Simulation of Deep-Bed Drying of Virginia Peanuts to Minimize Energy Use

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(ABSTRACT)

A deep-bed drying model simulating the drying of peanuts in a fixed bed is required for designing energy-efficient and automatically controlled dryers. A deep-bed drying model consists of a thin-layer drying model to calculate the moisture release from the material and a set of mass and energy balances. An experimental setup was constructed to determine drying rates of Virginia-type peanuts under 14 different drying air conditions. Selected empirical and semi-theoretical models available for modeling thin-layer drying rates were fitted to the collected data using nonlinear regression techniques. The modified Page's model and the two-term exponential model fitted the data better than other models considered. A deep-bed drying model PEATECH based on four coupled partial differential equations consisting of four variables, air temperature, peanut temperature, air humidity, and peanut moisture content was developed. Validation of the model was accomplished by using the data collected from 36 deep-bed drying experiments conducted using three laboratory dryers during 1987, 1988, and 1989. PEATECH predicted the variables within a peanut bed with an accuracy of less than ± 6%. The energy saving potential of exhaust-air recirculation was established by conducting simulated experiments using a modified version of PEATECH.

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Chapter 1

Introduction

Both academic researchers and industrialists have an interest in the development of simulation models of the drying of biological materials. Understanding of the mechanisms involved in the drying of biological materials, selection and development of numerical and statistical tools, and validation of the models thus developed using experimental data constitute the major interests of the researcher. However, the emphasis of the industry is on monetary justification, which defines the overall objectives of any simulation.

The monetary justification for simulation of the drying of biological materials stems from the needs to design more economically competitive dryers and to conserve energy in existing dryers. Dryers consume energy in two forms: electrical energy to drive the fans, and heat energy to elevate the temperature of the drying air. In drying applications in agriculture, heat energy is the major concern because it is directly dependent on petroleum fuels.

Farmers use 3 to 4 percent of all the energy consumed in the United States, and the total food system consumes 12 to 17 percent of total energy consumption. American farmers use 5.0 billion liters (120 trillion Btu) of liquified petroleum gas (LPG) annually just for drying crops. Corn drying alone consumes 60 TJ each year in the United States (Friedrich, 1978). Therefore, conservation strategies can be expected to affect farmers' budgets significantly.

Energy conservation in existing agricultural production systems is one avenue available for investigation that would make food production less dependent on petroleum-based fuels. Energy conservation costs are typically less than the costs to produce energy through the development of new technology, and have beneficial effect on the environment in comparison to energy produced and used. Further, conservation technologies can generally be implemented at a faster rate and with less governmental involvement in the near term than new technologies.

Energy savings offer the potential for substantial reductions in peanut production costs. The total peanut production of the United States is 1.7 million Mt (Woodroof, 1983). American peanut farmers use approximately 70 ML of LPG per year, at a cost of $210 million per year. The cost of LPG for Virginia peanut farmers is $30 million per year. If one-third of this drying energy could be saved, the result would be a significant reduction in peanut production costs for Virginia farmers.

There are three main approaches to conserving energy in peanut drying: using an alternate energy source such as solar heat, employing an intermittent air supply, and partial recirculation of drying air. Partial recirculation of drying air provides the best way of conserving energy in peanut drying because it improves the quality of peanuts (lower shell damage) while saving energy (Young, 1985).

A model simulating the drying process in a peanut dryer is useful for studying the drying process itself as well as the energy-saving potential of exhaust air recirculation. Since real experiments with peanut dryers are expensive and time consuming, even if the farmers are willing to cooperate, computer simulation of peanut drying provides a powerful tool for researchers to evaluate different strategies of energy conservation. The models can also be used for designing different types of dryers and for finding ways of improving the performance of existing dryers. The goal of this study is to develop a simulation model of the peanut-drying process that will be useful in energy conservation research.

Even though the development and the validation of a simulation model is an involved task, once developed the model becomes merely a tool at the users' end. This tool can be used in peanut quality assessment research, for controlling drying parameters in field conditions, and in research on conservation of energy.

The mold growth in peanuts during drying and the splitting damage while shelling are the main physical factors in determining peanut quality. Mold growth starts at the top layers in the dryer if peanuts are dried too slowly, and the splitting damage occurs if peanuts are dried too fast. Therefore, for good quality peanuts, drying parameters such as airflow, inlet temperature and drying time should be optimized, and can be by use of a model to conduct simulated experiments, provided that the quantitative information relating drying rates to the mold growth and the shelling damage is available.

A peanut-drying model would have several other uses in agricultural research, including its use as a submodel of an expert system dealing with, for example, the economic impact of changing fuel prices on the agricultural sector in Virginia.

A deep-bed drying model for Virginia-type peanuts based on Troeger and Butler's drying equations was developed by Cook et al. (1982) and was tested using the data collected from the same laboratory dryers used for developing the model (Kulasiri, 1988). The model did not predict air temperature, air humidity, peanut temperature, and moisture content of peanuts in a dryer accurately enough to be used in the future research. Therefore, a better model consisting of a thin-layer drying model developed specifically for Virginia-type peanuts, a different mathematical formulation, and a more accurate computational technique than that used in the previous model was needed.

Chapter 2

Objectives

The goal of this research was to develop a simulation model of the peanut-drying process that will be useful in energy conservation research.

The specific objectives of this research are:

1. a. To develop an experimental setup to determine thin-layer drying rates of Virginia peanuts.

   b. To develop drying-rate models for Virginia peanuts based on experimental data and using statistical methods.

   c. To develop a model for equilibrium moisture content for Virginia peanuts based on published data.

2. To simulate drying of a peanut pod using the finite element method.

3. To develop a deep-bed drying model for peanuts and validate the model using data collected from laboratory dryers.

4. To establish the energy-saving potential of exhaust-air recirculation in peanut drying.

Chapter 3

Modeling Thin-Layer Drying of Virginia-Type Peanuts

3.1 Introduction

Drying of thin layers of food products has been studied by many researchers in an effort to understand the deep-bed drying of materials (Sharaf-Eldeen et al., 1979). The thin-layer drying characteristics of a material are determined experimentally by passing air at constant temperature and humidity through a thin layer of the material, and recording the weight loss or gain. The data collected are used (1) to find parameters in semi-theoretical or empirical models using statistical procedures, and (2) to validate theoretical models.

The objective of this study presented in this chapter was to determine experimentally the thin-layer drying rates of Virginia-type peanuts, and to fit suitable models to data collected using statistical procedures. The ability to accurately model the data with a minimum number of parameters and the efficient implementation of the model in simulation of deep bed drying are emphasized in the development of statistical models.

This chapter contains four sections. In Section 3.2, pertinent literature is reviewed, and an overview is given of the nonlinear regression procedures used. The experimental methods and materials used are presented in Section 3.3; Section 3.4 deals with the statistical analysis of data and presents the thin-layer drying models tested. The development of a model for equilibrium moisture content of peanuts, based on the data collected from the literature, is discussed in Section 3.5. Section 3.6 gives a summary and conclusions for the chapter.

3.2 Literature Review

3.2.1 Modeling Drying Characteristics of Biological Materials

3.2.1.1 Introduction

Sharaf-Eldeen et al. (1979) described the drying of food products as a "complex thermophysical and physiochemical" process consisting of simultaneous heat and mass (moisture) transfer within the substance as well as between the surface of the substance and the surrounding medium. When a particle of the product to be dried is surrounded by drying air, heat is transferred to the surface of the particle, evaporating the surface moisture. This evaporation of surface moisture triggers moisture and/or vapor movement and heat transfer within the particle. While the temperature of the particle increases towards the surrounding temperature, moisture content decreases towards the equilibrium moisture content.

The process of drying farm crops can be divided into two periods: (1) a constant-rate period during which the external conditions such as temperature, humidity and air flow determine the drying rate and (2) a falling-rate period during which diffusion mechanisms within the substance in response to external conditions govern the drying rate. The boundary heat and mass transfer coefficients, geometry of the particle, area exposed to the drying medium, and difference in temperature and humidity between the gas stream and the wet surface of the solid affect the drying rate during the constant rate period (Fortes and Okos, 1980). The falling rate period starts after the constant rate period. The point of departure is called the critical point. The falling rate period may consist of two zones (Agrawal and Singh, 1977; Hamdy et al., 1977; Harmathy, 1969; Henderson and Henderson, 1968). During the first zone, moisture in the surface pores evaporates and the evaporating surface decreases. The first falling rate period is called the unsaturated surface zone or funicular state. The second falling rate period is marked by the unsaturated surface pores and the 'vaporization front' moving into the solid. The drying rate is governed by the mechanisms for internal moisture transfer. This second falling rate period is called the internal moisture control zone or pendular state. The terms "funicular" state and "pendular" state are used to describe the drying of nonhygroscopic materials (Fortes and Okos, 1980). Brooker et al. (1974) stated that cereal grains do not have a constant rate period, provided they are not harvested immaturely and do not have water condensed on their surfaces. Henderson and Perry (1976) asserted that most food products do not have a constant rate period. Young and Whitaker (1971) stated that there was no constant rate drying period for peanuts even with an initial moisture content as high as 106 percent dry basis (51.45 percent wet basis).

Sharaf-Eldeen et al. (1979) listed six mechanisms they hypothesized to describe moisture movement in capillary porous products during the falling rate period:

1. Capillary flow: liquid flow due to surface forces.
2. Liquid diffusion: liquid movement due to moisture concentration differences.
3. Surface diffusion: liquid movement due to diffusion of moisture on the pore surfaces.
4. Vapor diffusion: Vapor movement due to vapor concentration differences.
5. Thermal diffusion: Vapor movement due to temperature differences.
6. Hydrodynamic flow: Liquid and vapor movement due to total pressure differences.

Because of the complexity of the mechanisms involved in drying, simplifying assumptions have to be made for development of conceptual bases for mathematical modeling to be possible.

It is important to model the drying behavior of a layer of individual particles so that the deep bed drying of biological products such as cereal grains, fruits, and vegetables may accurately be modeled (Sharaf-Eldeen, 1979; Baker-Arkema et al., 1967; Barre et al., 1971; Baughman et al., 1973; Baughman et al., 1971; Boyce, 1966; Hamdy and Barre, 1970; Henderson and Henderson, 1968). Three basic types of models have been used to simulate the drying behavior of biological materials:

1. semi-theoretical and empirical models,
2. diffusion models, and
3. simultaneous heat and moisture transfer models (SHMT).

Since semi-theoretical and empirical models are the ones considered in this chapter, they are discussed in the following sections. The other two types are discussed in Chapter 4.

3.2.1.2 Semi-theoretical and Empirical Models

Many drying models for various biological materials are based on an equation first presented by Lewis (1921). He hypothesized that the drying rate during the falling rate period is proportional to the instantaneous difference between the moisture content of the material and the equilibrium moisture content corresponding to the condition of the drying air.

$$\frac{dM}{dt} = -K\ (M-M_e) \qquad [3.1]$$

where

M = moisture content at time t, decimal, dry basis

t = time, h

M_e = equilibrium moisture content, decimal, dry basis

K = drying constant, 1/h

Eqn. [3.1] can be integrated with respect to time and rearranged as

$$\frac{M-M_e}{M_i-M_e} = MR = e^{-Kt} \qquad [3.2]$$

where

M_i = initial moisture content, decimal, dry basis

MR = moisture ratio

Eqn. [3.2] is known as the exponential or logarithmic or one-term exponential model. It can be modified by adding more exponential terms, and a model with more than one exponential term fits thin-layer drying data better for some products such as parboiled rice (Byler et al., 1987). Eqn. [3.2] has been extensively used by researchers to model thin-layer drying data of various food products (Jayas and Sokhansanj, 1986; Bruce, 1985). The asymptotic value of the drying curve has been used as the equilibrium moisture content for Eqn. [3.2]. McWeen and O'Callagham (1955) called it the dynamic equilibrium moisture content in their study of wheat-grain drying, and Becker and Sallans (1959) named it the effective surface moisture content. Usually, the dynamic equilibrium moisture content is higher than the actual equilibrium moisture content (Henderson and Perry, 1976). The concept of the dynamic equilibrium moisture content has been used by many researchers (Allen, 1960; Hall and Rodrigues-Arias, 1958; Henderson and Pabis, 1962). Henderson and Pabis (1962) presented an Arrhenius type equation for the constant K.

$$K = a \exp \left[\frac{-b}{T_{abs}} \right] \qquad [3.3]$$

where

a = material constant, 1/h

b = material constant, K

T_{abs} = temperature of drying air, K

Eqn. [3.2] has been observed to underestimate the drying rate during the initial stages of drying and overestimates it in the final stages (Hall and Rodrigues-Arias, 1958; Henderson and Pabis, 1962; Menzies and O'Callagham, 1971; Sharaf-Eldeen et al., 1978; Troeger and Hukill, 1971). Byler et al. (1987) used one-term, two-term, three-term, and four-term exponential models to fit data from the thin layer experiments for parboiled rice. Each exponential term introduces two additional parameters to be evaluated and at the same time reduces the error of the model.

Page (1949) introduced an exponent to the time variable to overcome the shortcomings of the exponential model.

$$MR = \exp(-Kt^n) \qquad [3.4]$$

where

n = empirical drying exponent

Sokhansanj et al. (1987) listed the applications of equation [3.4] to a model of the drying behavior of oil-seed sunflower, barley, wheat, canola, shelled corn, beans, and rice.

Chen and Johnson (1969), in a study of kinetics of moisture movement in hygro-scopic materials, proposed the following model to explain drying behavior by analogy to chemical kinetics:

$$\frac{dM}{dt} = -K\,[M - M_e]^n \qquad [3.5]$$

Troeger and Hukill (1971) modeled the thin-layer drying of corn kernels using three equations of the above form.

Thompson et al. (1968) modeled the drying time, t, for thin-layer drying of shelled corn using the following equation:

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

where A and B are empirical coefficients that depend on the temperature of drying air.

3.2.1.2.1 **Semi-theoretical and Empirical Models in Peanut Drying**

Woodward et al. (1971) modeled the drying rate of freshly harvested Starr Spanish, Early Runner, and Florigiant Virginia-type peanut pods, kernels, bald kernels, split kernels, and hulls using Eqn [3.1]. The models were based on thin-layer drying experiments employing a drying air temperature of 35 C and 37% relative humidity.

Troeger and Butler (1979) used the following model to simulate the rate of peanut drying using solar energy:

$$\frac{dM}{dt} = -a\,(M_i - M_e)\,(MR)^b \qquad [3.7]$$

where

M	=	moisture content, decimal, dry basis
t	=	time, h
M_i	=	initial moisture content, decimal, dry basis
M_e	=	equilibrium moisture content, decimal, dry basis
MR	=	moisture ratio (dimensionless), which is defined by

$$MR = \left[\frac{(M-M_e)}{(M_o-M_e)}\right] \qquad [3.8]$$

a and b are functions of drying conditions defined by the following equations:

For $MR \geq 0.40$,

$$a_1 = 0.02320 + 0.00045T + 0.00063T_{dp} + 0.00045T_{dp}M_o + 0.0080M_o \qquad [3.9]$$

$$b_1 = 3.264 - 0.0252T - 0.0162T_{dp} - 0.0342T_{dp}M_o - 0.6080M_o \qquad [3.10]$$

For $0.12 < MR < 0.40$,

$$a_2 = a_1\,(2.40 - M_o) \qquad [3.11]$$

$$b_2 = b_1\,(0.88 - 0.20\,M_o) \qquad [3.12]$$

For MR $\leq$ 0.12,

$$a_3 = a_2\,(2.40 - M_o) \qquad [3.13]$$

$$b_3 = b_2\,(0.88 - 0.20\,M_o) \qquad [3.14]$$

where

T = dry bulb temperature of air, C

T_{dp} = dew point temperature of air, C

The values of the above coefficients were determined statistically using experimental data obtained from a multi-layer peanut dryer with a depth of 0.3 m. Cundiff et al. (1983) suggested that if the transition moisture ratios (MR) were changed at 0.7 and 0.2 instead of 0.40 and 0.12, a better drying rate model for Virginia-type peanuts could be obtained.

3.2.1.2.2. **Discussion on Semi-theoretical and Empirical Models**

Jayas et al. (1988) presented an excellent discussion on applications of Eqns. [3.2] and [3.4] to explain the drying behavior of biological materials. They stated that two parameters in Page's equation pose difficulties in comparing the effects of independent variables such as airflow rates, type of materials, initial moisture content, material history, drying temperature, and relative humidity. They further explained why Page (1949) had to introduce the exponent n.

> "Page (1949) does not give any reason for the introduction of n other than it resulted in a better fit to the experimental data. An examina-

tion of the basic assumption in the development of the equation and the duration of Page's tests explain why n was needed. In the derivation of Eqn. [3.2] it was assumed that the only resistance to moisture movement inside the drying particles or that the only resistance to moisture movement is at the surface of the material particles. This assumption is reasonable during the initial part of drying of the material when moisture is uniformly distributed throughout the particle. As drying progresses the resistance to moisture movement inside the kernels cannot be assumed negligible unless a tempering time is provided to allow for redistribution of the moisture in the particles before continuing further drying. Page (1949) conducted his experiments for long duration (>100h) and thus the validity of Eqn. [3.2] under his conditions became questionable." (Jayas et al. 1988).

Jayas et al. (1988) further suggested that Eqn. [3.2] should be used for short duration tests, Eqn. [3.4] should be used for long duration tests, and the equilibrium moisture content (M_e) should be evaluated using non-linear regression as a second or third parameter. This approach makes the predetermined equilibrium moisture content models unnecessary.

Multi-term exponential models used by Byler et al. (1987) deserve serious attention. To evaluate parameters in each term, non-linear regression techniques have been used. Parameters are then related to drying air conditions by using statistical methods or by assuming the forms of relationships and regressing them with the overall model (Byler et al., 1984).

3.2.2. **Equilibrium Moisture Content of Peanuts**

The adsorbed moisture within a peanut exerts a vapor pressure in the immediate surroundings in proportion to the moisture content of the peanut. The equilibrium relative humidity is defined as the ratio of the moisture vapor pressure at the equilibrium state to the saturated vapor pressure of pure water at the temperature of the peanut. The moisture content at equilibrium is known as the equilibrium moisture content.

