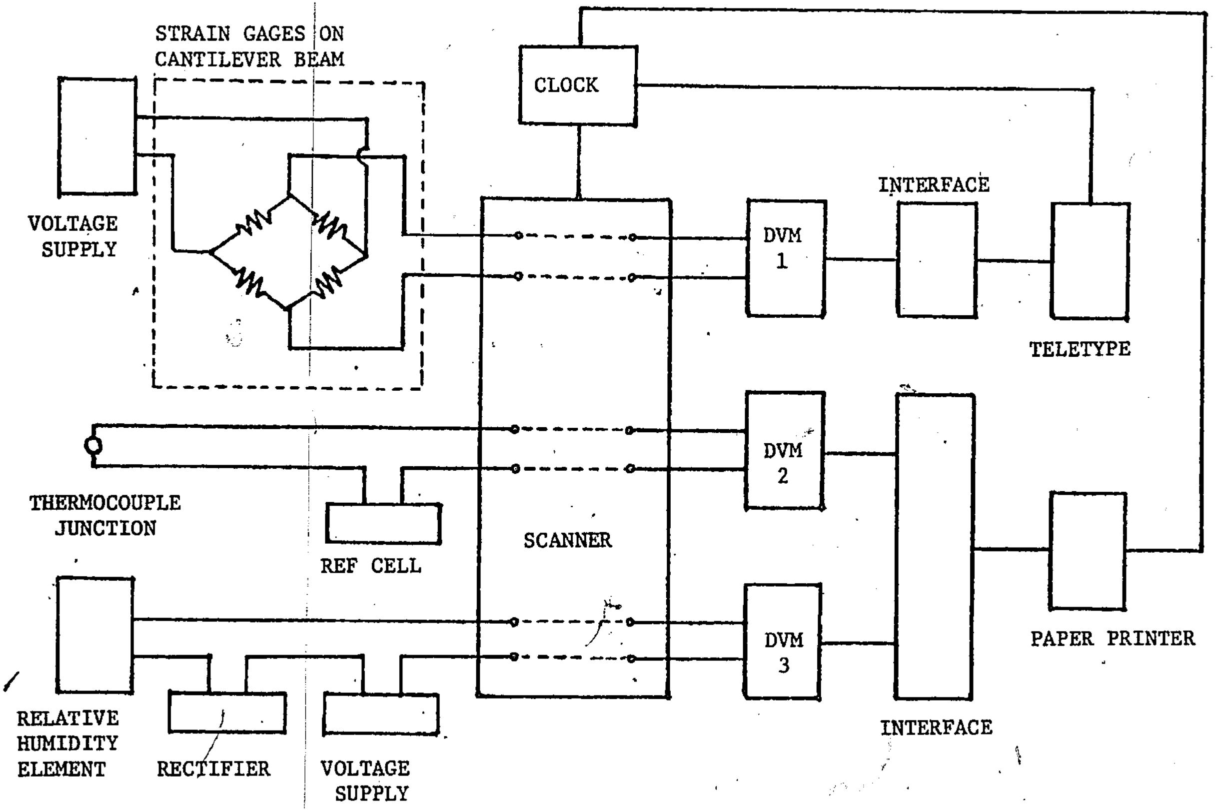


Fig. 2. Schematic diagram of the automatic recording system

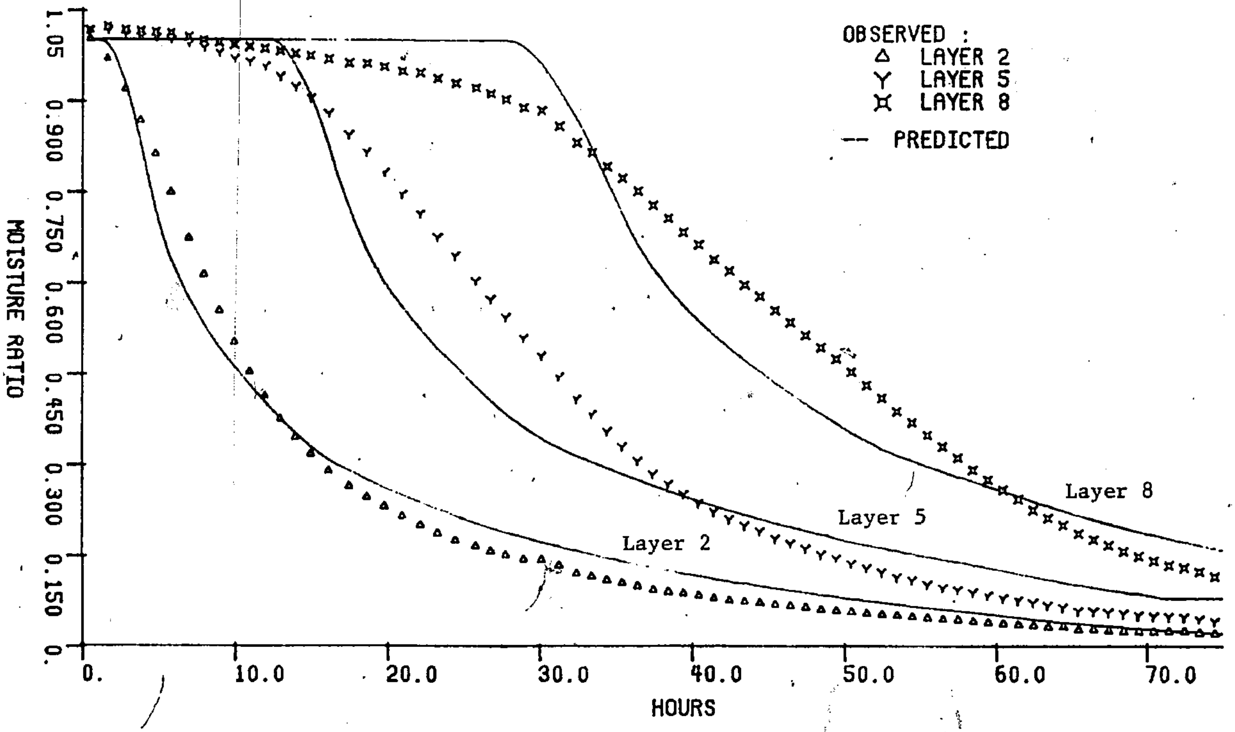


Fig. 3. Predicted and observed moisture ratios obtained from Test-1 using vapor-liquid diffusion thin layer model