Beasley and Dickens (1963) studied the relationship between equilibrium relative humidity (ERH) and the equilibrium moisture content (EMC) of NC-2 Virginia bunch peanuts. They experimentally determined the equilibrium moisture curves for hulls, whole pods, and kernels at three different temperatures, 10 C, 21 C, and 32 C. Within the relative humidity range of 20% to 100%, the following observations and remarks can be made:

(a) Because hulls are more hygroscopic by nature than kernels, hulls had a higher equilibrium moisture content than either kernels or whole pods below 95% ERH and at all temperatures tested.

(b) Kernel moisture and whole pod moisture show exponential response at high ERH values (above 90%) while hulls show less rapid increase in equilibrium moisture content at high ERHs.

(c) The behavior of whole pods is closer to that of kernels than of hulls.

The experimental values were fitted to the following equation developed by Henderson (1952) and the constants thus found were given in their publication:

$$1 - rh = e^{-KTM^n} \quad [3.15]$$

where

rh = relative humidity, decimal

T = absolute temperature, R

M = moisture content, decimal, dry basis

K & n = characteristic constants of the material

Henderson and Perry (1976) stated that Eqn. [3.15] can be thermodynamically proved, but the variation in ERH with temperature has never been justified. Beasley and Dickens (1963) did not validate the accuracy of Eqn. [3.15] with other data.

Troeger and Butler (1970) gave equilibrium moisture versus relative humidity plots for three varieties of peanuts (Starr Spanish, Early Runner, and Florigiant) in three forms (whole pods, kernels only, and hulls only). They used dry peanuts as well as green peanuts for their tests and made the following conclusions:

(a) The equilibrium moisture contents of green peanuts and dry peanuts were not significantly different at low relative humidities.

(b) When the temperature was increased, the equilibrium moisture content decreased for a given relative humidity within the low and medium relative humidity range and increased at high relative humidities.

(c) The mold growth experienced during the tests at high relative humidities affected the weight of the samples and lowered the moisture contents.

They gave the following relationships for the equilibrium moisture contents of hulls, whole pods, and kernels:

Dry basis EMC of hulls = 1.4 x dry basis EMC of whole pods.

Dry basis EMC of kernels = 0.87 x dry basis EMC of whole pods.

These relationships were valid for the range of relative humidities investigated.

Young (1976) determined experimentally the sorption and desorption equilibrium moisture content curves of Virginia-type peanuts, NC-5 variety, at four different temperatures (15, 25, 35, and 45 C). He accommodated the hysteresis between the wetting and drying processes when modeling the data. Five equations widely used in modeling the equilibrium-moisture-content curves for biological materials were investigated. The equilibrium-moisture-content isotherms for whole pods were not included in the investigation.

Troeger and Butler (1979) used the data given by Beasley and Dickens (1963) to derive the following equation for Virginia-type peanuts:

$$M_e = (-\ln (1-rh))^{0.7} \left[\frac{111}{(T_a + 273)} \right]^{2.4} \qquad [3.16]$$

where

T_a = dry bulb temperature of drying air, C

rh = relative humidity of drying air, decimal

Cundiff et al. (1983) also used Eqn. [3.16] in their computer model to simulate peanut drying with exhaust-air recirculation.

Analyses of data given by Beasley and Dickens (1963), Troeger and Butler (1970), and Young (1976) reveal that the equilibrium moisture contents reported under similar conditions and for the same material are within 5% to 30% if relative humidity is less than 80%. Generally, the equations do not fit well with experimental desorption data at low relative humidities (below 40%), while experimental sorption data agrees well with the equations. At low relative humidities, deviation between a value given by an equation and the corresponding experimental equilibrium-moisture content (desorption) can be as high as 50 percent.

3.2.3 An Overview of Nonlinear Regression

3.2.3.1. Introduction

Gallant (1987) presented an excellent treatment on nonlinear regression that explains its theoretical foundations as well as its practical applications. A univariate nonlinear regression model is of the form,

$$y_t = f(x_t, \theta^o) + e_t \qquad [3.17]$$

where

$t = 1, 2, \ldots\ldots n$

Here, observed, univariate responses, y_t, depend on corresponding k-dimensional inputs, x_t, through the response function $f(x_t, \theta^o)$. θ^o is a p-dimensional vector of unknown, true parameters, and the e_t vector contains the experimental errors that are assumed to be independently and identically distributed with near zero and unknown variance σ^2. An example of a nonlinear model is as follows:

$$y = \theta_1 + \theta_2 \cos \theta_3 X + \theta_4 e^{-\theta_5 X} + e_t \qquad [3.18]$$

where

$$\theta = \begin{Bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \end{Bmatrix} = \text{parameters to be evaluated for given data}$$

X = independent variable (known)

y = dependent variable (known)

e_t = error

In some cases it is possible to transform a nonlinear model into a linear one, and to use linear regression techniques to find parameters. But this procedure violates the assumptions made on the error term in the original model and has questionable statistical validity (Byler, 1983). Apart from that, transformations can be used only for simple, exponential, nonlinear models.

3.2.3.2. **Methods of Parameter Estimation**

An estimate for the θ^o vector, θ, can be found by using the methods for computing least square estimators such as the modified Gauss-Newton and the Levenberg-Marquardt (Gallant, 1987). These methods require initial estimates of parameters, and do not guarantee statistically-valid parameter estimates for a given set of data. Since these methods find parameter estimates that minimize the residual sum of squares iteratively, it is also possible to have several different sets of parameter estimates which converge the residual sum of squares function to local minimums. Draper and Smith (1981) discussed rules of thumb to guess initial estimates required to avoid pitfalls in the iterations.

The Statistical Analysis System (SAS) provides the NLIN procedure for parameter estimation of nonlinear regression models (SAS, 1985). The NLIN procedures facilitate the use of four iterative techniques: modified Gauss-Newton, Marquardt, gradient, and false position method, in the development of a nonlinear regression model for the given data (SAS, 1985). The success of fitting a model to data depends on the model selected, the experimental errors involved, and the experience of the researchers in fitting nonlinear models to data.

3.2.3.3 **Selection Criteria for Models**

Selecting a suitable model for a given set of data can become a tedious task. The decision to use a particular model may be based either on the physics of the phenomenon or on the past experience of other researchers in dealing with similar phenomena. First, linear models should be attempted before nonlinear models are used to explain data. However, when the model is a solution of an underlying differential equation, linear models are not suitable to explain data. Then, appropriate nonlinear models should be identified, and each model should be fitted to the data using a statistical procedure such as NLIN. The models that cannot be fitted to a given set of data, using available iterative techniques, should be rejected. Criteria used to select the best model from the remaining models should be based on the statistical validity of the models and the experimental error associated with the data.

The following criteria have been used in selecting a suitable model:

1. **Mean Square Error (MSE):**

The lower the MSE, the better the model represents the data. However, seeking models with a MSE lower than the corresponding estimate of MSE for the experimental data will lead to overparameterization in the model.

2. **Statistical Significance of Estimated Parameters:**

Once the parameters of a model are estimated, each parameter should be tested for statistical significance using either the t-test or the Wald test (Gallant 1987). If all the parameters are not statistically significant in a model, it should be discarded in favor of another having statistically significant parameters.

3. **Coefficient of Determination (R^2):**

If a model can be fitted to given data using iterative methods, the R^2 value is greater than 0.90 in most cases; therefore, R^2 is not a powerful tool in discriminating nonlinear models as in linear regression. Still, the R^2 value indicates the variability accounted for by the model with respect to the total variability of the data.

4. **Residual Plots:**

Draper and Smith (1981) gave an excellent review of the role of residual plots in linear regression. Ideally, a residual plot should not have an identifiable pattern if the model describes the data well because it is assumed in the development of linear and nonlinear regression models that the error (residual) is a normally distributed random variable. However, in practice, experimental errors can have patterns. For example, inexpensive electronic balances often show a temperature and time-dependent drift that cannot be considered as patternless or random. In general, residual plots should be used to discriminate models when model MSEs are significantly higher than the corresponding experimental MSEs of the data.

3.3 Experimental Methods and Materials

An experimental set-up was developed to measure the weight loss of a thin layer of peanuts exposed to constant drying conditions as the drying progressed. The following design criteria were used:

1. Weight loss should be recorded without interruptions during a test. Periodic weighing of the sample outside the drying environment is not satisfactory because the test material can gain or lose moisture while being weighed, and this error can be significant over a large number of observations. In addition, removal of the sample for weighing requires time and punctuality from persons taking the data.

2. The factors affecting the drying rate (air temperature and relative humidity) should be able to be controlled.

3. The airflow rate through the layer should be monitored during each test.

4. The test chamber should be insulated to keep variations in the air conditions across the chamber to a minimum.

5. Air conditions (temperature and relative humidity) should be periodically monitored during each test.

3.3.1 Experimental Setup

The apparatus developed for this study, which meets the criteria mentioned above, is shown in Fig. [3.1]. The tray carrying the thin layer was suspended in the chamber from an electronic digital balance (Ohaus 3001), and the data acquisition system recorded the weight loss every five minutes. The software for the data acquisition was written in BASIC, and contained provisions to initialize the balance at the beginning of each test. The balance had a maximum capacity of 3200 g. The outlet of the air conditioning unit was connected to the inlet of a settling duct using

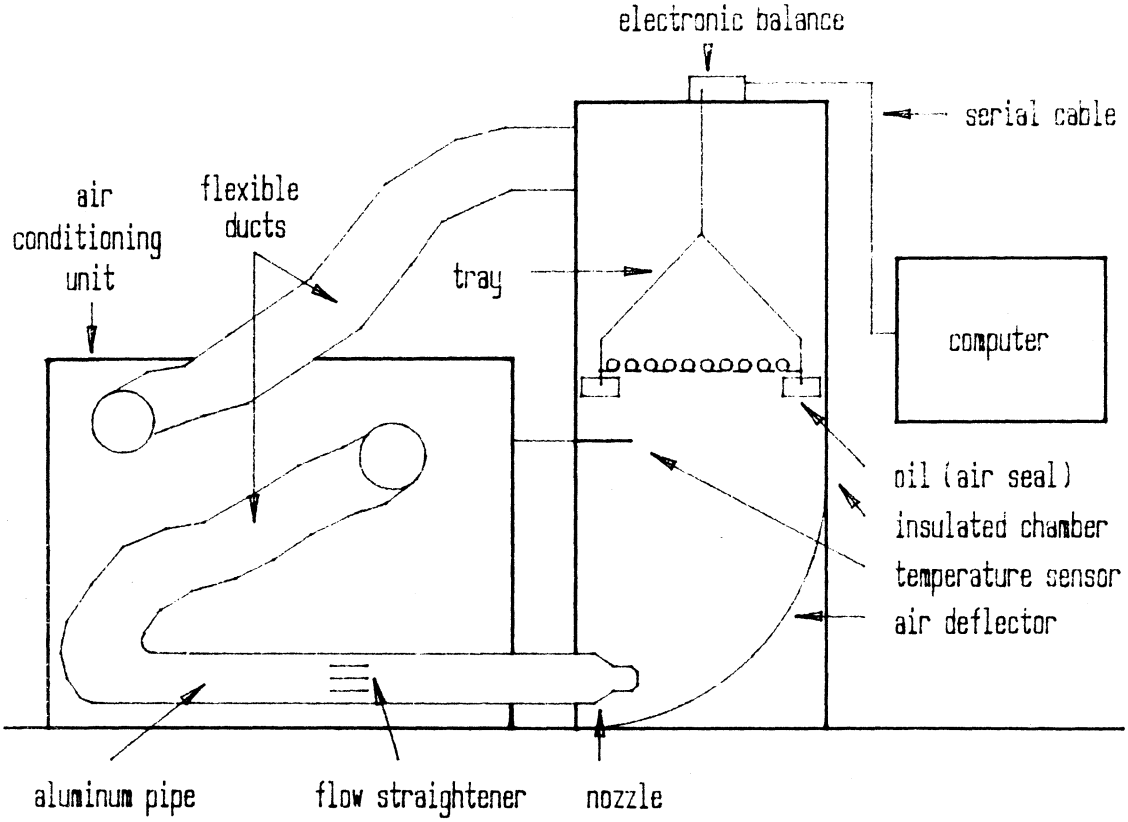

Figure 3.1. Thin-layer drying equipment.

insulated flexible ducts. The settling duct, made of 15.2-cm diameter aluminum pipe, had a flow straightener 13 cm upstream of the inlet of the chamber (Fig. 3.1). A 5.08-cm nozzle was installed at the inlet of the chamber to measure the airflow. The outlet of the chamber was connected to the inlet of the air conditioning unit using insulated flexible ducts.

The walls of the chamber consisted of three layers: an inner layer of 0.95-cm thick plywood, an intermediate layer of 3.8-cm thick polystyrene insulation and an outer layer of 0.64-cm thick plywood. The chamber was divided horizontally into a lower plenum chamber and an upper test chamber. An air-tight door was provided in the test chamber for inserting and removig the test samples. An air deflector was installed to obtain a uniform velocity across the thin layer.

The tray, with inside dimensions of 30 cm x 30 cm and a tare weight of 0.820 kg, had sheet metal sides and a wire mesh bottom. To obtain an air seal, it was floated in a light oil bath. The oil layer between the tray walls and the container walls damped outside vibrations, thereby minimizing random errors in the data. However, extremely large vibrations on the laboratory floor could affect the measurements.

The dry bulb temperature at a point 2.5 cm below the plane of the oil container was the controlling input to the air conditioning unit. The dry bulb temperature and the relative humidity of air entering the layer were monitored 5 cm below the center of the tray using a precision hygrometer and thermometer unit (Humi-check 5, Beckman Industrial). The Humi-check 5 measures relative humidity with an accuracy of ± 1% in the range 10 to 80%, and dry bulb temperature with an accuracy of ± 0.4

C in the range 0 to 50 C. It also provides a very high precision of ± 0.3% for relative humidity and ± 0.2 C for dry bulb temperature.

3.3.2. **Test Procedure**

The Aminco-Aire unit was set for the desired dry bulb temperature and relative humidity and was operated for at least 2 hours prior to each test to obtain stable conditions. The dry bulb temperature and the relative humidity inside the closed chamber were independently checked using the hygrometer-thermometer unit.

Peanuts used in the tests were brought from the Tidewater Agricultural Experiment Station, Suffolk, Virginia, and stored in a controlled environmental chamber at 5 C and 95% relative humidity to minimize moisture loss. Peanuts were hand cleaned to remove soil particles before being placed in the tray. The initial weight of peanuts for each test (1000 g) was measured using another electronic balance outside the chamber. A representative sample of peanuts was also taken to determine initial moisture content. The tray was immediately suspended in the chamber from the digital balance and visually checked to insure that it was floating in the oil bath. Immediately after the door was closed, the balance was zeroed and the data acquisition started. Except for one 30-hour test, each test lasted 45 hours.

During each test, the dry bulb temperature and the relative humidity entering the layer were recorded every 6 hours. Variations in the dry bulb temperature and the relative humidity were ± 0.3 C and ±2% about the set values, respectively. The means of the recorded dry bulb temperatures and the relative humidities represented the air conditions for the test. A test was conducted for each of 17 different conditions of air.

3.3.3. **Error Analysis for the Experiments**

Estimates of experimental mean square error (MSE) can be obtained from estimates of maximum possible errors in experiments. It is assumed that the experimental error is normally distributed with a variance, σ^2, and a zero mean. (This assumption is also made in the theoretical development of linear and nonlinear regression (Draper and Smith, 1981)). Then the maximum experimental error is approximately equal to 1.96σ at a 95% confidence level, and the corresponding mean square error (MSE), which is the estimate of the variance, σ^2, can be calculated from (maximum possible error/1.96)^2.

It is assumed that the temperature fluctuation in the chamber has a negligible effect on the moisture content of the material. This effect can not be quantified in an experimental situation even if it exists. Dry basis moisture content at a given time, M(t), is related to weight loss, $\Delta W(t)$, initial moisture content (dry basis), M_o, and the initial weight of the sample, W_o, as follows:

$$M(t) = \frac{W_o \left[\frac{M_o}{1+M_o} \right] - \Delta W(t)}{W_o \left[\frac{1}{1+M_o} \right]} \qquad [3.19]$$

This equation can be arranged:

$$M(t) = M_o - (1+M_o) \frac{\Delta W(t)}{W_o} \qquad [3.20]$$

Applying the chain rule in partial differentiation;

$$dM(t) = \frac{\partial M(t)}{\partial W(t)} d[\Delta W(t)] + \frac{\partial M(t)}{\partial W_0} d[W_0] \qquad [3.21]$$

where

$$\frac{\partial M(t)}{\partial \Delta W(t)} = \frac{-(1 + M_0)}{W_0} \qquad [3.22]$$

$$\frac{\partial M(t)}{\partial W_0} = \frac{(1 + M_0)}{W_0^2} \Delta W(t) \qquad [3.23]$$

Therefore, the error in dry basis moisture content can be written as follows:

$$dM(t\ ) = \left| \frac{-(1+ M_0)}{W_0} d[\Delta W(t)] + \frac{(1+ M_0)}{W_0^2} \Delta W(t) d[W_0] \right| \qquad [3.24]$$

where

$d[\Delta W(t)]$ = error in weight loss measurement, g

$d[W_0]$ = error in initial sample weight measurement, g

The second term in Eqn. 3.24 is one order less than the first term; therefore,

$$dM(t) = \left| \frac{-(1+ M_0)}{W_0} d[\Delta W(t)] \right| \qquad [3.25]$$

Therefore, the estimated mean square error for the data

$$\approx \left[\frac{1}{1.96} \left| \frac{-(1+ M_0)}{W_0} d[\Delta W(t)] \right|_{max} \right]^2 \qquad [3.26]$$

Since the daily temperature fluctuations inside the laboratory were more than 8°C during the drying experiments, a test was conducted to measure the drift. A known weight (1800 g) similar to the weight of the tray filled with peanuts was hung from the balance, and its weight was recorded with time. The average drift from the actual weight ranged from -5 g to +5 g during a day. Therefore, it is reasonable to assume that the maximum error in measuring weight loss is 5 grams. But, this error could be greater if any outside disturbances occurred. Mean square error estimates for experimental data can be calculated using the Eqn. [3.26] and are given for several experiments in Table 3.1. The average of these values (1.80×10^{-5}) was used as the guideline in developing statistical models.