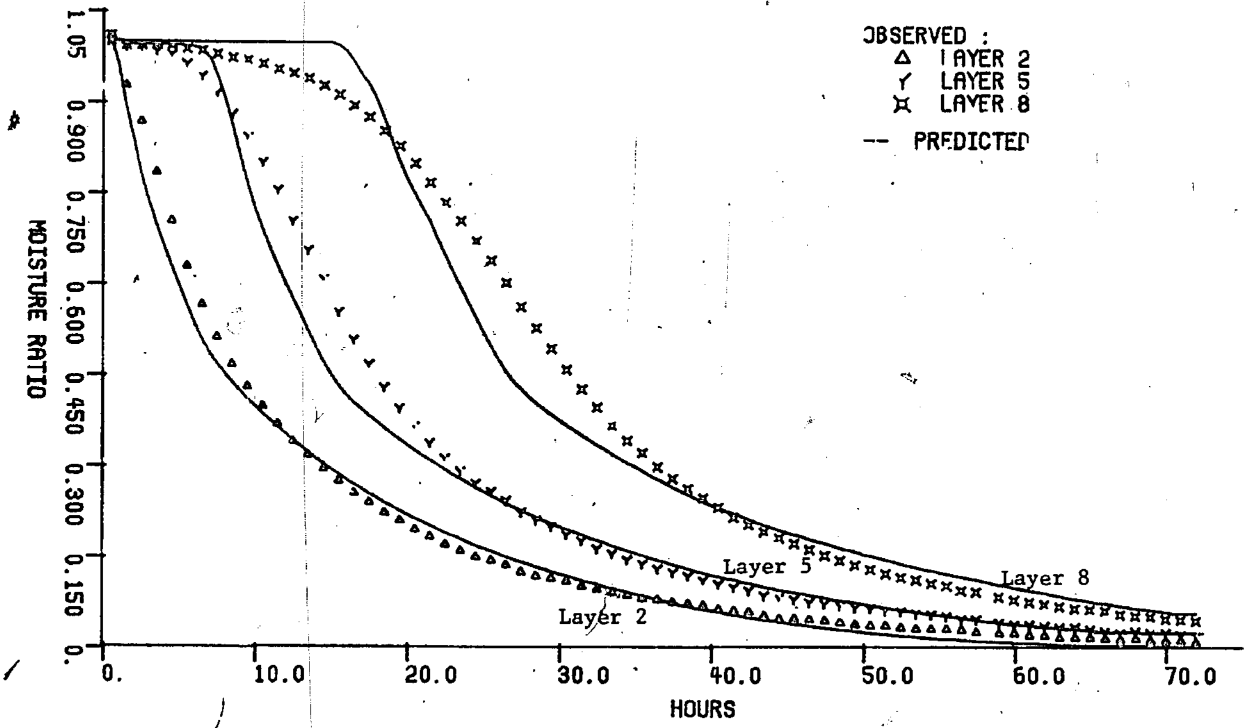


Fig. 4. Predicted and observed moisture ratios obtained from Test-2 using vapor-liquid diffusion thin layer model

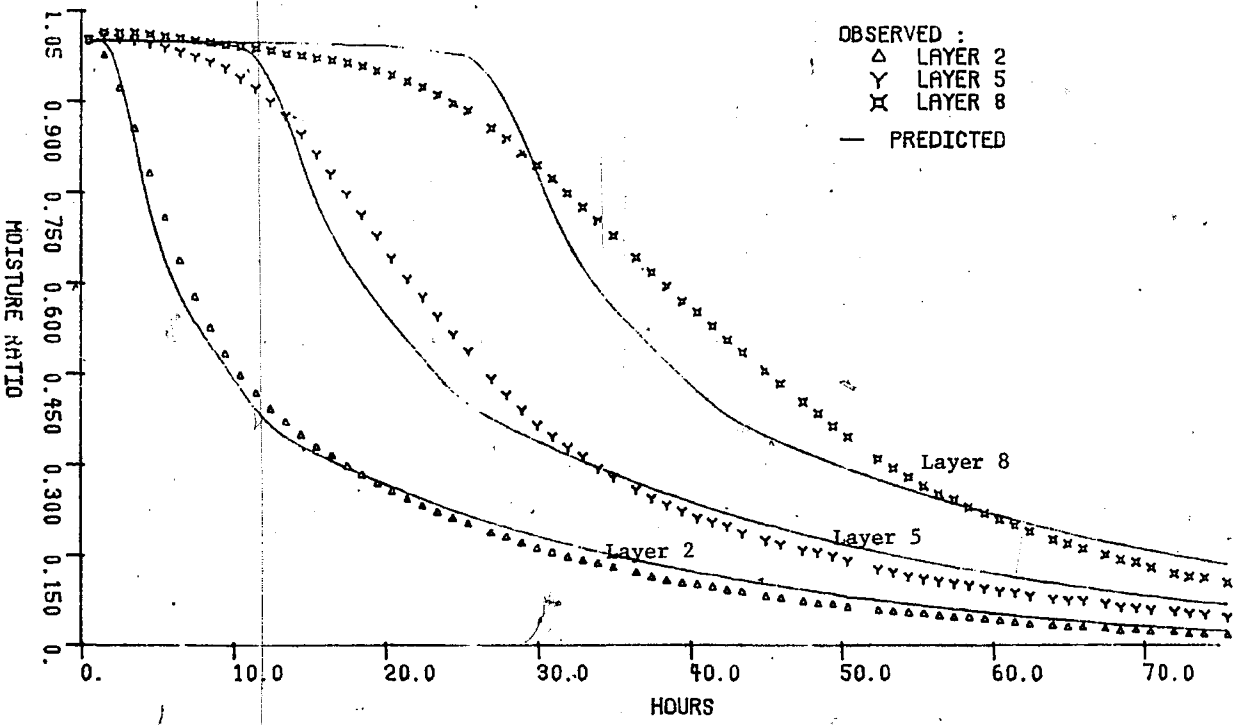


Fig. 5. Predicted and observed moisture ratios obtained from Test-3 using vapor-liquid diffusion thin layer model