3.4.0. **Data Analysis and Model Development**

3.4.1. **Introduction**

Weight loss data were converted to dry basis moisture content (decimal), and the moisture content (dry basis) was plotted versus time (hours) for each test. Three tests were found to have significant irregularities in the data; therefore they were excluded from the analysis. These irregularities were mainly due to vibrations of the laboratory floor which caused the tray to move relative to the oil container. The air conditions and the initial moisture contents included in the analysis are given in Table 3.2. Dry bulb temperature ranged from 27.4 C to 35.5 C, relative humidity varied from 22.6% to 60.3%, and initial moisture content ranged form 0.596 to 0.773 (dry basis, decimal). (The moisture content of peanuts used in these tests was high because they were subjected to a heavy rain during windrow drying.)

Table 3.1. Estimated MSE values for tests.

Test No.	Initial moisture (decimal, dry basis)	MSE (Estimated)
1	0.6914	1.86×10^{-5}
3	0.6014	1.67×10^{-5}
6	0.6874	1.85×10^{-5}
9	0.7107	1.90×10^{-5}
12	0.6756	1.83×10^{-5}

Table 3.2. Drying air conditions and initial moisture contents for tests.

Test No.	Dry Bulb Temperature (C)	Relative Humidity (%)	Initial Moisture (decimal, dry basis)
1	35.00	26.4	0.6914
2	35.25	36.9	0.6114
3	35.23	49.0	0.6014
4	35.47	60.2	0.6164
5	30.33	32.2	0.6308
6	30.40	38.6	0.6847
7	30.50	47.7	0.6433
8	30.57	60.3	0.6098
9	25.20	62.1	0.7107
10	25.20	46.7	0.7541
11	24.05	31.5	0.6840
12	32.48	22.6	0.5968
13	32.90	35.7	0.5968
14	27.40	47.23	0.7727

The traditional approach to modeling thin layer drying data is to use Page's equation [Eqn. 3.4] to find the parameters K and n. Then, these parameters are related to the air conditions. As seen from Section 3.2.1.2, this approach has been applied to a large number of biological materials; therefore, it was considered first in the data analysis. The other models considered were models represented by Eqns. 3.5, 3.6, and 3.7, the modified version of Page's model as discussed in section 3.2.1.2.2, and multi term exponential models. Since each case cannot be discussed because of space limitations, only the models which fit the data best are discussed here.

3.4.2. **Modeling the Parameters**

The thin-layer drying data for a constant condition of air are normally used to obtain model parameters that are specific for that condition of air. These parameters should be expressed in terms of conditions of air, if the model is to be used in drying simulation. Two approaches are used in the literature:

1. Once the parameter values for each constant drying condition (usually temperature, relative humidity or dew point temperature) are known, the regression models are developed expressing the parameters as dependent variables and the air conditions as independent variables.

2. The parameters are assumed to behave according to an equation and are regressed with the original model. This approach was used by Byler et al. (1984) in modeling the drying rates of parboiled rice.

The first approach has been widely reported in the literature because it allows the behavior of parameters with respect to air conditions to be modeled without subjecting them to behave in a predetermined way, given that there are no firm theoretical foundations to specify the relationships between parameters and air conditions. In addition, computational expense is considerably less in the first approach. Therefore, the first approach is used in this analysis.

3.4.3 **Traditional Approach**

Page's model (Eqn. 3.4) was rearranged in the following form to fit the data:

$$M = (M_i - M_e) \exp(-Kt^n) + M_e \qquad [3.27]$$

where

K	=	empirical drying constant
n	=	empirical drying exponent
M_i	=	initial moisture content, decimal, dry basis
M_e	=	equilibrium moisture content, decimal, dry basis

The equilibrium moisture content of peanuts was modeled by using Eqn. [3.16] as developed by Troeger and Butler (1979).

The NLIN procedure was used to find the parameters K and n for each test. The K and n parameters are given in Table 3.3 along with the respective R^2 values and Mean Square Error (MSE) values for each test. The General Linear Model (GLM) procedure in SAS (1985) was used to develop the following models for K and n:

$$\ln(K) = -0.780523 - 0.144026\,T + 0.00358T^2 + 2.13914H + 0.715991M_i - 0.137131TH \qquad [3.28]$$

$$R^2 = 0.93$$

$$n = 0.98867 + 0.019836T - 0.000608T^2 - 1.033613H - 0.63824017M_i + 0.0499769TH \qquad [3.29]$$

$$R^2 = 0.90$$

where

T	=	dry bulb temperature, C
H	=	relative humidity, decimal
M_i	=	initial moisture content, decimal, dry basis

Figs. 3.2 and 3.3 show graphs of the fitted Page's models with the appropriate parameter values along with the observed moisture content data for two of the 14 tests. The variability of the data is accounted for by the model to a high degree, as seen from the high coefficients of determination (R^2) for each test (Table 3.3). The maximum MSE of the tests was 7.3 x 10^{-5}, and the minimum MSE was 1.9 x 10^{-5}. These MSE values are higher than the estimated MSE of the experimental data (1.80 x 10^{-5}), indicating that Page's model does not fit the data to the maximum possible accuracy contained in the data. However, the parameters K and n were statistically significant for all tests, and convergence was excellent in the parameter search. An overall accuracy of ± 1.3% (dry basis) was observed.

3.4.4 **Exponential Models**

Since the solutions to remove the differential equations for the diffusion phenomena contain a series of exponential terms, the exponential models are considered to have a "theoretical" basis. The one-term exponential model, Eqn. [3.2], can be expanded into two-, three-, and four-term exponential models. The following models were considered:

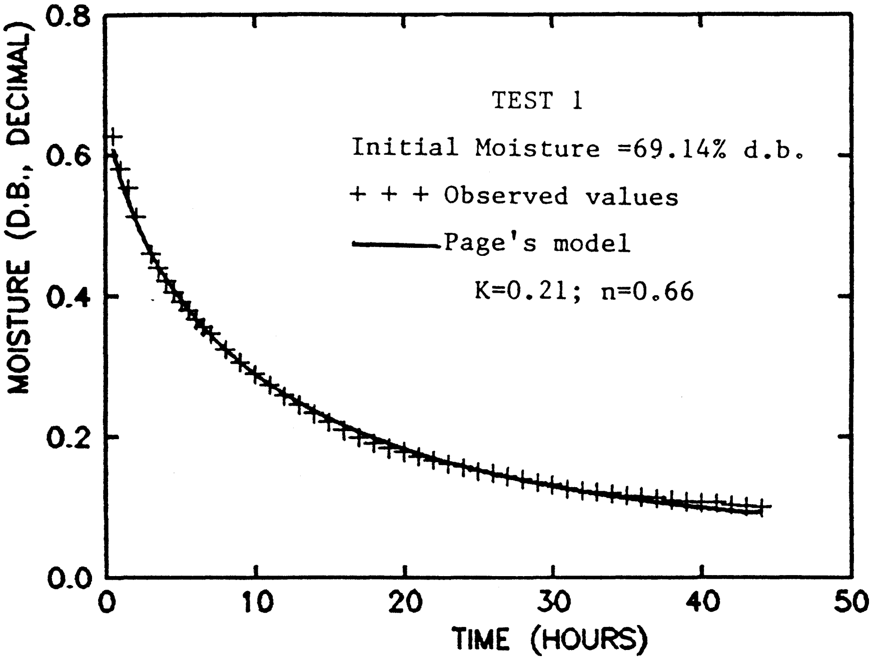

Figure 3.2. Drying curve for peanut pods at 35 C dry bulb temperature and 26.4% relative humidity.

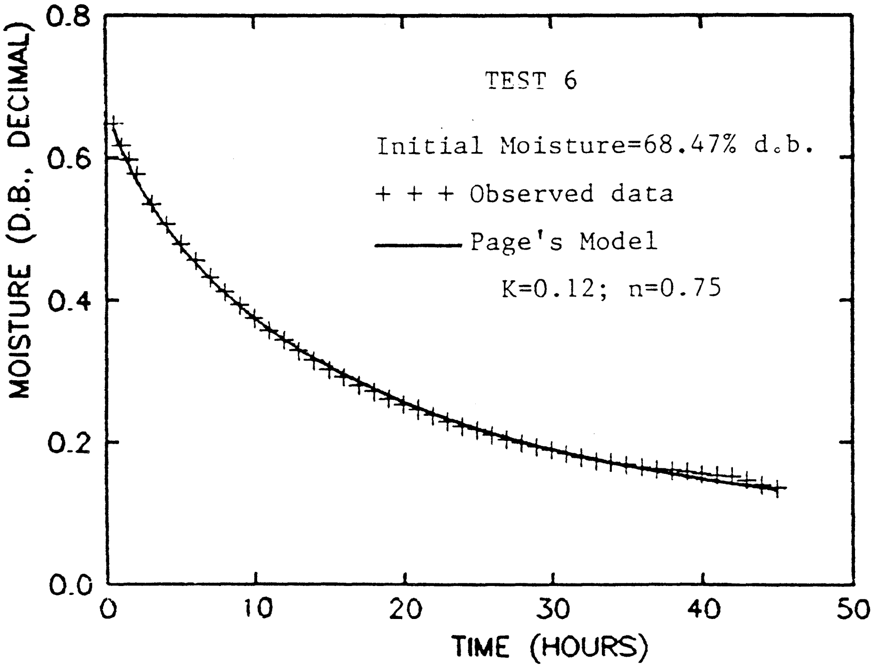

Figure 3.3. Drying curve of peanut pods at 30.4 C dry bulb temperature and 38.6% relative humidity.

Table 3.3. Drying constant, K; drying exponent, n; mean square error, MSE; and coefficient of determination, R^2; for each test.

Test	K	n	MSE ($x10^{-5}$)	R^2
1	0.21005	0.65659	3.7	0.9995
2	0.13094	0.85347	3.3	0.9935
3	0.10028	0.91687	6.6	0.9926
4	0.07209	0.97297	6.2	0.9993
5	0.11261	0.83005	2.9	0.9997
6	0.12038	0.74772	1.9	0.9998
7	0.09337	0.87721	2.4	0.9998
8	0.07374	0.90989	5.6	0.9995
9	0.08347	0.79570	7.3	0.9914
10	0.10661	0.70962	2.6	0.9999
11	0.13322	0.73006	2.5	0.9998
12	0.15764	0.75832	7.2	0.9993
13	0.15129	0.76372	4.2	0.9991
14	0.11051	0.76372	4.2	0.9997

<u>One-term exponential</u>

$$M = P_1 \exp(P_2 t) + P_3 \qquad [3.30]$$

<u>Two-term exponential</u>

$$M = P_1 \exp(P_2 t) + P_3 \exp(P_4 t) + P_5 \qquad [3.31]$$

<u>Three-term exponential</u>

$$M = P_1 \exp(P_2 t) + P_3 \exp(P_4 t) + P_5 \exp(P_6 t) + P_7 \qquad [3.32]$$

where M = moisture content, decimal, dry basis

P_i = ith parameter

The four-term exponential model cannot be fitted to the data in most tests with statistically significant parameters; therefore, it is not presented here. The NLIN procedure was used to find parameters for the 14 tests.

3.4.4.1 **One-term Exponential Model**

Eqn. [3.30] was fitted to the 14 data sets, and the calculated parameters (P_1, P_2 and P_3) and the mean square errors (MSE) are given in Table 3.4. A t-test was conducted at the 0.025 level for each parameter to test its statistical significance in the model. Table 3.4 summarizes the results. Seven out of fourteen tests had acceptable MSE values, which are lower than 1.8×10^{-5}. Since Eqn. [3.30] is a rearranged version of Eqn. [3.2], P_3 should represent the equilibrium moisture content. The values of P_3 range from 0.079 to 0.185 for the tests excluding Tests 2 and 3, and can be considered as pseudo-equilibrium moisture contents. However, because of the high MSE values in seven tests, the one-term exponential model can not be considered as an adequate representation of the data.

Table 3.4. Parameter values (MSE), and the summary of significant tests for paramters of the one-term exponential model.

Test No.	Parameters			MSE ($X10^{-5}$)	Statistically significant parameters
	P_1	P_2	P_3		
1	0.5064	-.1042	0.1067	12.3	P_1, P_2, P_3
2	0.5163	-.0624	-0.129	8.3	P_1, P_2, P_3
3	0.6123	-.0399	-.0855	0.8	P_1, P_2, P_3
4	0.5088	-.0643	0.0792	5.3	P_1, P_2, P_3
5	0.4891	-.0987	0.1309	1.5	P_1, P_2, P_3
6	0.5178	-.0731	0.1289	3.2	P_1, P_2, P_3
7	0.4992	-.0757	0.0996	0.8	P_1, P_2, P_3
8	0.5205	-.0685	0.1263	0.4	P_1, P_2, P_3
9	0.5041	-.0556	0.1731	3.3	P_1, P_2, P_3
10	0.5194	-.0605	0.1851	1.8	P_1, P_2, P_3
11	0.5150	-.0940	0.1113	1.6	P_1, P_2, P_3
12	0.5157	-.0699	0.1087	2.9	P_1, P_2, P_3
13	0.5817	-.0669	0.1453	5.4	P_1, P_2, P_3
14	0.4613	-.1047	0.1104	5.4	P_1, P_2, P_3

3.4.4.2 **Two-term Exponential Model**

Eqn. [3.31] was fitted to the 14 data sets, and the calculated parameters (P_1, P_2, P_3, P_4, and P_5) and MSE values for 12 tests are given in Table 3.5. The parameters of the model for Tests 8 and 9 could not be found using the iterative techniques available in NLIN procedures because the model had more parameters than necessary to represent the data of these tests. The MSE values of 9 out of the 12 tests are lower than 1.8×10^{-5}; therefore, the two-term exponential models can be considered as an adequate representation of the experimental data. The data for Test 4 were also subjected to overparameterization because, as shown in Table 3.5, two parameters (P_3 and P_4) were not statistically significant. Negative P_5 values of Tests 2 and 3 should be disregarded in parameter modeling since P_5 is a statistical estimate of the equilibrium moisture content. Unless the data is more accurate than predicted by the model, adding exponential terms do not improve the model. The overall accuracy of the two-term exponential model was 0.8% (dry basis) for the data.

3.4.4.3 **Three-term Exponential Model**

The MSE can be reduced considerably by adding another exponential term to the two-term exponential model, as shown by Table 3.6 which gives the results of three tests. But three out of seven parameters were not statistically significant according to the t-tests. Therefore, the three-term exponential model is not a suitable model for the data collected.

As discussed in the previous sections, Eqn. [3.31] accurately models the thin layer drying data of Virginia peanuts. The parameters P_1, P_2, P_3, P_4, and P_5 were then modeled as dependent variables, with dry bulb temperature, relative humidity, and initial moisture content as independent variables. Statistical procedures such as

Table 3.5. Parameter values, MSE, and summary of significant tests for parameters of the two-term exponential model.

Test No.	Parameters P_1	P_2	P_3	P_4	P_5	MSE ($x10^{-5}$)	Statistically significant parameters
1	0.435	-.078	0.161	-.558	0.088	5.43	P_1, P_2, P_3, P_4, P_5
2	0.499	-.051	0.115	-.780	-.014	0.63	P_1, P_2, P_3, P_4, P_5
3	0.620	-.038	0.072	-2.705	-.101	0.14	P_1, P_2, P_3, P_4, P_5
4	0.505	-.063	0.053	-2.346	0.077	5.19	P_1, P_2, P_5
5	0.487	-.093	0.021	-1.401	0.124	0.75	P_1, P_2, P_3, P_4, P_5
6	0.480	-.061	0.082	-.379	0.111	0.38	P_1, P_2, P_3, P_4, P_5
7	0.488	-.072	0.025	-.417	0.096	0.52	P_1, P_2, P_3, P_4, P_5
10	0.504	-.054	0.052	-.414	0.172	0.27	P_1, P_2, P_3, P_4, P_5
11	0.502	-.065	0.062	-.864	0.101	0.97	P_1, P_2, P_3, P_4, P_5
12	0.499	-.088	0.050	-.808	0.106	0.47	P_1, P_2, P_3, P_4, P_5
13	0.445	-.097	0.054	-.933	0.106	0.63	P_1, P_2, P_3, P_4, P_5
14	0.567	-.061	0.067	-.749	0.134	2.96	P_1, P_2, P_3, P_4, P_5

Table 3.6. Parameter values, MSE, and summary of significant test for parameters of the three-term exponential model.

Test	Parameters							MSE	Statistically
No.	P_1	P_2	P_3	P_4	P_5	P_6	P_7	($x10^{-5}$)	significant parameters
1	0.4103	-0.0911	0.145	-0.635	0.2601	-.0037	-.1287	0.486	P_1, P_2, P_3, P_4
3	0.6260	-0.363	0.0146	-0.3574	11.838	-13.5930	-.1141	0.078	P_1, P_2, P_3, P_4
5	0.4019	-0.0932	0.0844	-0.0931	0.0189	-1.217	0.123	0.817	P_1, P_2, P_3, P_7

RSQUARE, GLM, and NLIN that are available in SAS (1985) were used to find the best linear and nonlinear relationships to model the parameters. The following equations were selected to represent the parameters based on R^2 values, MSE values, and statistical significance of coefficients:

$$P_1 = -16.5045 + 1.726728T - 1.7035368H - 0.05653458T^2 + 2.17813376H^2 + 0.00060788T^3 \quad [3.33]$$

(R^2 = 0.92; MSE = 0.00024)

$$P_2 = -\exp\left[\frac{-793.451}{T + 273.16}\right] \quad [3.34]$$

(R^2 = 0.97; MSE = 0.00019)

$$P_3 = 0.37160906 - 0.05151512T + 1.508066H - 2.01897106H^2 + (2.33112 \times 10^{-5})\, T^3 + 0.47366461M_i \quad [3.35]$$

(R^2 = 0.89; MSE = 0.0003755)

$$P_4 = 25.49014 - 1.00766T + 0.017543T^2 - 110.8695H + 319.81465H^2 - 290.364TH^3 \quad [3.36]$$

(R^2 = 0.895; MSE = 0.085)

$$P_5 = 0.14379375 - 0.0191857 \ln(-(T-23.4359)\ln(H)) \quad [3.37]$$

(R^2 = 0.97; MSE = 0.0006)

where T = dry bulb temperature of air, C

H = relative humidity of air, decimal

M_i = initial moisture content, decimal, dry basis

Since these relationships were statistically derived, they are valid only in the ranges of independent variables; from 24.9 C to 35.5 C for temperature, from 0.226 to 0.603

for relative humidity, and from 0.59 dry basis to 0.77 dry basis for initial moisture contents.