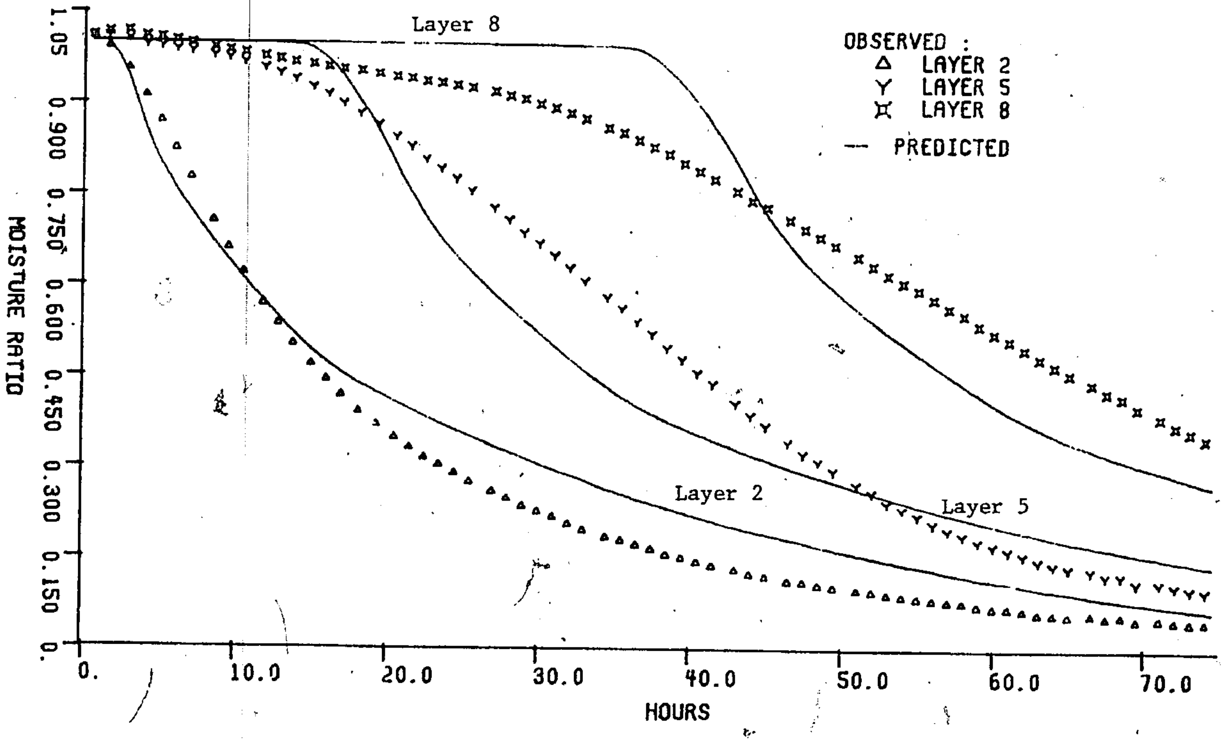


Fig. 6. Predicted and observed moisture ratios obtained from Test-4 using vapor-liquid diffusion thin layer model

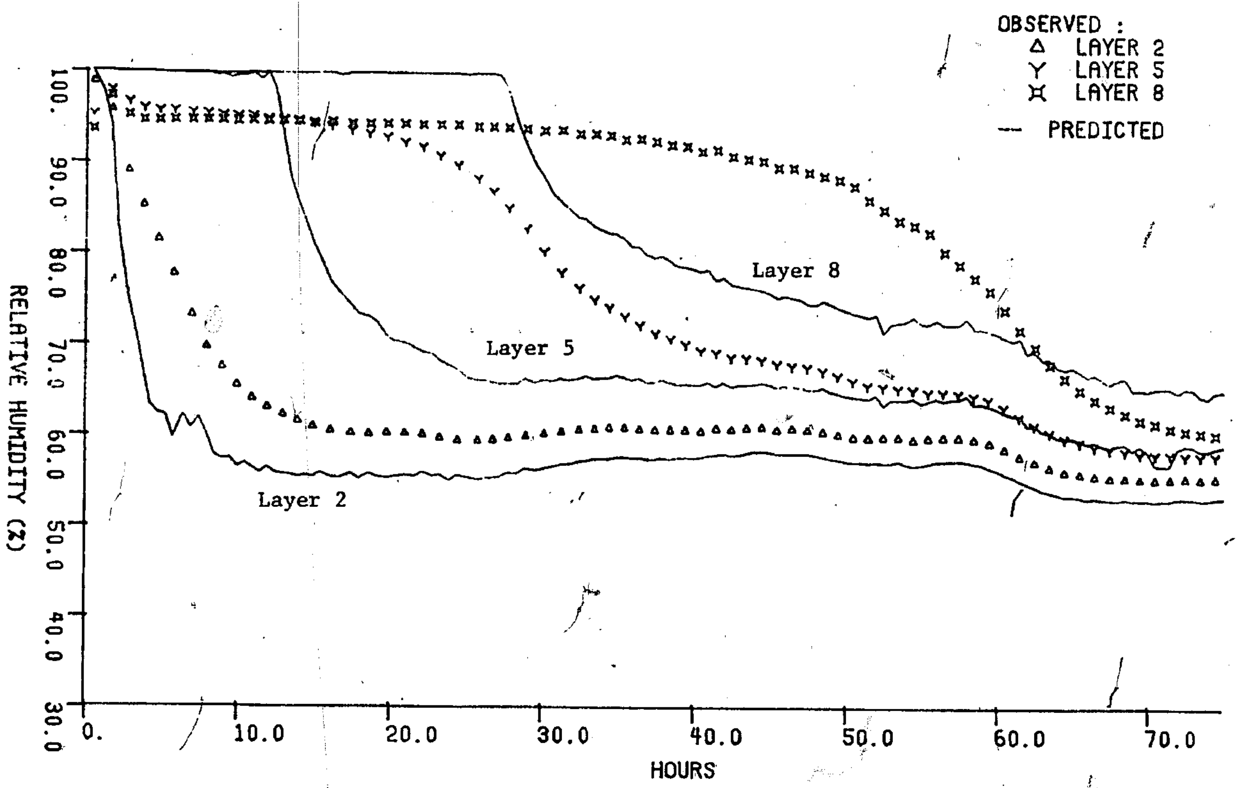


Fig. 7. Predicted and observed values of relative humidities of air leaving a layer for Test-1 using vapor-liquid diffusion thin layer model