3.4.5 Modified Page's Model

Page's model, Eqn. [3.4], can be rearranged as follows to express the dry basis basis moisture content at a given time t:

$$M - M_e = (M_i - M_e) \exp(-Kt^n) \qquad [3.38]$$

where
- M = moisture content, decimal, dry basis
- M_e = equilibrium moisture content, decimal, dry basis
- M_i = initial moisture content, decimal, dry basis
- K,n = constants

If M_e is to be determined from the data as proposed by Jayas et al. (1988), Eqn. [3.38] can be modified by treating M_e as an independent variable.

$$M = (M_i - M_e) \exp(-Kt^n) + M_e \qquad [3.39a]$$

or

$$M = P_1 \exp(-P_2 t^{P_3}) + P_4 \qquad [3.39b]$$

where P_i $(i = 1, 2, 3, 4)$ = parameters to be determined

The parameters were calculated using the NLIN procedure, and Table 3.7 gives the parameter values and the corresponding MSE values for the tests. All parameters were statistically significant for all tests, and MSE values were significantly smaller than for the other models tested, which had a larger number of parameters.

Table 3.7. Parameter values and MSEs for the modified Page's model.

Test	P_1	P_2	P_3	P_4	MSE ($x10^{-5}$)
1	0.37546	0.10312	0.91189	0 .08347	0.258
4	0.25536	0.02706	1.441219	0.11511	0.707
5	0.26123	0.06517	1.22813	0.15457	0.241
6	0.35718	0.07606	0.91796	0.10209	0.339
7	0.23163	0.04910	1.17237	0.10782	0.349
8	0.24777	0.05697	1.01878	0.13809	0.216
9	0.21118	0.02618	1.47896	0.24012	0.413
10	0.20632	0.05121	1.03315	0.17732	0.232
11	0.24426	0.04765	1.10964	0.10779	0.467
12	0.24967	0.06342	1.14002	0.11471	0.087
13	0.21818	0.08745	1.04686	0.10818	0.171
14	0.24855	0.03354	1.25797	0.15855	3.002

The parameters can be expressed in terms of the dry bulb temperature of drying air, the relative humidity, and the initial moisture content, using procedures available in SAS.

$$P_1 = M_i - 0.2143293 + 0.040251 \ln [- (T - 19.721976) \times \ln (H)] \qquad [3.40]$$

$(R^2 = 0.98;\ MSE = 0.000477)$

$$P_2 = 0.028483 \exp [-99.072835 (T + 273.16)^{-339.58} - 0.7433548 \ln (H)] \qquad [3.41]$$

$(R^2 = 0.94;\ MSE = 0.000354)$

$$P_3 = 1.51370 \exp [- 0.0023406T + 0.2358596 \ln (H)] \qquad [3.42]$$

$(R^2 = 0.98;\ MSE = 0.0289)$

$$P_4 = 0.24590663 - 0.05697218 \ln [- (T-20.235327) \ln (H)] \qquad [3.43]$$

$(R^2 = 0.984;\ MSE = 0.00077)$

where

T = dry bulb temperature of air, C

H = relative humidity of air, decimal

3.5 Equilibrium Moisture Content of Peanut Pods

Steele (1981) reviewed all the literature on equilibrium moisture content (EMC) of peanuts for a report to American Peanut Research and Education Society (APRES). Relationships presented by each researcher for the EMC of peanuts were usually based on a limited amount of data collected by that researcher. For example, Eqn. [3.16] was developed by Troeger and Butler (1979) using data reported by Beasley and Dickens (1963), which consisted of three temperature levels, 10 C, 21.1 C and 32.2 C, and eight relative humidity levels at each temperature level. No attempt was made to combine the data or to develop an equation representing all the available data. Since experimental determination of EMC is expensive and time consuming, these valuable data should be used to the maximum possible extent.

Since few differences in EMC have been observed between varieties (Steele, 1981), the data reported for peanut pods were pooled, and Henderson and Chung-Pfost equations were fitted to the data. The equilibrium temperatures for the data ranged from 10.0 C to 60.0 C, and the equilibrium relative humidity from 11.4% to 98%. The Henderson equation fitted to the data can be written as follows:

$$M_e = \left[\frac{-\ln(1.0 - rh)}{0.172994\,(T+273.16)}\right]^{0.59329} \qquad [3.44]$$

where M_e = equilibrium moisture content, decimal, dry basis

rh = equilibrium relative humidity, decimal

T = equilibrium temperature, C

MSE for Eqn. [3.44] was 0.0000446 and the standard deviation was 0.00667 (= 0.67% d.b.).

The Chung-Pfost equation can be given in general form as:

$$M_e = E - F \ln[-(T+C)\ln(rh)] \qquad [3.45]$$

where E, F, and C are material dependent constants.

The MSE for Eqn. [3.45] was 0.0000359, corresponding to a standard deviation of 0.00599 (= 0.6% d.b.). Table 3.8 gives values of E, F, and C for peanut pods along with values for several other agricultural products reported in the literature. Since the Chung-Pfost equation provided a marginally better model than the Henderson

Table 3.8. Constants of EMC equation.

Product	C	E	F
Wheat durum	112.350	0.415593	0.055318
Wheat hard	50.998	0.395155	0.056788
Barley	91.323	0.368149	0.402787
Corn, yellow dent	30.205	0.379212	0.058970
Rice, rough	35.703	0.325525	0.046015
Soybean	24.576	0.375314	0.066818
Peanut pods	60.025	0.252007	0.042909

equation did, based on MSE values and E, F, and C values that are comparable with those for other agricultural products, Eqn. [3.45] can be chosen to represent the EMC of peanut pods. In addition, the use of the Chung-Pfost equation for peanut pods would add to efforts to find a standard relationship for the EMC of agricultural products.

3.6 Summary, Conclusions and Recommendations

Thin layer drying characteristics for Virginia-type peanuts were determined using a laboratory-scale experimental set-up. The data were fitted to numerous models available in the literature using nonlinear regression procedures. The parameters in the models were determined, and then related to the conditions of the drying air and the initial moisture content. A Chung-Pfost-type equation was developed for the equilibrium moisture content of peanut pods using data available in literature.

The following conclusions were drawn from this study:

1. The drying rates of Virginia-type peanuts can be determined successfully using the experimental set-up shown in Fig. 3.1.

2. The accuracy of the data largely depended upon the accuracy of the balance. Since models are data dependent, the higher the accuracy of the data, the better the fitted models will be.

3. For many engineering applications in which accuracy is not as critical as in scientific research, the "traditional approach" can be used to fit the moisture content data with an overall accuracy of ± 1.3% (dry basis). Eqns. [3.27] through [3.29] can be used to model the drying rates in the

traditional approach.

4. Among exponential models, the two-term exponential model fitted the data best, with an overall accuracy of 0.8% (dry basis). Eqn. [3.31] and Eqns. [3.33] through [3.37] can be used to calculate the drying rates of peanut pods, should the two-term exponential model be used.

5. The modified Page's model fitted the data with an overall accuracy of 0.46% (dry basis). The modified Page's model has 4 parameters, while the two-term exponential model has 5 parameters; the overall accuracy is better in the modified Page's model. Therefore, in the ranges of temperature and relative humidity tested, the modified Page's model provides the best mathematical representation of the thin-layer drying rates of Virginia peanuts.

The following recommendations can be given for future research:

1. The experimental setup (Fig. 3.1) should be used in every peanut-season to determine the drying rates of peanuts, so as to expand the data base available for modeling of thin-layer drying rates. Different temperatures and initial moisture ranges should be used if more statistically valid models are required.

2. A more accurate balance will improve the accuracy of the data and ease the model fitting procedures. (The balance used [Ohaus 3001] showed a significant increase in drifting after 17 tests.)

3. The effect of airflow on drying rate should be studied by conducting experiments with different flow rates.

4. The models developed in this chapter should be used only in the temperature and relative humidity ranges employed in the tests, along with appropriate air velocity correction factors.

Chapter 4.

Application of Diffusion Models in Drying of Virginia-Type Peanuts

4.1 Introduction

In Chapter 3, the empirical and semi-theoretical models used in drying of biological materials were discussed, and selected models were fitted to the collected data using statistical procedures for Virginia-type peanuts. Even though the most of the bulk drying models are based on empirical thin-layer equations, increasing attention is being paid to modeling the transfer mechanisms within a particle using the governing differential equations. The major advantage of this approach is that, once an acceptable model is developed, the model can be used in drying conditions where actual data are not available. In other words, these models do not have the limitations of temperature and humidity ranges that thin-layer drying models do. The disadvantages are the difficulty in identifying suitable transfer mechanisms within non-homogeneous porous materials, the complexity of models requiring sophisticated numerical techniques for solution, and the lack of physical properties such as the diffusivities, conductivities, and densities of biological materials. Despite these difficulties, many researchers attempt to understand the transfer mechanisms within materials using theoretical models. These attempts are facilitated by powerful numerical techniques such as the finite element method for solving partial differential equations.

The objectives of the study presented in this chapter were: (1) to review the diffusion models that can be used in drying biological materials and (2) to solve a simplified model that represents transfer mechanisms within a peanut pod under drying conditions, using the finite element method (FEM) to illustrate the advantages in using FEM in drying research. Even though the application of FEM to model deep-bed drying is beyond the scope of the present study, the attempt here is to discuss the use of in drying of biological materials. Since the application of FEM to drying biological materials, in general, has not been attempted to a significant extent, another objective of this discussion is to highlight the specific research that has to be done before FEM can be applied to deep-bed drying.

4.2 Literature Review

4.2.1 Mass Transfer Models

Many researchers have accepted diffusion as the dominant mechanism in the falling rate period of drying (Hamdy and Barre, 1969; Hamdy and Johnson, 1968; Whitaker and Young, 1972; Whitaker et al., 1969). Fick's second law of diffusion as applied to liquids can be written as follows:

$$\frac{\partial M}{\partial t} = \nabla(D \nabla M) \qquad [4.1]$$

where

M = local moisture content, decimal, dry basis

D = moisture diffusivity, m^2/h

Babbit (1950) applied the diffusion equation to agricultural crops for the first time. Eqn. [4.1] was used by several investigators (Bakker-Arkema, 1967; Barre et al., 1971; Baughman, 1973); their underlying assumption was that liquid diffusion is the mechanism of moisture transfer. Recent theories on drying assume that liquid and vapor movement through a porous solid follow Fick's law.

When applying Eqn. [4.1], it was assumed that the material was homogeneous in order to simplify the solution procedures. The exact solution to Eqn. [4.1], as applied to a semi-infinite slab, was given by Henderson (1974). In deriving the closed-form solution to the liquid diffusion equation, he used the following assumptions:

1. The mechanism of moisture movement inside the individual particle is liquid diffusion.

2. The diffusion coefficient depends on the temperature of the drying air and this dependency is expressed in the form of an Arrhenius-type equation.

3. The drying rate is independent of airflow if the flow is turbulent.

4. The conditions are isothermal.

Even though Henderson's solution assumes isothermal conditions, heat energy is required to remove the moisture from the particles. Consequently, temperature gradients develop within the particle and between the passing air and each individual particle.

Young and Whitaker (1971b) stated that agricultural materials can not be considered as homogeneous. They further stated that the hygroscopic characteristics of different materials in a particle may be such that they have different equilibrium moisture contents, and, therefore, the moisture movement cannot be attributed simply to a moisture content gradient. They developed a finite difference method to solve the vapor-diffusion equation for a sphere consisting of n concentric shells of different materials.

The vapor-diffusion equation within a particular material j contained in a sphere is:

$$(1/r^2)\ \frac{\partial}{\partial r}\left[r^2 D_j \frac{\partial C}{\partial r}\right] = f_j \frac{\partial C}{\partial t} + (1-f_j)d_{sj} \frac{\partial M_j}{\partial t} \qquad [4.2]$$

where

d_{sj} = density of jth component of the solid, kg/m^3

f = void fraction

r = distance from center of sphere, m

t = time, s

C = vapor concentration, kg/m^3

D_j = vapor diffusivity, m^2/s

M_j = moisture content, decimal, dry basis

The assumptions underlying Eqn. [4.2] and used in the solution procedure are:

1. moisture content is linearly dependent on vapor concentration and temperature.

2. heat transfer is neglected.

3. hysteresis of sorption is neglected.

4. void space was assumed to be constant as diffusion proceeds.

5. solid and vapor are assumed to reach equilibrium instantaneously.

6. shrinkage of the body is neglected.

Whitney and Porterfield (1968) solved the diffusion equation based on a vapor concentration gradient similar to Eqn. [4.3] for a one-dimensional, porous, hygroscopic solid. Moisture content was assumed to be linearly related to temperature and vapor concentration. They compared the closed-form solution to experimental data from an experimental drying set-up for corn meal. Alverez and Legues (1986) solved Eqn. [4.1] to model the drying of Thompson seedless grapes using the finite difference method. They assumed that the effective diffusion coefficient depended upon time. The solution was a closed-form expression, which can be applied to particles with spherical shape and uniform material properties.

Bruce (1985) solved Eqn. [4.1] in spherical coordinates to model the drying of barley. The assumptions used were similar to Young and Whitakers' (1971b). The finite difference method was employed to solve the equation for a sphere. They acknowledged that they had to omit significant factors in the drying of biological materials, such as shape and anisotropy, in modeling the drying behavior.

Young and Whitaker (1971c) combined the closed-form solutions of liquid diffusion in a plane sheet and an infinite cylinder to obtain a closed-form solution for the finite cylinder, which they assumed to represent the shape of a peanut. The initial and boundary conditions used in the analysis along with the simplifying assumptions were as follows:

1. The drying body is initially at a uniform moisture content.

2. The surface instantaneously reaches equilibrium with the drying medium at t=0.

3. The surface is maintained at a constant drying condition at the beginning.

4. The mass diffusion coefficient is constant throughout the body.

5. The material is homogeneous.

The authors compared the analytical results with experimental data obtained from drying experiments carried out using green peanuts (NC5 variety). Their conclusions are summarized below:

1. The diffusion equation provides a better model for drying peanuts.

2. The finite cylinder model fits the data with a corrected diameter-to-length ratio which bear no physical resemblance to geometry of a peanut.

3. The diffusion model gives initial drying rates less than the actual, in the later stages of drying, and, drying rates greater than the actual.

4. 'A composite body model' should be developed to more accurately describe the drying of peanuts.

In a major development, Chhinnan and Young (1977a) developed two models based on vapor diffusion and liquid diffusion and compared the numerical solutions of these models with published experimental data. The geometric configuration used for the models 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 divided into concentric shells of thickness Δr. They assumed constant mass diffusivity in each component, instantaneous thermal equilibrium with the environment, instantaneous equilibrium between solid and vapor; they neglected shrinkage, capillary effects, change in void space, heat transfer effects, and interactions with other pods. The finite difference method was used to solve the governing equations.

The authors used the liquid and vapor diffusivity values of kernel and hull obtained for each drying condition that gave the best fit to the experimental data. They concluded that 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 gives a lower sum of squares of deviations between observed and predicted moisture ratio values.

Chhinnan and Young (1977b) presented a model based upon simultaneous diffusion of liquid and vapor and compared this model with their earlier reported work (Chhinnan and Young, 1977a). They used the same geometry and the same techniques to solve the equations in both experiments. The coupled liquid and vapor diffusion equation is given below.

$$D_l \nabla^2 C_l + D_v \nabla^2 C_v = \frac{\partial C_l}{\partial t} + \frac{\partial C_v}{\partial t} \qquad [4.3]$$

where

D_l = liquid diffusivity, m^2/h

D_v = vapor diffusivity, m^2/h

C_l = liquid concentration based on bulk volume, kg/m³

C_v = vapor concentration based on bulk volume, kg/m³

t = time, h

4.2.2 **Simultaneous Heat and Mass Transfer Models**

Luikov (1935) showed the importance of the temperature gradient for moisture migration in capillary porous bodies (Mikhailov and Ozisik, 1984). He developed a system of coupled differential equations using the thermodynamics of irreversible processes. Fulford (1969) surveyed work on the drying of solids by Luikov and his colleagues. No attempt will be made here to describe Luikov's rigorous theoretical development, but pertinent equations and assumptions are presented. Fortes and Okos (1980) gave a brief explanation of the development of Luikov's equations. Luikov assumed that both vapor and liquid diffusion are driven by both the total concentration gradient and the temperature gradient. He assumed that molecular and molar transfer of air, vapor, and water occurred simultaneously within the porous body. The transfer of vapor and air is due to diffusion, effusion (molecular transfer), and filtration when under pressure gradients (molar transfer). Liquid transfer is assumed to occur due to diffusion, capillary absorption, and filtration. Expressions similar to Fick's law have been used to model all these types of transfer.

For a short range of ΔM and ΔT and in the absence of a pressure gradient, Luikov's equation can be written as:

$$\frac{\partial M}{\partial t} = K_{11} \nabla^2 M + K_{12} \nabla^2 T \qquad [4.4a]$$

$$\frac{\partial T}{\partial t} = K_{21} \nabla^2 M + K_{22} \nabla^2 T \qquad [4.4b]$$

where

K_{11}, K_{22} = phenomenological coefficients

K_{12}, K_{21} = coupling coefficients

It can be seen from Eqns. [4.4a] and [4.4b] that the moisture and heat transfers affect each other and, therefore, should be considered simultaneously. But these coefficients are available for only a limited number of materials.

Several investigators have used simpler versions of Luikov's equations to model simultaneous heat and mass transfer in drying. Iradayaraj et al. (1988) used the heat conduction and the general diffusion equations to simulate grain temperature and moisture profiles.

$$\rho C \frac{\partial T}{\partial t} = \nabla(k \nabla T) \qquad [4.5a]$$

and

$$\frac{\partial M}{\partial t} = \nabla(D \nabla M) \qquad [4.5b]$$

where

ρ = density of the material

k = thermal conductivity

D = moisture diffusivity

Eqns. [4.5a] and [4.5b] can be obtained by neglecting the coupling effects in Luikov's equations ($K_{12} = K_{21} = 0$). Various other models, which are simplifications of Luikov's model, have been proposed for the moisture transfer in porous bodies. Application of Luikov's equations to the drying of biological materials with arbitrary shapes is a formidable task because of the lack of known physical properties and of a basic understanding of the drying mechanisms involved.