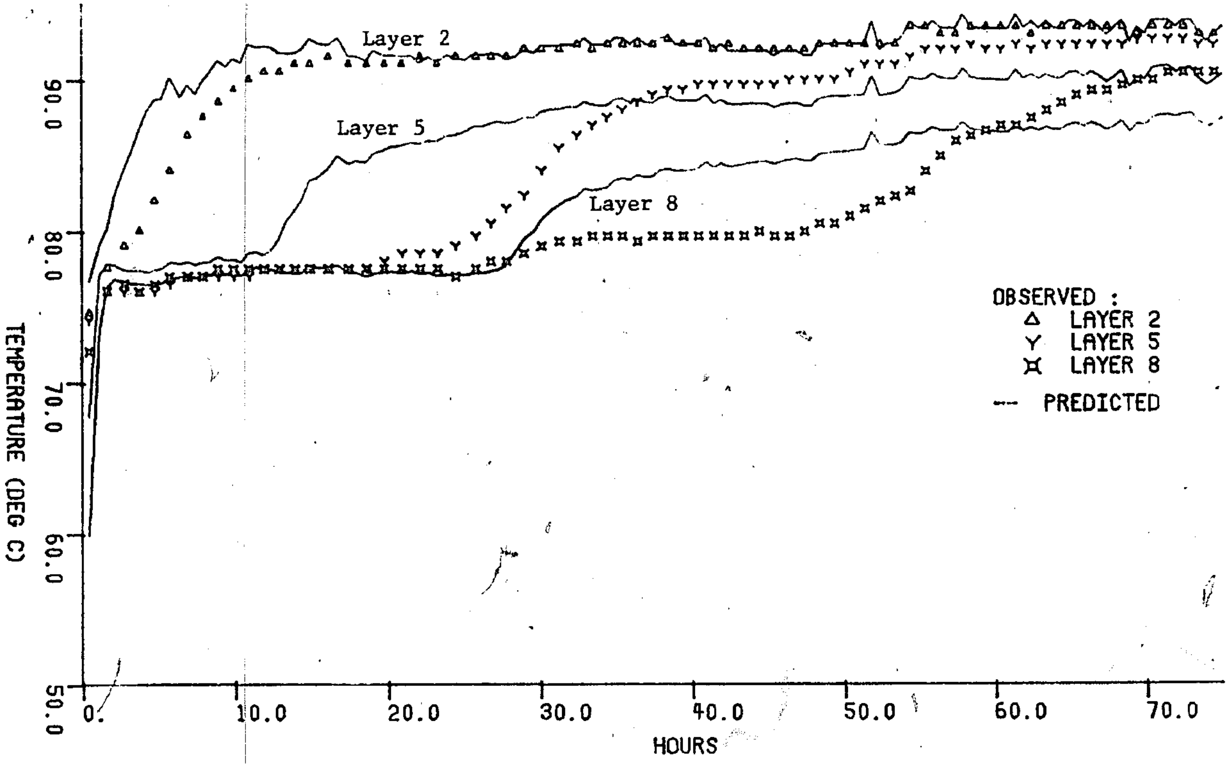


Fig. 8. Predicted and observed temperatures of air leaving various layers for Test-1 using vapor-liquid diffusion thin layer model

APPENDIX

DESCRIPTION OF ENTITIES IN THE FLOW CHART

Variables

AIRFLO - Airflow rate

DH - Change in humidity

DRWT - Array, dry weight of layers

DT - Time increment

FM - Final moisture content in each concentric layer of pods

FME - Experimental value of FM

H - Humidity of air entering LR

HF - Humidity of air leaving LR

IM - Initial moisture content in each concentric layer of pods

IOPT - If equal to 1, then take heat loss effects into account

LR - Layer number

MAXLR - Maximum number of layers

OS - Moisture content in outer shell of pod

PM - Moisture content of pod

PMF - Final PM

RH - Relative humidity of air entering LR

RHE - Array of experimental values of RH

RHEQ - Equilibrium RH

RHF - Relative humidity of air leaving LR

RMS - Array of root mean square of deviations between the predicted and experimental values of RH, T, and FM.

T - Temperature of air entering LR

TD - Temperature difference

TF - Temperature of air leaving LR

TIME - Time elapsed

TMAX - Maximum simulation time

TP - Temperature of Pod

TPF - Final TP

TWL - Temperature of wall

TWLF - Final TWL

Subroutines

EQLBRH (OS, T, RHEQ) - Computes RHEQ from OS and T

HUMDTY (RH, T, H) - Evaluates H from RH and T

RELHUM (RH, T, H) - Evaluates RH from H and T

THINLR (RH, T, IM, FM, PM) - This is the thin layer model, computes FM and PM from RH, T and IM

WETBLB (T, RH, TW, RHO) - Evaluates temperature TW, which is dry bulb temperature of intersection of relative humidity curve of RHO and wet bulb line defined by T and RH

Other Quantities

Letter in a trapezoidal box refers to branching in the flow chart.

Letters T and F near diamond shaped box refer to True or False value of the expression in the box, respectively.

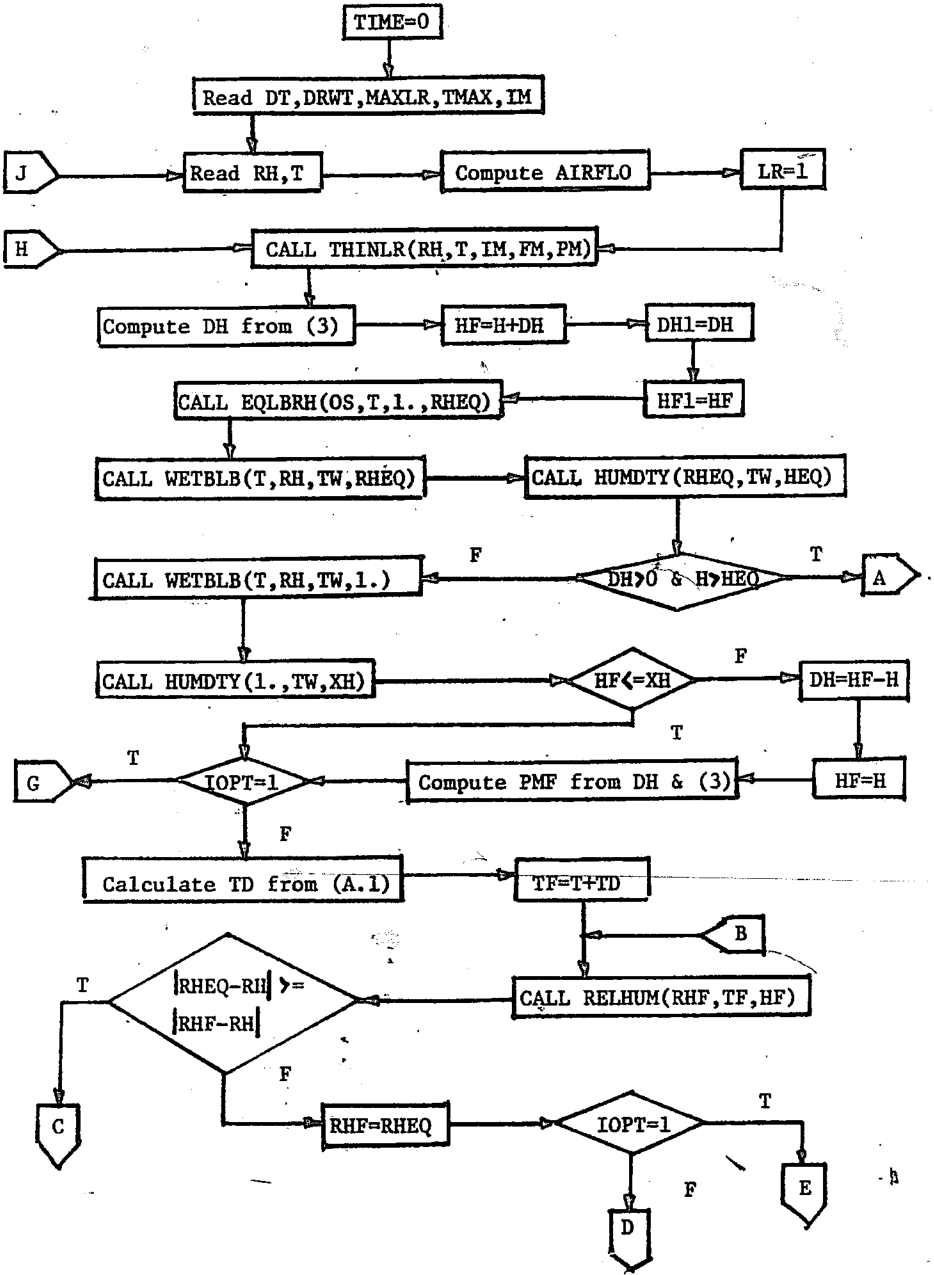
Numbers in parentheses refer to equations in Manuscript - III