4.3 Application of the Finite Element Method in Drying

4.3.1 Governing Equations

Luikov's equations are considered to be the only model available to model drying of porous materials that is based on rigorous theoretical development and supported by experimental data. Since there are serious limitations in applying Luikov's equations to biological materials, Luikov's equations should be simplified to more manageable forms. The following equations, given in cylindrical coordinates (r, z), can be derived from Luikov's equations if the coupling effects are neglected and isotropy within the material is assumed.

$$\frac{\partial M}{\partial t} = K_{11} \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial M}{\partial r} \right) + \frac{\partial^2 M}{\partial z^2} \right] \qquad [4.6]$$

where

K_{11} = D = coefficient of diffusivity

r = radial distance

z = axial distance

t = time

$$\frac{\partial T}{\partial t} = K_{22} \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right] \qquad [4.6b]$$

where

K_{22} = $\frac{k}{\rho c}$ = thermal diffusivity

k = thermal conductivity

ρ = density

c = specific heat

4.3.2 Finite Element Program

In the finite element method, the domain of interest is discretized into a finite number of elements; in this case the linear quadrilateral element was chosen for discretization. Since Eqns. [4.6a] and [4.6b] have the same form, the finite element formulation is the same for both equations.

$$\frac{\partial U}{\partial t} - \frac{K}{r} \frac{\partial}{\partial r} \left[r \frac{\partial U}{\partial r} \right] - K \frac{\partial^2 U}{\partial z^2} = 0 \qquad [4.7]$$

with boundary condition

$$K \frac{\partial U}{\partial r} n_r + K \frac{\partial U}{\partial z} n_z + h(U-U_\infty) = 0 \qquad [4.8a]$$

and the initial conditions

$$U = U_0 = T_0 \text{ or } M_0 \qquad [4.8b]$$

where

K = K_{11} or K_{22}

U = T or M

U_∞ = T_∞, outside temperature or
M_∞, equilibrium moisture content

n_r, n_z = direction cosines in the r and z directions

h = h, surface heat transfer coefficient or h_m, surface mass transfer coefficient

A peanut pod was assumed to be a symmetrical body having a cross-section as shown in Fig. 4.1. The finite element mesh consists of 44 four-node quadrilateral elements and 60 nodes, and the further improvements of this mesh does not improve the results significantly. A finite element program written for two-dimensional problems, FEM2D, was used to solve for the heat and moisture transfers in a peanut pod. (FEM2D is given by Reddy, 1984.) The Crank-Nicholson scheme was used for the time approximation.

4.4 Results and Discussion

Since individual physical properties are not available for hulls and kernels, a peanut pod was assumed to be homogeneous. Thermal conductivity and moisture diffusivity are moisture dependent, but there are no experimental data available for hulls and kernels at different moisture levels. Because of the lack of experimental data, the model has only a limited usage. However, for the purpose of this discussion, the values estimated by Chhinnan and Young (1977b) and their experimental drying data given by them are used.

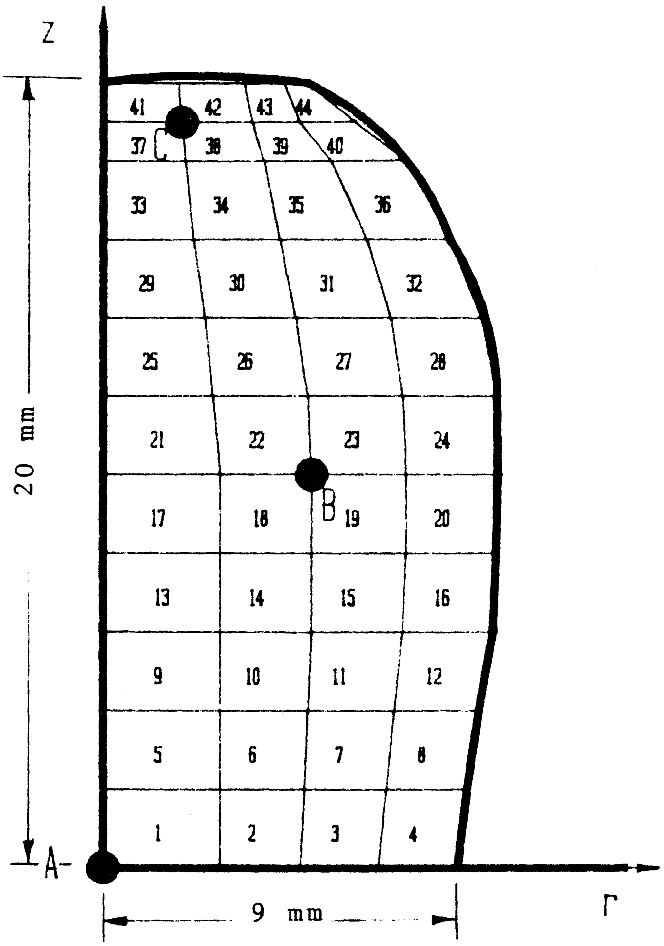

Figure 4.1. The finite element mesh of a peanut pod used in the model.

The following values are used in the solution:

T_∞ = drying air temperature = 43.3 C

M_∞ = equilibrium moisture content = 0.029 decimal, dry basis

T_0 = initial temperature of the material = 20.0 C

M_0 = initial moisture content = 1.04 decimal, dry basis

= 0.51 decimal, wet basis

h_m = 0.05 m/s

h = 60.0 W/m^2 C

C = 2903 J/kg

ρ = 1100 kg/m^3

k = 0.13 W/m C

D = thermal diffusivity at 43.3C = 1.20 m^2/h

The surface heat and mass transfer coefficients for similar drying situations were obtained from Irudayaraj et al. (1988). The finite element solution will give the temperature and moisture distributions within a peanut pod surrounded by air having a dry bulb temperature of 43.3 C and a relative humidity of 18%.

A portion of the output giving the moisture distribution is given in Appendix A. Fig. 4.2 gives the moisture contents at three nodes, A (node 1), B (node 28) and C (node 52). The moisture content at node A decreases at a rate slower than that at nodes B and C. At C, the moisture content reaches the equilibrium moisture content faster because node C is much closer to the boundary. Fig. 4.3 shows the mass average moisture content given by the model and the experimental drying data reported by Chhinnan and Young (1977b). Given the inaccuracies that would have been introduced by the physical properties used, the model predicts the drying curve quite accurately. The nodal temperatures at A, B, and C and the mass average temperature are given by Fig. 4.4. It can be seen that the maximum temperature difference between nodes is less than 8 C at any given time.

The finite element method provides a way to solve Luikov's equations for a domain with arbitrary shapes. For successful solutions to Luikov's equations using the finite element method, the following research should be conducted:

1. The coefficient of diffusivity, D, of hulls and kernels should be determined and relationships between D and the moisture content should be established experimentally.

2. The thermal conductivity, density and specific heat of peanuts should be checked for possible correlation with the moisture content.

3. The surface mass transfer coefficient, h_m, should be determined under packed-bed situations.

Once the experimental data are available, drying of a peanut pod can be modeled to obtain the drying rate and the temperature of the particle at the same time. Then this model can be incorporated into a deep-bed drying model without having to depend on thin-layer drying data.

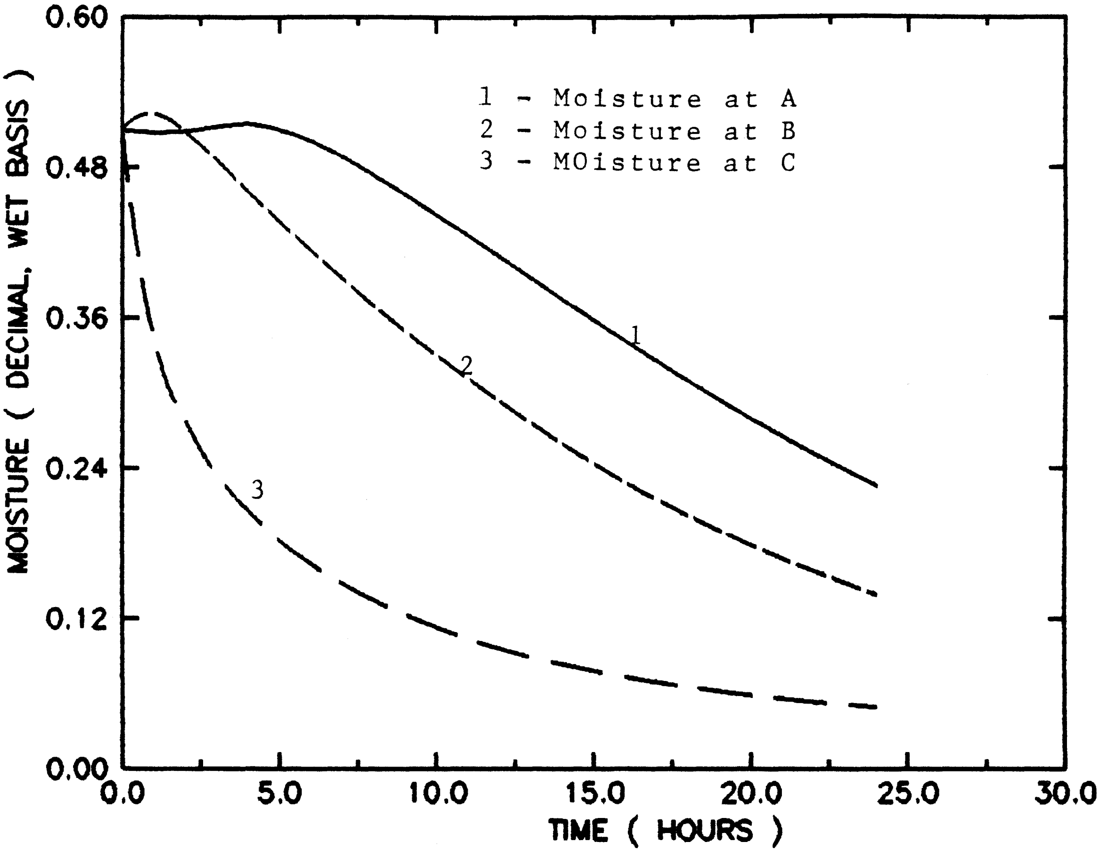

Figure 4.2. The moisture content variations at nodes A, B, and C as drying progresses.

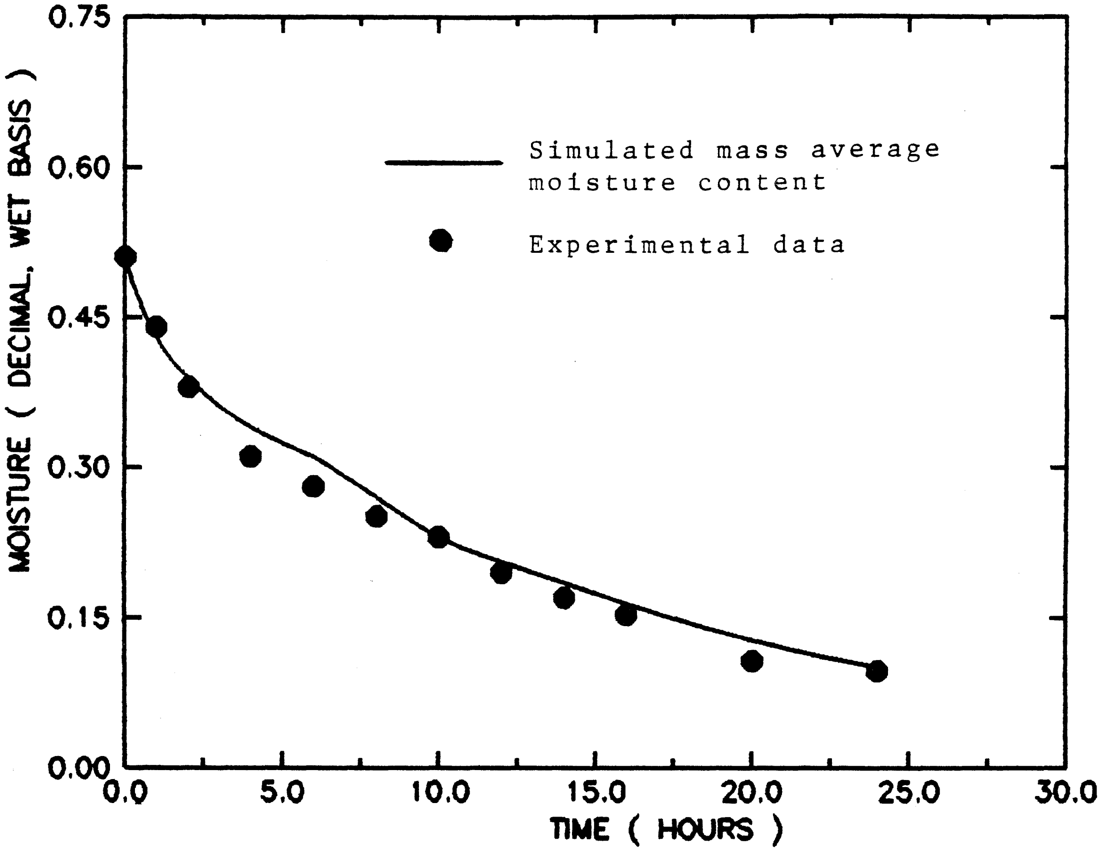

Figure 4.3. The mass average moisture content given by the finite element model and the experimental data reported by Chhinnan and Young (1977b) for the same drying conditions.

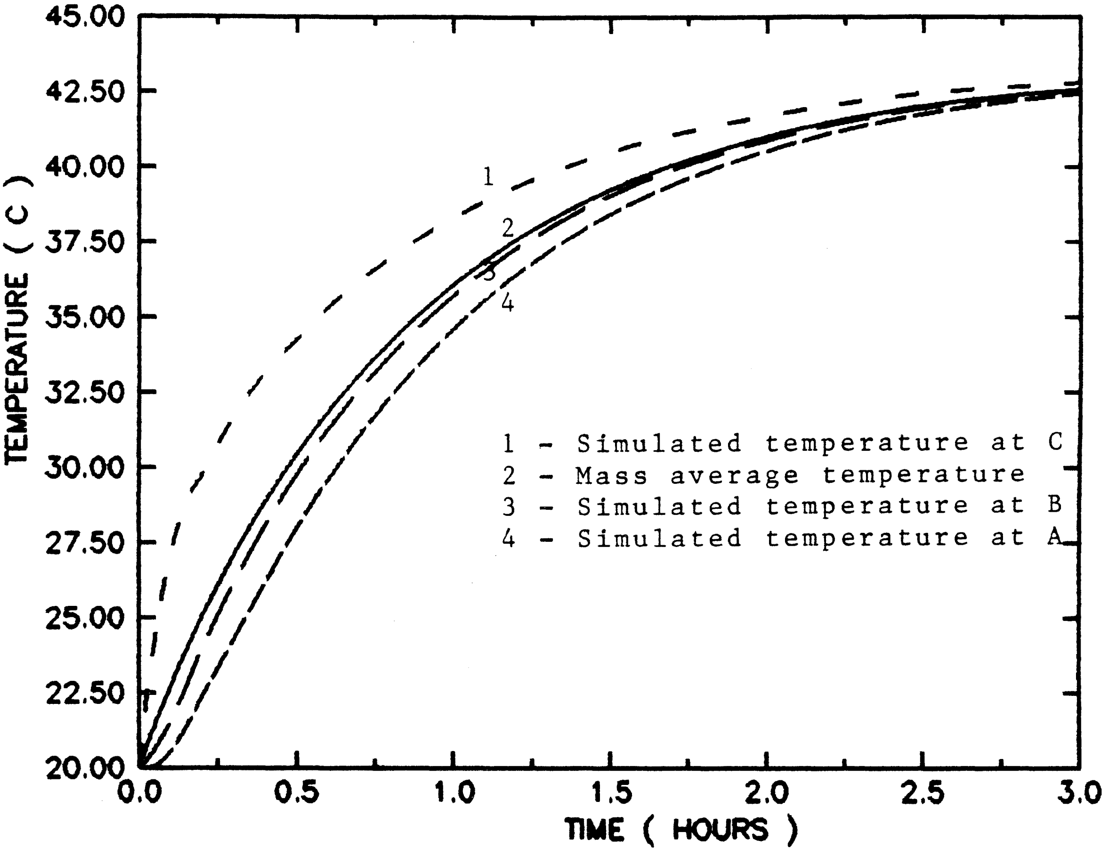

Figure 4.4. The temperatures at nodes A, B, and C and the mass average temperature given by the finite element model.

Chapter 5.

Development and Validation of a Deep-Bed Drying Model for Peanuts

5.1. Introduction

In Virginia, peanuts are dried in single-pass batch dryers (trailers) having cross sectional areas 8.4, 10, and 11.4 m^2. Trailers are usually filled to an effective depth of 1.52 m, and artificially dried from 25-28% (w.b.) to 10% (w.b.). Depending on weather conditions, the drying process normally takes from two to three days when the recommended maximum drying air temperature, 35 C, and the recommended airflow rate, 10 m^3/min per m^3 of peanuts, are used (Beasley and Dickens, 1963). In the peanut-growing regions of Virginia, daily average ambient temperatures generally range from 10 C to 30 C, and ambient relative humidity is below 60% during the hearvest season. Once the ambient air is heated to 30-35 C, the relative humidity of drying air decreases; therefore, in general, peanuts are dried with air having a relative humidity of less than 30%.

When drying air passes through a bed of wet peanuts, peanuts at the very bottom of the dryer release moisture at rapid rates into the air, increasing its humidity. Peanuts are dried at lower rates as the drying air moves higher in the bed. Drying continues until the moisture content at a point in the bed reaches the equilibrium moisture content of the peanuts corresponding to the air conditions at that point. In addition, if drying air gets saturated (relative humidity $\approx$ 100%), water condensation on the surface of peanut pods can occur, increasing the apparent moisture content. For Virginia conditions, there is some level between the bottom and the top where the air has gained sufficient moisture that no drying occurs above this level. This level in the bed is known as the "drying front." After some interval of time when the peanuts below the drying front have dried to the point where the air is not saturated as it passes through them, the drying front begins to move upward. At each level above the initial establishment of the drying front, there is some delay before drying begins. The maximum delay occurs at the top layer. Minimum recommended airflow is set by the requirement to begin drying the top layer before sufficient time has elapsed for mold growth to begin.

The drying of biological materials is a complex phenomenon consisting of mass (moisture) transfer and heat transfer simultaneously occurring between the material and the drying air. The most important variables involved in the process are the air temperature, the air humidity (mass of water vapor per unit mass of dry air), the moisture content of the material (mass of moisture per a unit mass of dry solids), and the product temperature. At a given time, all these variables are coupled through mass and heat (energy) conservation equations. Usually, these equations are first order or second order partial differential equations that must be solved numerically.

The finite difference and the finite element methods, two numerical techniques widely used for solving partial differential equations, are two potential techniques for solving the derived equations. Even though the finite element method is more flexible and versatile in every respect when compared to the finite difference method, the first-order, one-dimensional, coupled partial differential equations can easily be solved with relatively low computer time using the finite difference techniques, provided that the selected finite difference scheme is stable.

Strikwerda (1989) discussed the finite difference schemes used in solving partial differential equations. Consider the following differential equation:

$$U_t + a\, U_x = O \qquad [5.1]$$

where

t = time

x = spacial dimension

a = constant

$$U_t = \frac{\partial U}{\partial t}$$

$$U_x = \frac{\partial U}{\partial x}$$

If t and x can be expressed as nk and mh respectively, where n and m are arbitrary integers and k and h are positive numbers, then Eqn. [5.1] can be written as follows using different schemes:

Forward Time Forward Space Scheme:

$$\frac{U_m^{n+1} - U_m^n}{k} + a\,\frac{U_{m+1}^n - U_m^n}{h} = 0 \qquad [5.2a]$$

Forward Time Backward Space Scheme:

$$\frac{U_m^{n+1} - U_m^n}{k} + a\,\frac{U_m^n - U_{m-1}^n}{h} = 0 \qquad [5.2b]$$

Forward Time Central Space Scheme:

$$\frac{U_m^{n+1} - U_m^n}{k} + a\,\frac{U_{m+1}^n - U_{m-1}^n}{2h} = 0 \qquad [5.2c]$$

Leap-Frog Scheme:

$$\frac{U_m^{n+1} - U_m^{n-1}}{2k} + a \frac{U_{m+1}^n - U_{m-1}^n}{2h} = 0 \qquad [5.2d]$$

Lax-Friedrich's Scheme:

$$\frac{U_m^{n+1} - \frac{1}{2}[U_{m+1}^n + U_{m-1}^n]}{k} + a \frac{U_{m+1}^n - U_{m-1}^n}{2h} = 0 \qquad [5.2e]$$

Using one of the schemes outlined, a set of differential equations can be transformed into a set of algebraic equations, which should be solved after proper boundary and initial conditions are applied. Of the above schemes, the forward-time, forward-space and the forward-time, backward-space schemes are the least stable; therefore, stability conditions should be carefully imposed if those schemes are used.

The development of a bulk drying model for Virginia peanuts using the finite difference method and the validation of the model using experimental data are discussed in this chapter. Section 5.2 presents the development of the model including its computer implementation, and the model is validated in Section 5.3. Conclusions and recommendations are given in Section 5.4.

5.2 Model Development

Many theoretical models have been presented to represent mass and heat transfers in a fixed bed (Bakker-Arkema et al., 1974). Application of these models to bulk drying of many biological products is hindered by (1) lack of basic bed parameters such as equilibrium moisture contents, convective heat transfer coefficients, and drying rate constants; (2) complexity of solution techniques involved; and (3) variability in the physical properties of the product itself. Therefore, it is necessary to make simplifying assumptions when they can be justified as having negligible effect on the output variables.

5.2.1 Assumptions in the model

The following assumptions were made in the development of the model:

1. The volume shrinkage of peanuts during drying is negligible. (In practice 2-4% volume shrinkage can be observed in an undisturbed bed of peanuts after about 60 hours of drying.) In the model, this assumption is imposed by having a constant bulk density for peanut solids throughout the drying period. Since volume shrinkage of peanuts has not been studied in detail, data are not available to model the change of bulk density in the drying process.

2. The temperature of a peanut pod can be represented by an average temperature, disregarding the temperature gradient within the particle. Based on this assumption, possibly the most crucial one in the model, the model calculates an effective temperature for peanuts instead of actual temperatures in the particle. Since the temperature gradient within a particle does not have a practical significance in the drying process except for studying thermal stresses, this approach is appropriate in the present study.

3. Heat capacities of peanut solids and of dry air are constant during the temperature range involved, 20 C - 35 C. This assumption is usually made in heat transfer calculations without significant errors in results.

4. Air flow is plug-type, meaning that there is no velocity gradient across the cross-sectional area of the dryer.

5. Heat conduction from one peanut pod to another through contact is negligible. This assumption is reasonable because the dominant mode of heat transfer is convection in a drying process.

5.2.2 Governing Partial Differential Equations

Energy and mass balances are written on a differential volume located at an arbitrary point in the fixed bed using four variables: the dry basis moisture content of peanuts (M), the air temperature (T_a), the air humidity ratio (H), and the peanut temperature (T_p). Assuming a cross sectional area of the bed as A, the enthalpy balance for the air can be written on a differential volume, Adx, located at a height x from the bottom of the bed as follows:

energy out = energy in - energy transferred to peanuts by convection

$$(F_aC_a + F_aC_vH) \left[T_a + \frac{\partial T_a}{\partial x} dx \right] Adt =$$

$$(F_aC_a + F_aC_vH)\ A\ T_a\ dt - ha\ A\ dx\ (T_a - T_p)\ dt \qquad [5.3]$$

Rearranging,

$$[F_aC_a + F_aC_vH] \frac{\partial T_a}{\partial x} + ha\,[T_a - T_p] = O \qquad [5.4]$$

where

T_a = air temperature, C

T_p = peanut temperature, C

A = cross sectioned area, m^2

H = air humidity ratio, kg of vapor/kg of dry air

C_a = specific heat capacity of air, J/kg•C

C_v = specific heat capacity of water vapor, J/kg•C

F_a = mass flux of air, $kg/m^2 \cdot h$

t = time, h

h = surface heat transfer coefficient, $J/h \cdot m^2 \cdot C$

a = specific area of peanuts, m^2/m^3

The specific area of peanuts, a, is the surface area of peanuts per m^3 of packed bed.

The energy balance for peanuts can be written as follows:

Energy transferred to peanuts by convection
= change in internal energy in peanuts + energy for evaporation

$$haAdx(T_a - T_p)dt = (\rho_p C_p + \rho_p C_w M)\,Adx\,\frac{\partial T_p}{\partial t}dt$$

$$+ [h_{fg} + C_v\,(T_a - T_p)]\,F_a\,\frac{\partial H}{\partial x}dxAdt \qquad [5.5]$$

Rearranging,

$$(\rho_p C_p + \rho_p C_w M) \frac{\partial T_p}{\partial t} + [h_{fg} + C_v(T_a - T_p)] F_a \frac{\partial H}{\partial x} - ha(T_a - T_p) = O \qquad [5.6]$$

where

ρ_p = bulk density of peanut solids, kg/m³

C_p = specific heat capacity of water, J/kg•C

C_w = specific heat capacity of water, J/kg•C

h_{fg} = heat of vaporization of saturated water, J/kg

M = moisture content of peanuts, decimal, dry basis

The mass balance for the water vapor in the air can be written as follows:

moisture transferred from peanuts to air = moisture out - moisture in

$$-\rho_p \; Adx \; \frac{\partial M}{\partial t} \; dt = F_a \; A \left[H + \frac{\partial H}{\partial x} \; dx \right] dt - F_a AHdt \qquad [5.7]$$

Rearranging,

$$F_a \; \frac{\partial H}{\partial x} + \rho_p \frac{\partial M}{\partial t} = O \qquad [5.8]$$

The change in moisture content with time can be modeled by using a thin-layer model for Virginia-type peanuts.

$$\frac{\partial M}{\partial t} = f\,(M_i,\, T_a,\, rh,\, t) \qquad [5.9a]$$

where

f = drying rate function for peanuts, kg/h

T_a = air temperature, C

rh = air relative humidity, decimal

t = time, h

M_i = initial moisture content, decimal, dry basis

The thin-layer equation used is the first derivative of Eqn. [3.27] with respect to time.

$$\frac{\partial M}{\partial t} = (M_i - M_e)\,(-Knt^{n-1})e^{-Kt^n} \qquad [5.9b]$$

Any other thin-layer equation can easily be substituted for Eqn. [5.9a] in the model.

The system of partial differential equations (PDEs) given by Eqns. [5.4], [5.6], [5.8], and [5.9] constitutes a mathematical model for the peanut-drying process in a fixed bed. The system of PDEs must be solved numerically because it is impossible to find exact solutions. It is essential, however, to use an accurate value for the specific area for the peanuts, a, and an established relationship for surface heat transfer coefficient, h, if the solutions are to be realistic.

5.2.3 **Surface Heat Transfer Coefficient**

The models found in the literature for the heat transfer coefficient in a bed of biological particles were derived from heat transfer studies in packed beds. Boyce (1965) used the following relationship for volumetric heat transfer in barley and wheat:

$$h_v = 856{,}800 \left[g_a \frac{(T + 273)}{P_{atm}} \right]^{0.6011} \qquad [5.10]$$

where

g_a = mass flux of air, $kg/m^2 \bullet s$

T = air temperature, C

P_{atm} = atmospheric pressure, Pa

h_v = volumetric heat transfer coefficient, $W/m^3 \bullet K$

Sokhansanj (1984) reported the following relationship for the surface-heat transfer coefficient:

$$h = 100\, g_a^{0.49} \qquad [5.11]$$

where

g_a = mass flux of air, $kg/m^2 \bullet s$

h = surface heat transfer coefficient, $W/m^2 \bullet K$

Note that h_v and h are volume based and surface-area based, respectively. Eqn. [5.11] was used in the model after conversion of units of mass flux, g_a, to $kg/m^2 \bullet h$.

$$h = 100 \left[\frac{F_a}{3600} \right]^{0.46} \qquad [5.12]$$

where

F_a = mass flux of air, $kg/m^2 \bullet h$.

5.2.4 **Specific Area of Peanuts**

The specific area, a, is defined as the surface area of particles contained in a unit volume of space. If the mean surface area of a peanut and the number of unit volume of space. If the mean surface area of a peanut and the number of peanuts in a unit volume are known, then a mean value for the specific area of peanuts can be obtained by multiplying the two quantities. This value was treated as a constant in the model implying that the change of surface area and shrinkage during the drying process were negligible.

A random sample of 60 Virginia-type peanuts was used to measure the surface area. For each particle, the shell was split into two parts along the seam and the shape of the cross section was drawn on paper. Then the length of the pod was divided into 10 segments and diameters at each point were measured. The total surface area of a pod was calculated by adding the surface area of each segment calculated as the side area of a cylinder or the end area of a cone for the two end segments. The average surface area for peanuts was 1.413×10^{-3} m^2/pod.

The number of peanut pods per unit volume was obtained by counting the number of peanuts 'tightly' packed in a known volume (3.65×10^{-3} m^3). Five replications were made, and the mean was 134276 pods/m^3 (approximately 3800 pods/ft^3). Therefore, the mean specific area of Virginia peanuts was 188 m^2/m^3.

5.2.5 Modeling Condensation

As drying air passes through wet peanuts, it collects water vapor, and in the beginning of the drying process the drying air may reach the saturation point (relative humidity $\approx$ 100.0%) before leaving the bed. The water vapor in the saturated air stream condenses on cooler surfaces of peanut pods, increasing the apparent moisture content of peanuts. During the condensation, heat energy is released to the air stream; air humidity decreases; and the peanut temperature is assumed to remain constant. The following procedure was used in modeling the condensation:

1. When the relative humidity is equal to or greater than 0.999999, the new air humidity ratio, H_{new}, is set equal to the humidity ratio corresponding to the saturated air having equal dry bulb and wet bulb temperatures.

2. Mass balance is written for the moisture:

   $(\text{moisture in air + moisture in peanuts})_{\text{before condensation}} =$

   $(\text{moisture in air + moisture in peanuts})_{\text{after condensation}}$

This procedure gives the new moisture content, M_{new};

$$M_{new} = M_{old} + \frac{F_a \, \Delta t}{\rho_p \, \Delta x} (H_{old} - H_{new}) \qquad [5.13]$$

where

F_a = mass flux of air, $kg/m^2 \bullet h$

M_{old} = moisture content - before condensation, decimal, dry basis

M_{new} = moisture content - after condensation, decimal, dry basis

H_{old} = humidity ratio of air before condensation, kg/kg of dry air

H_{new} = humidity ratio of air after condensation, kg/kg of dry air

Δt = time increment, h

Δx = space increment, m

ρ_p = bulk density of peanut solids, kg/m^3

3. The energy balance is written for both air and peanuts assuming that the peanut temperature remains constant.

(energy of air + energy of peanuts)$_{\text{before condensation}}$ =

(energy of air + energy of peanuts)$_{\text{after condensation}}$

This step gives the new dry bulb temperature, T_{new};

$$T_{new} = \frac{[T_{old}\,(C_a + C_v\,H_{old}) + h_{fg}\,(H_{old} - H_{new})]}{(C_a + C_v\,H_{new})} \tag{5.14}$$

where

C_a = specific heat of air, J/kg•C

C_v = specific heat of water vapor, J/kg•C

T_{old} = dry bulb temperature of air before condensation

h_{fg} = heat of condensation, J/kg

During the condensation of water vapor, air humidity decreases and air temperature increases, as seen from Eqns. [5.13] and [5.14]. The model given here calculates the condensation in a bed reasonably well, and is based on Bakker-Arkema's (1974) model for condensation in corn drying. Bakker-Arkema (1974) neglected the increase in the stored energy of the material when the condensation of water vapor occurs.

5.2.6 **Effect of Airflow**

The effect of airflow on drying rate is modeled by multiplying the thin layer drying rate by a velocity factor, f_v.

$$f_v = \left[\frac{\text{Apparent air velocity in the bed}}{\text{Apparent air velocity on which the thin layer equation is based}}\right]^m \tag{5.15}$$

The value of m was taken as 0.70 (Colson and Young, 1988). Apparent air velocity affects the drying rate significantly, and the model should reflect these effects. In the absence of data on velocity effects in peanut drying, the use of an approximate relationships such as Eqn. [5.15] is appropriate. However, sensitivity of the thin-layer model [Eqn. (5.9a)] to air velocity should be determined and then can be used to refine the model further.

5.2.7 The Finite Difference Scheme

The set of PDEs given by Eqns. [5.4], [5.6], [5.8], and [5.9] was solved using the Leap-Frog scheme, which was more stable than other schemes discussed in Section 5.1. First, time and distance from the bottom of the bed were expressed in terms of small increments, Δt and Δx respectively.

$$\text{time} = t = n\Delta t \qquad [5.15a]$$

$$\text{distance} = d = m\Delta x \qquad [5.15b]$$

The air temperature at a height of d and at time t, for example, can be written as $T_{a,m}^{n}$; superscript and subscript indicating the time and the distance, respectively (Figure 5.1). The four variables involved at any point (n,m) in the mesh are:

1. air temperature, $T_{a,m}^{n}$ (C)
2. air humidity, H_{m}^{n} (kg/kg of dry air)
3. peanut temperature, $T_{p,m}^{n}$ (C)
4. moisture content of peanuts, M_{m}^{n} (decimal, dry basis)

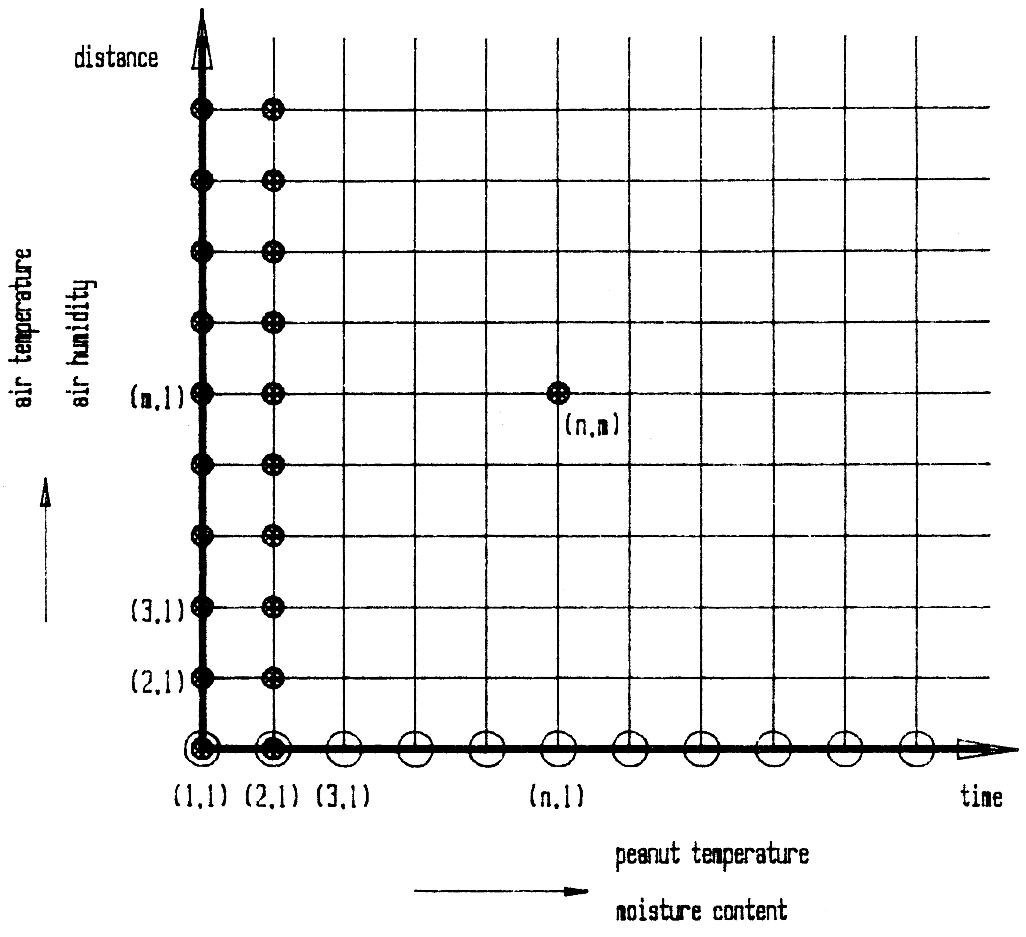

Figure 5.1. Time and distance mesh for the Leap-Frog scheme used in solving the set of PDEs.