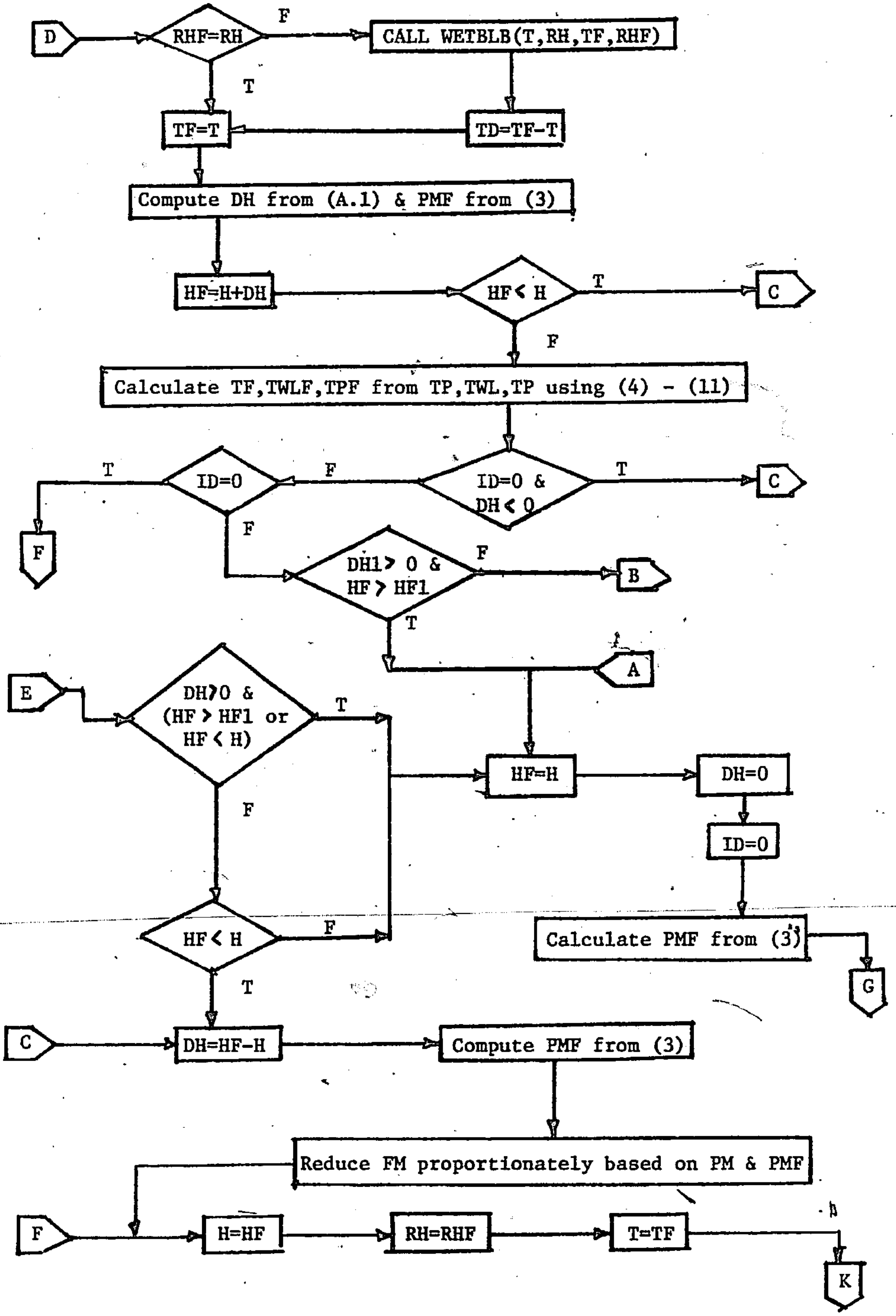
(A.1) refers to the following equation:

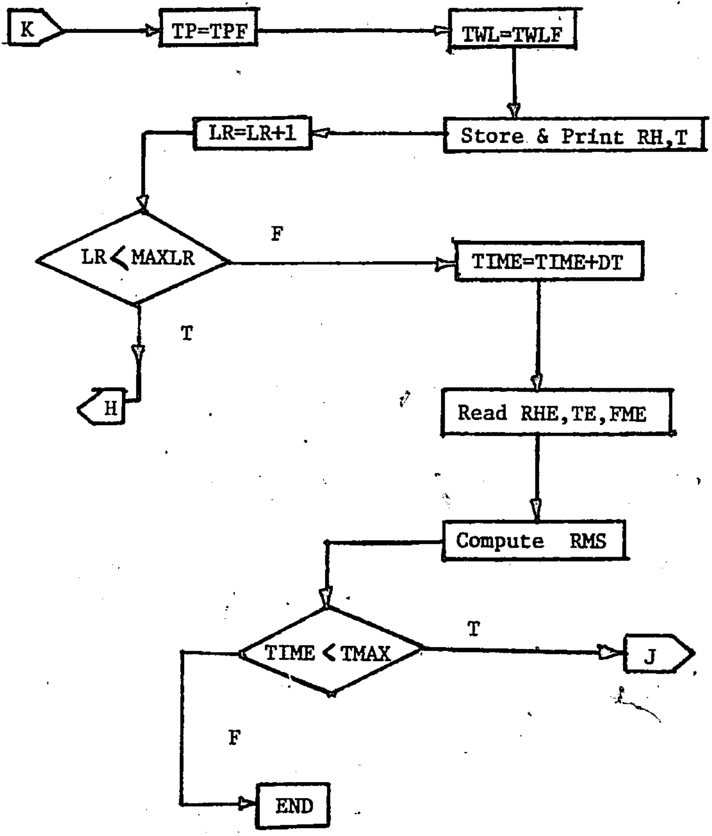
$$\Delta t = -\Delta H \; h_{fg}/(C_{pa} + C_{pv} \; H) \qquad \text{(A.1)}$$

For symbols in (A.1) refer to the main text of Manuscript - III.

FLOW CHART OF BULK MODEL




D
RHF=RH
F
T
CALL WETBLB(T,RH,TF,RHF)
TF=T
TD=TF-T
Compute DH from (A.1) & PMF from (3)
HF=H+DH
HF < H
T
C
F
Calculate TF,TWLF,TPF from TP,TWL,TP using (4) - (11)
T
ID=0
F
ID=0 & DH < 0
T
C
F
F
DH1 > 0 & HF > HF1
F
B
T
A
E
DH>0 & (HF > HF1 or HF < H)
T
HF=H
DH=0
ID=0
Calculate PMF from (3)
G
F
HF < H
F
T
C
DH=HF-H
Compute PMF from (3)
Reduce FM proportionately based on PM & PMF
F
H=HF
RH=RHF
T=TF
K


K
TP=TPF
TWL=TWLF
Store & Print RH,T
LR=LR+1
LR < MAXLR
F
T
H
TIME=TIME+DT
Read RHE,TE,FME
Compute RMS
TIME < TMAX
T
J
F
END

77

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