The partial derivatives in the set of PDEs can be formulated as follows:

$$\frac{\partial T_a}{\partial x} = \frac{T_{a,m+1}{}^n - T_{a,m-1}{}^n}{2\Delta d} \qquad [5.16a]$$

$$\frac{\partial H}{\partial x} = \frac{H_{m+1}{}^n - H_{m-1}{}^n}{2\Delta x} \qquad [5.16b]$$

$$\frac{\partial T_p}{\partial t} = \frac{T_{p,m}{}^{n+1} - T_{p,m}{}^{n-1}}{2\Delta t} \qquad [5.16c]$$

$$\frac{\partial M}{\partial t} = \frac{M_m{}^{n+1} - M_m{}^{n-1}}{2\Delta t} \qquad [5.16d]$$

The above relationships are then substituted into Eqns. [5.4], [5.6], [5.8], and [5.9] and rearranged to have the following algebraic expressions to solve for four variables.

For air temperature:

$$T_{a,m+1}{}^n = T_{a,m-1}{}^n \left[\frac{F_aC_a + F_aC_vH_m{}^n - ha\Delta x}{F_aC_a + F_aC_vH_m{}^n + ha\Delta x}\right] + \left[\frac{2ha\Delta x\, T_{p,m}{}^{n-1}}{F_aC_a + F_aC_vH_m{}^n + ha\Delta x}\right] \qquad [5.17]$$

$$T_{a,m}{}^n = (T_{a,m+1}{}^n + T_{a,m-1}{}^n)/2 \qquad [5.18]$$

For peanut temperature:

$$T_{p,m}^{n+1} = \frac{(1+F_1)}{(1-F_1)} T_{p,m}^{n-1} + \frac{2ha\Delta t\ T_{a,m}^{n}}{(1-F_1)\ [\rho_p C_p + \rho_p C_w M_m^{n}]}$$

$$- \frac{(h_{fg} + C_v T_{a,m}^{n})}{(1-F_1)[\rho_p C_p + \rho_p C_w M_m^{n}]} \left[\frac{F_a \Delta t}{\Delta x}\right] [H_{m+1}^{n} - H_{m-1}^{n}] \qquad [5.19]$$

where

$$F_1 = \frac{C_v F_a \Delta t\ [H_{m+1}^{n} - H_{m-1}^{n}]}{2\Delta x\ [\rho_p C_p + \rho_p C_w M_m^{n}]} - \frac{ha\Delta t}{[\rho_p C_p + \rho_p C_w M_m^{n}]} \qquad [5.20]$$

$$T_{p,m}^{n} = (T_{p,m}^{n+1} + T_{p,m}^{n-1})/2 \qquad [5.21]$$

For humidity of air:

$$H_{m+1}^{n} = H_{m-1}^{n} - \frac{2\rho_p \Delta x}{F_a} \left[\frac{M_m^{n+1} - M_m^{n-1}}{2\Delta t}\right] \qquad [5.22]$$

$$H_m^{n} = (H_{m+1}^{n} + H_{m-1}^{n})/2 \qquad [5.23]$$

For moisture content of peanuts:

$$M_m^{n+1} = M_m^{n-1} + 2\Delta t\ f\ (T_{a,m-1}^{n}, H_{m-1}^{n}, M_{m-1}^{1}) \qquad [5.24]$$

$$M_m^{n} = (M_m^{n+1} + M_m^{n-1})/2 \qquad [5.25]$$

In the simulation, calculations of air humidity and air temperature proceed in the space direction while the calculations of peanut temperature and moisture content proceed in the time direction (Fig. 5.1). To start the computing of variables using Eqns. [5.17] - [5.25], the nodes shown in Fig. 5.1 were initialized using initial and boundary values.

First, air temperature and humidity values are assigned to nodes along the time axis fixing m at 1. These are the conditions of air entering the peanut bed. Then, the moisture contents are calculated for these nodes using the thin-layer equation. Initial moisture content and peanut temperature are assigned to nodes along the space axis when n=1. The distributions of humidity, moisture content, and peanut temperature throughout the bed for n=1 and n=2 are calculated by using forward difference equations based on Eqns [5.6], [5.8], and [5.9]. The air temperature distributions throughout the bed for n=1 and n=2 are calculated assuming adiabatic drying conditions. (See a listing of the FORTRAN program in Appendix B for the exact procedure). After the initializing procedure is completed, Eqns [5.24], [5.25], 5.22], [5.23], [5.17], [5.18], [5.20], [5.19], and [5.21] are used in that order to calculate the variable values for the entire time-space mesh, proceeding first in the space direction and then incrementing in time.

The numerical scheme used to solve the PDEs gives approximate values of the variables. If the values are not close to the exact solutions and behave in a haphazard way, the numerical scheme is unstable. Even though Leap-Frog schemes are more stable than other schemes, instability might occur if large values of Δx and Δt are used for given parameters such as bulk density of peanut solids and specific heat capacity of peanut solids. Reduction in Δx and Δt increases the time and memory requirements for computer execution; therefore, maximum possible values of Δx and Δt which give stable solutions should be used. Test of the scheme with different Δt and Δx values found that the Δt value of 0.10 hour and the Δx value 0.01 m should produce reasonable solutions, except for the first half hour of drying time and for the first 3-4 space nodes (m=1 to 4). If the solution is unstable for a longer period of time, Δt should be reduced further. If Δx and Δt are equal to 0.01 m and 0.1 h respectively, for example, the number of nodes required in the time-space mesh to model the drying process of a peanut bed having a depth of 1.1 m for 60 hours is 66711 (= 601 x 111); if the time step is halved (= 0.05), the number of nodes required is 133,311, which is an almost 100% increase in number of nodes.

5.2.4 A Computer Program of the Model

A program was written in FORTRAN 77 language to simulate the drying process in a peanut bed using the numerical scheme previously discussed. The main consideration of the program, PEATECH FORTRAN, was flexibility for further improvements and modifications, especially in inputs and outputs; therefore, PEATECH was structured into three main modules:

1. Preprocessing module
2. Processing module (core)
3. Postprocessing module

In the Preprocessing module, the inputs are read and written out; required variables for the Processing module are calculated; and inlet humidity and air temperature values are interpolated using the IMSL routine CSDEC for cubic-spline interpolation. Inlet humidity and air temperature values are passed on to the Processing module.

In the Processing module, the PDEs are solved using the Leap-Frog scheme. The subroutine CONDEN, which models condensation; the function TLRATE, which models the thin layer drying rates; the function FLOW, which models the mass flux of air; the function EMC, which models the equilibrium moisture content; and the subroutine PSYC, which calculates the conditions of air are used in the module to model the drying process. The Processing module outputs air humidity, peanut temperature, air temperature, and moisture content of the peanuts at the nodes of the time-space mesh (Fig. 5.1).

Once all the variable values are available from the Processing section, required outputs are written out to an external file in the Postprocessing section. For the purpose of testing and validating the model, the variable values were written out along with time for some selected locations in the bed. The program given in Appendix B with a variable listing gives: (1) average moisture content of the bed; (2) time taken to dry peanuts to 10% (w.b.); and (3) air humidity, dry bulb and wet bulb temperatures of air, peanut temperature, and moisture content at locations 0.05 m apart in the bed at intervals of 1 hour. Since, the Postprocessing module is completely outside the loops of the Processing module, it can easily be modified to get required outputs without the computational procedure itself having to be understood.

5.3.0 **Validation of the Model**

5.3.1 **Introduction**

Validation can be defined as determining whether a model is an accurate representation of the real-world system under study (Law and Kelton, 1982). Since a simulation model of a real-world system is always only an approximation of the actual system, regardless of the technical sophistication of the model, the objective of the validation process is to perceive the degree to which the model agrees with the system. In most cases, it is impossible to establish the absolute validity or invalidity of a model. If the model output data and data from a corresponding real-world system are in reasonable agreement, confidence in the "validity" of the model increases.

Although there are no established procedures in model validation, the following approaches are frequently found in literature.

1. Face validation: The behavior of the model seems reasonable to people who are knowledgeable about the real-world system under study.

2. Validation by inspection: The output variables of the system that can be measured are compared with the corresponding values from the model using graphs, charts, and tables.

3. Statistical validation: For stochastic simulation models, output data from the model can be compared with the measured data using statistical tests such as t, Mann-Whitney, two sample chi-square, and two sample Kolmogorov-Smirnov to determine whether the underlying distributions of the two data sets can be regarded as the same. But, for time-dependent outputs, these tests are not directly applicable (Law and Kelton, 1982). Fundamental statistical quantities such as the coefficient of correlation between the model output and the measured data and the mean percentage deviation of the simulated values from the measured values are used to determine how closely the model represents the actual system. It should also be noted that the accuracy of measured values is a factor in the validation.

The data from a series of tests conducted using three laboratory scale dryers during the peanut harvest seasons in 1987, 1988, and 1989 were used to validate the bulk peanut-drying model, PEATECH. Peanuts used for these tests were grown at the Tidewater Agricultural Experiment Station, Holland, Virginia.

5.3.2 Drying Tests in Laboratory Dryers

5.3.2.1 Laboratory Dryers

The three laboratory dryers used in the tests were built by the Department of Agricultural Engineering in 1981 (Cook et al., 1982). The configuration of each dryer is shown in Fig. 5.2. A dryer consists of four ducts having an inner uniform cross section of 0.5 m x 0.5 m. The vertical section above the fan can be removed and peanuts to be dried can be stored in it. The height of the drying bed is approximately 1.0 m. The top horizontal duct and the other vertical duct serve as passages for recirculating air. The amount of recirculated air can be controlled by a hinged door located just above the ambient air entrance.

The innermost layer of the walls consists of 0.95-cm thick plywood, and the outer layer is made of 0.64-cm thick plywood. A 3.81-cm thick layer of polystyrene insulation provides high resistance to heat flow through the walls.

Each dryer has a centrifugal fan driven by a 0.56-kw electric motor, which is mounted outside the dryer. The fan speed is varied using a variable speed drive. A 60-tooth gear is mounted on the fan shaft; each tooth generates a pulse as it passes near a magnetic sensor. These pulses are counted by a frequency counter and displaced as rpm.

Air is heated using finned strip heaters (Chromalox OTF-19 128258) that can be controlled to maintain air temperature at a set value. During the tests, three 1500-W, 240-V heaters are used in each dryer. The temperature of air below the material bed is controlled by digital temperature controllers (Eurotherm Model 918) with a rated accuracy of ± 1C. This temperature controller varies the current to the heaters according to the set point and the temperature reading below the material bed. The temperature sensor for the controller is an iron constantan thermocouple junction (ANSI type J).

Air is exhausted through a metal vent at the top of the crop-drying column into a sheet metal duct which channels the exhaust to the outside of the building. The vent opens when there is a positive pressure inside the exhaust duct.

The three dryers were installed side by side in the field laboratory building of the Agricultural Engineering Department. The ambient air entering the dryers was the air in the unheated building.

5.3.2.2 **General Procedure of Tests**

Peanuts were transported approximately 430 km in a covered truck from the Tidewater Agricultural Experiment Station, Suffolk, to Blacksburg, and loaded into the dryers. First, the dryer columns were removed and weighed to obtain tare weights. Then the columns were filled with peanuts to a depth of 1.0 m and weighed again. Samples were taken during column filling for determination of initial moisture content. The top-layer baskets (tare weight was known) were filled with peanuts, weighed, and placed in the tops of the drying columns. The top-layer baskets were connected to the load cells, and the gap between the dryer column and the top section

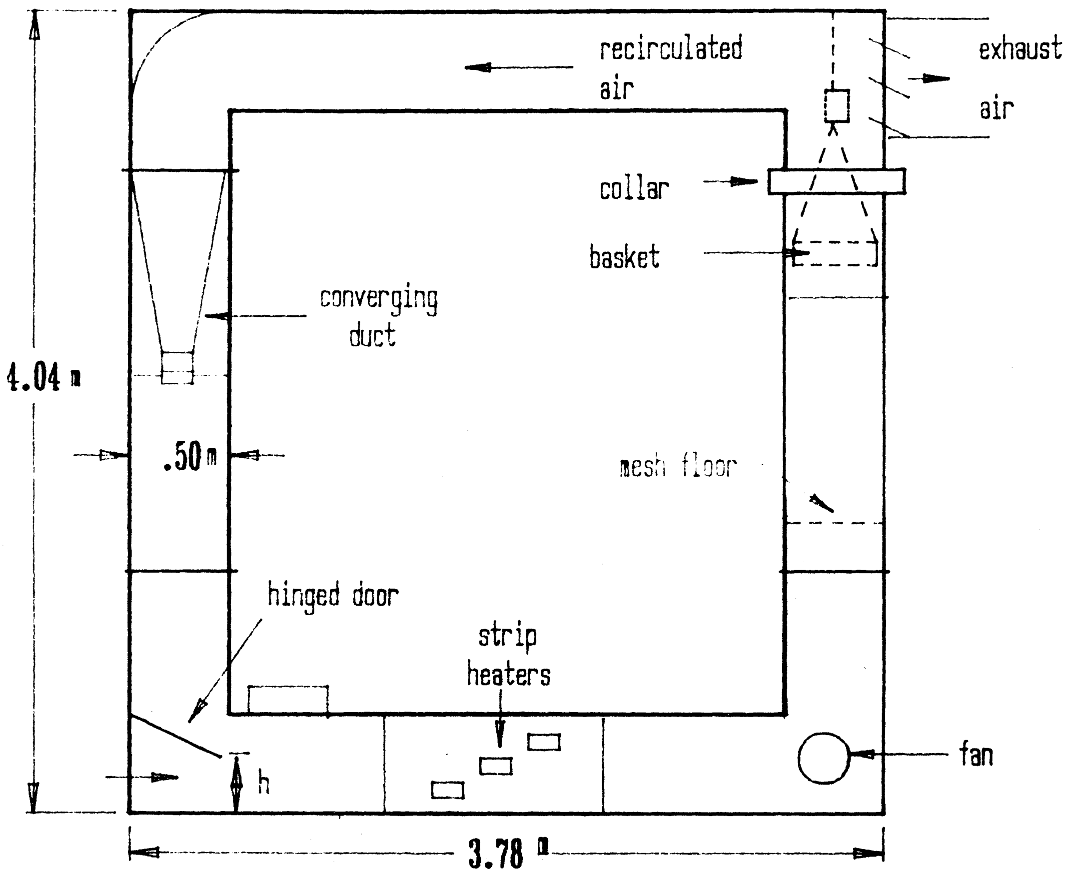

Figure 5.2. Configuration of a dryer.

of the dryer was sealed with a wooden collar on each dryer. Plastic pipe was connected to a port between the top of the peanut bed and the top-layer basket. This pipe formed a closed loop which was used to sample air above the peanut bed, flow it past a wet bulb sensor, and return it to the column. The dryer fan was set at a specified speed, and heater controllers were set at 35 C. Usually, duration of a test was 50-72 hours. During this interval, the following observations were made every four hours (except at 0400 hours) on each of the three dryers:

1. Static pressure readings were made at piezometer rings below the peanut beds using a micromanometer.

2. Dry bulb temperature of the air entering the peanut bed was measured using a thermistor probe in the 1987 and 1988 tests. A hygrometer unit with a temperature sensor (Humi-chek 5) was used in the 1989 tests.

3. Relative humidity of entering air was measured using a Humi-chek 5 in the 1989 tests.

4. Dry bulb and wet bulb temperature of air leaving the peanut bed and entering the top layer basket was measured using a thermistor probe.

5. Dry bulb and wet bulb temperature of ambient air was measured with a thermistor probe in the 1987 and 1988 tests. Humi-chek 5 was used in the 1989 tests to measure the temperature and relative humidity of ambient air.

6. A vane-type anemometer was used to measure the velocity of air being returned through the top horizontal duct to the inlet. This measurement was made at the outlet of the converging duct (Fig. 5.2), and multiplication by duct cross-sectional area gave the volume flow.

7. Air temperature inside the peanut beds at three locations, 0.3, 0.6, and 0.9 m above the mesh floor was measured with copper-contantan thermocouples (ANSI type T).

The following observations were recorded using a data acquisition system every 15 minutes:

1. Heat energy input, determined by measuring the amperage and the voltage to the resistance heaters.

2. Weight of the top-layer baskets.

At the end of drying, each dryer column was weighed separately without the top-layer basket. Six peanut samples from each column were taken for final moisture content determinations. The top-layer baskets were also weighed, and three peanut samples taken to determine the moisture content (ASAE S410.1).

5.3.2.3 **Measurements in Drying Tests**

ASHRAE Standard 41-66 gives the procedure for dry bulb and wet bulb temperature measurements. Instrument accuracy for dry-bulb and wet-bulb temperature should be ± 0.2 C for the dry-bulb temperature range 0 to 60 C and the wet-bulb temperature range 0 to 32 C. The thermistor probes (Omega type

ON-910-44007) used in the experiments meet these standards.

When measuring wet-bulb temperature using mercury-in-glass thermometers and other sensing devices of similar diameter, an air velocity of 3.6 m/s to 10.2 m/s, preferably near 5.1 m/s, is recommended. Cotton tubing of fairly soft, fine mesh weave is recommended as a suitable material for the wet bulb wick. The wick should be cleaned or replaced and the portion of the wick exposed to the air stream should extend one-half inch from the thermistor bulb. Since the air velocity above the peanut bed is low, an accurate reading of wet bulb temperature could not be taken by placing the thermistor probe covered with a wick directly in the air stream. Therefore, sampling ducts were constructed in all three dryers above the top-layer baskets. Blowers (Dayton model 1C939) rated at 1.698 m^3/min were used to circulate air from the area above the peanuts through the test sections where the thermistor probes were inserted.

Current transducers (Scientific Columbus Model CT510 A 2-2) were used to measure electrical energy input to the resistance heaters. The transducers produce a 0-1 mA output proportional to a 0-25 A input. The output currents of the transducers were directed across a 0.5 KΩ resistor, and the voltage drop recorded using a computer (IBM PC). The sampling rate was 128 samples per second, and the average reading was calculated every 10 seconds. The computer records the average value every 10 minutes.

The recirculated airflow rates were measured with a calibrated, converging duct-vane type anemometer set-up. In the 1989 tests, a precision hygrometer (Humi-chek 5, Beckmann Industrial) was used to measure the dry bulb temperature and the relative humidity of ambient air and of air entering the peanut bed. The hygrometer has accuracies of ± 0.2 C in measuring temperature and ± 1% in measuring relative humidity.

5.3.2.4 **An Overview of the 1989, 1988, and 1987 Tests**

A total of four tests, each using the three dryers located at the field laboratory, were conducted during the fall of each year for the three years 1987, 1988, and 1989. Each test consisted of three drying experiments; therefore, twelve drying experiments were done each year. Every year, two shipments of peanuts were brought from Suffolk, Virginia; the first was used for the first and second tests (six drying experiments), and the second shipment was used for the rest of the tests. The remainder of a shipment, after the three dryers were loaded for a test, was stored in a controlled environment chamber set at 90% relative humidity and 2 C dry bulb temperature for use in the following test. Because of the high relative humidity and low temperature, moisture loss of the peanuts stored in the chamber should have been negligible. However, a moisture loss of 5-6% (wet basis) was observed over a period of a week.

The average initial moisture content of peanuts for the 1989 tests ranged from 28% to 41% (wet basis), and the peanuts generally had a moisture content variation of 3-7% (wet basis) within a batch. (Peanuts stored in the controlled environment chamber had a higher moisture content variation within a batch). The average initial moisture contents for the 1988 and 1987 tests ranged from 24% to 30% (wet basis), and the moisture content variation was 3-4% (wet basis) within a batch.

Initial weight of peanuts in a dryer ranged from 85-98 kg for all tests, and the airflow ranged from 8.4 to 11.3 $m^3/min/m^3$ of peanuts. (Airflow was determined from the fan curve at 475 rpm, which was developed using the experimental data. The experimental procedure was given by Kulasiri, 1988.)

5.3.3 **Testing of the Model Using the Collected Data**

5.3.3.1 **Input and Output Variables**

The deep-bed peanut drying model, PEATECH, can be considered as a blackbox consisting of a set of input and output variables. The input variables are inlet air temperature and humidity, initial moisture content of peanuts, bulk density of peanut solids, initial peanut temperature, and static pressure below the bed. The data files were prepared using the data collected. Except for bulk density of peanut solids, initial peanut temperature and initial moisture, the other inputs were time-dependent; therefore, the time at which they were measured was also given in the data files.

The output variables considered in this analysis were air temperature and humidity at 1.0 m height, air temperature at 0.3, 0.6 and 0.9 m heights, the average moisture content of the top layer basket, and the final average moisture content of the peanuts. Since air temperature at 1.0 m is an indication of the heat transfer process within the dryer and humidity at 1.0 m indicates moisture removal from the peanuts, the behavior of the model with respect to the actual system can be established by comparing the values given by the model with the measured values of these variables. However, inclusion of other measurable outputs will strengthen the validation process.

Simulated peanut temperature inside the bed was also stored in an output file so that these temperatures could be compared with air temperature measured at different heights in the bed. Theoretically, peanut temperature should approximately equal to air temperature, except at the beginning of the drying.

The time at which drying starts (moisture content begins to decrease) at a given height is when the "drying front" reaches the peanuts at that level. Simulated moisture contents along the bed should show the upward movement of the drying front, and the time lags associated with the drying front reaching a given level should agree with experimental observations.

Since the model does not accommodate variability in the initial moisture content of the peanuts, the accuracy of the model also depends on initial uniformity in the moisture content of the peanuts. Variability of the initial moisture content can be included in the model if enough data are available. But studies on the moisture content variability of peanuts after windrow drying were not available in the literature.

5.3.3.2 **Methods of Comparison**

Methods of validation were discussed in Section 5.3.1. The following approaches were used for the validation of the model.

1. Graphical comparison: Simulated and measured values of a variable were plotted against time, and were visually inspected for closeness and patterns in the data.

2. Correlation coefficient: The correlation coefficient r is a measure of the strength of the relationship between two variables. Ott (1984) gave the necessary equations to compute r. If the correlation coefficient between the measured values and the simulated values of a variable is close to 1.0, then the two sets of values show a strong positive correlation. On the other hand, if r is negative, the two sets of values are negatively correlated. For example, if the measured values are increasing while the simulated values are decreasing, then r is negative. The correlation coefficient, however, is not a measure of closeness between the two sets of values.

3. Mean deviation: Suppose X_i is the measured value of a variable and Y_i is the simulated value of the same variable at a given time, T_i. If there are n measured and simulated values available, mean deviation can be defined in two ways.

a. Mean Deviation (Method 1)

$$\text{Mean deviation} = D_1 = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{X_i - Y_i}{X_i} \right| \times 100$$

b. Mean Deviation (Method 2)

$$\text{Mean deviation} = D_2 = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{X_i - Y_i}{X_i} \right) \times 100$$

D_1 is the summation of the absolute values of the percentage deviation divided by the number of observations, n. Thus, D_1 gives the largest mean percentage deviation that could be expected between the measured and simulated values. D_2 is always less than or equal to D_1 because of the averaging effect of positive and negative percentage deviations. D_2 can be considered as the mean percentage deviation that could normally be expected over the range of the measured values. Both of these deviations were used in the comparison of the simulated and the measured values.

5.3.3.3 **Results and Discussion**

The data files prepared for each experiment were used as inputs for the model, which was run using the space increment, Δx, of 0.01 m and the time increment, Δt, of 0.1 hour. Values of the constants used are given in Table 5.1. Even though smaller values of Δx and Δt would have increased the accuracy of the model in some cases, the above values were used for each run to maintain the consistency of the model for all cases under discussion and to save computer time. The drying experiments conducted in 1989 are mainly used in this discussion for the following reasons:

1. The thin-layer drying equation used in the deep-bed drying model was developed using the peanuts obtained for the 1989 tests; therefore, errors introduced by the thin-layer drying equation were minimal for the 1989 tests. Use of this equation facilitates the validation of the basic mathematical formulation and the computational technique of the drying process used in the tests.

Table 5.1 Values of the constants used in the drying simulations.

Description	Notation	Value	
Specific heat of air	C_a	1.007×10^3	J/kg•K
Specific heat of dry solids	C_p	2.9308×10^3	J/kg•K
Specific heat of water vapor	C_v	1.877×10^3	J/kg•K
Specific heat of saturated water	C_w	4.178×10^3	J/kg•K
Specific area of peanuts	a	188	m^2/m^3
Air density	ρ_a	1.1614	kg/m^3

2. The conditions of inlet air, both the dry bulb temperature and the relative humidity, were directly measured using a precision hygrometer during the 1989 tests, and these measurements were more accurate than those made with the thermistor probe in 1987 and 1988.

3. In the 1989 tests, air temperatures at 0.3, 0.6, and 0.9 m above the mesh screen were measured using thermocouples.

The graphs of the measured and the simulated variables for the drying experiment conducted in column 1 in test 1 in 1989 (Notation: 89 T1C1) were plotted against time (Figs. 5.3, 5.4, 5.5, and 5.6). The simulated dry bulb temperature at 1.0 m was in excellent agreement with the measured dry bulb temperature (Fig. 5.3), with a correlation coefficient of 0.993, a D_1 of 3.91% and a D_2 of 0.70% (The calculated correlation of coefficients, D_1, and D_2 for the output variables are given in Tables 5.2, 5.3, 5.4, 5.5, 5.6, and 5.7). The maximum deviation between the measured and the simulated temperatures, 2 C, occurred at 40.0 hours. The model underpredicted the temperature during the first 20 hours and overpredicted it during the remainder of the drying period, giving a mean percentage deviation of 0.70%. The largest mean percentage deviation that could be expected over the drying period was 3.91%. The simulated humidity at 1.0 m agreed well with the measured humidity, except for the first 8 hours of drying time and from 20 to 30 hours (Fig. 5.4). The relatively low correlation coefficient (0.815) and the relatively high D_1 and D_2 (7.42 and +3.84%) indicate that the agreement between the simulated and the measured values is not excellent, but, given the possibility of experimental errors in the wet bulb temperature and airflow measurements, these values are quite acceptable.

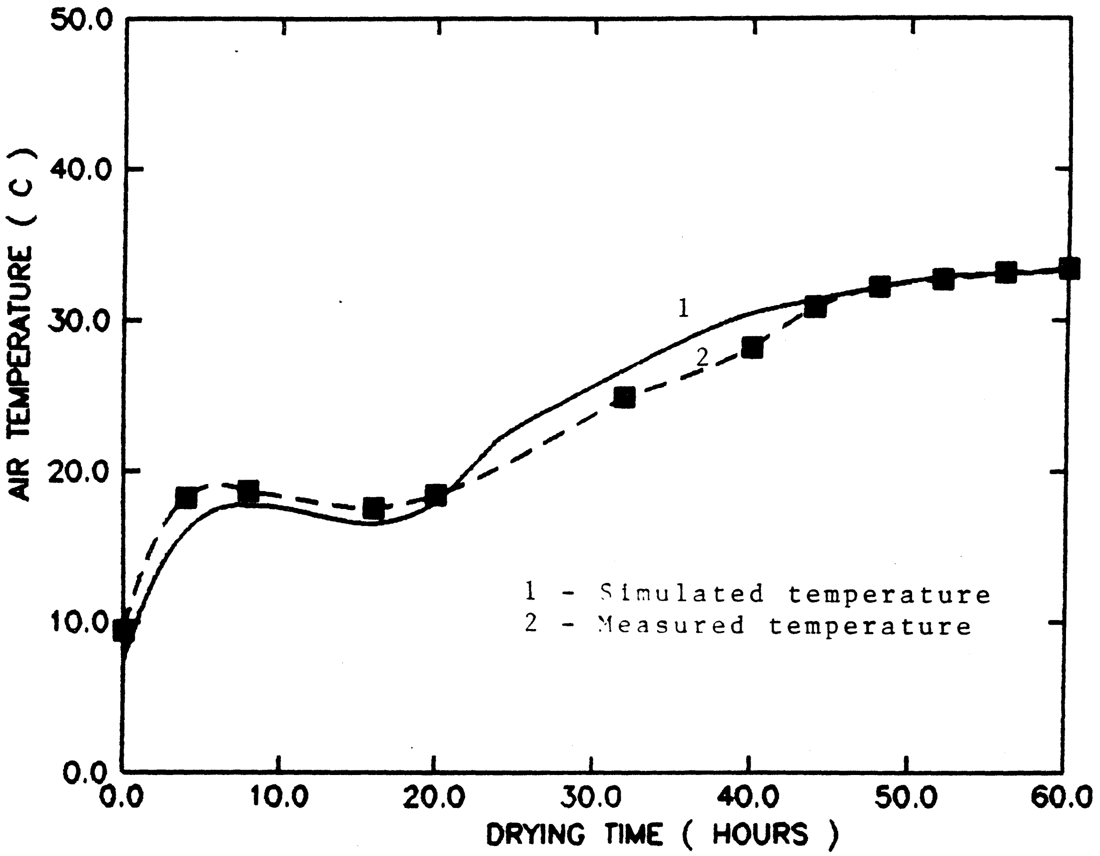

Figure 5.3. The measured and the simulated temperatures of air exiting the peanut bed in the 89 T1C1 experiment.

Table 5.2. The coefficients of correlation and the mean percentage deviations for the measured and the simulated values of air temperature at 1.0 m height from a selected number of experiments.

Experiment	Coefficient of Correlation	D_1 (D_2) (%)
89 T1C1	0.993	3.91 (+0.70)
89 T1C2	0.988	4.51 (+1.25)
89 T1C3	0.970	6.76 (+2.36)
89 T2C2	0.994	3.73 (-0.34)
89 T2C3	0.994	2.42 (+0.12)
89 T2C1	0.986	2.71 (+0.37)
89 T3C2	0.995	5.07 (-0.03)
89 T4C2	0.985	9.00 (-1.00)
89 T4C1	0.982	8.61 (-1.08)
88 T1C3	0.873	9.62 (+6.23)
88 T3C3	0.900	9.00 (+7.21)

Table 5.3. The coefficients of correlation and the mean percentage deviations for the measured and the simulated values of air humidity at 1.0 m height from a selected number of experiments.

Experiment	Coefficient of Correlation	$D_1 (D_2)$ (%)
89 T1C1	0.815	7.42 (+3.84)
89 T1C2	0.859	4.67 (+3.48)
89 T1C3	0.851	7.25 (-1.64)
89 T1C1	0.982	4.94 (-4.79)
89 T2C2	0.984	2.33 (-1.64)
89 T2C3	0.989	3.13 (+3.13)
89 T3C2	0.987	4.71 (+1.55)
89 T4C2	0.978	8.12 (+6.81)
89 T4C1	0.975	5.76 (-1.39)
88 T1C3	0.974	11.53 (-5.42)
88 T3C3	0.818	30.00 (-20.2)

Table 5.4. The coefficients of correlation and the mean percentage deviations for the measured and the simulated values of air temperature at 0.3 m height from a selected number of experiments.

Experiment	Coefficient of Correlation	$D_1 (D_2)$ (%)
89 T1C3	0.998	5.53 (+5.53)
89 T1C1	0.994	5.02 (-4.73)
89 T4C1	0.922	5.15 (-0.26)

Table 5.5. The coefficient of correlation and the mean percentage deviations for the measured and the simulated values of air temperature at 0.6 m height from a selected number of experiments.

Experiment	Coefficient of Correlation	$D_1 (D_2)$ (%)
89 T1C3	0.993	6.07 (+6.04)
89 T1C1	0.994	3.67 (-0.19)
89 T4C2	0.997	5.27 (-2.79)

Table 5.6. The coefficient of correlation and the mean percentage deviations for the measured and the simulated values of air temperature at 0.9 height from a selected number of experiments.

Experiment	Coefficient of Correlation	$D_1 (D_2)$ (%)
89 T1C2	0.991	4.05 (+1.32)
89 T1C1	0.994	8.07 (-8.07)
89 T2C2	0.986	5.71 (-3.21)

Table 5.7. The coefficient of correlation and the mean percentage deviations for the measured and the simulated values of top-layer moisture content from a selected number of experiments.

Experiment	Coefficient of Correlation	D_1 (D_2) (%)
89 T1C1	0.985	3.33 (+2.36)
89 T1C2	0.989	3.25 (-2.60)
89 T2C2	0.980	3.86 (-3.10)
89 T3C3	0.951	10.89 (+5.06)

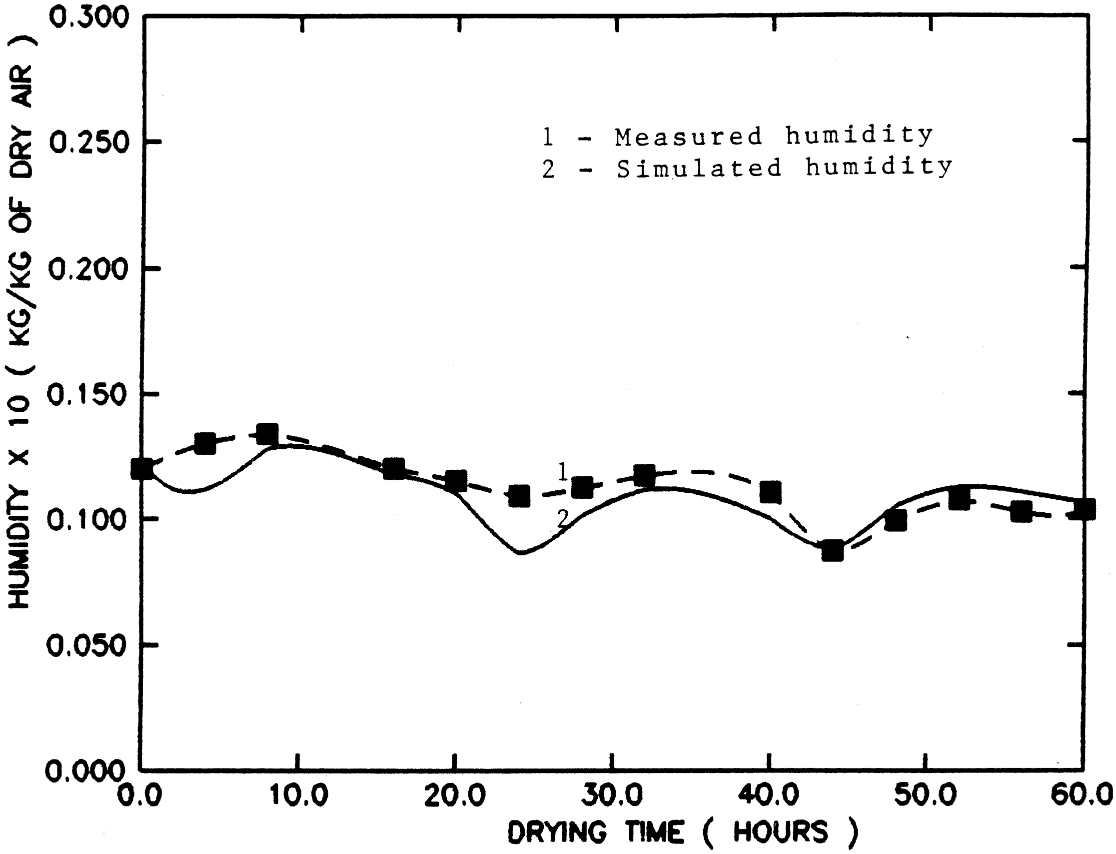

Figure 5.4. The measured and the simulated humidities of air exiting the peanut bed in the 89 T1C1 experiment.

The model simulated the air humidity and the temperature at the top of the bed reasonably well for the entire drying period; therefore, it can be deduced that the mathematical formulation of the heat and moisture transfer processes inside the bed was fairly accurate, and it can be expected that the moisture release rate from the peanuts calculated by the model at any position in the bed should be in close agreement with the actual moisture release rate. These results are clearly seen in Fig. 5.5, which shows the observed and the average moisture content (decimal, wet basis) of the top-layer basket plotted against drying time. The high correlation coefficient (0.985) and the low D_1 (3.3%) indicate an excellent agreement between the simulated and the measured values up to 36 hours of drying. The time taken for the drying front to reach the top layer was about 20 hours, and this time lag was accurately simulated by the model. Since the initial moisture content, 41% wet basis, was high, the drying front took a long time to reach the top layer in the bed; and, once it reached the top layer, drying proceeded at a slower pace than in bottom layers because of the high humidity and low temperature of the air reaching the top layer. Considerable electronic drift was observed in the load-cell readings after about 36 hours of drying; therefore, the measured data after 36 hours were not given in Fig. 5.5. This electronic-drift may have been caused by the inability of the load cell to cope with the weight change in a high humidity environment for a long period of time. This drift was not significantly present in 1987 and 1988 data, probably because the humidity levels in 1987 and 1988 tests were not as high as those in 1989 tests. The high humidity level experienced by the load cells was consistent throughout the drying period (Fig. 5.4).

The air temperatures measured at the 0.3, 0.6, and 0.9 m heights are additional indicators to check how well the model simulated the heat transfer process within the

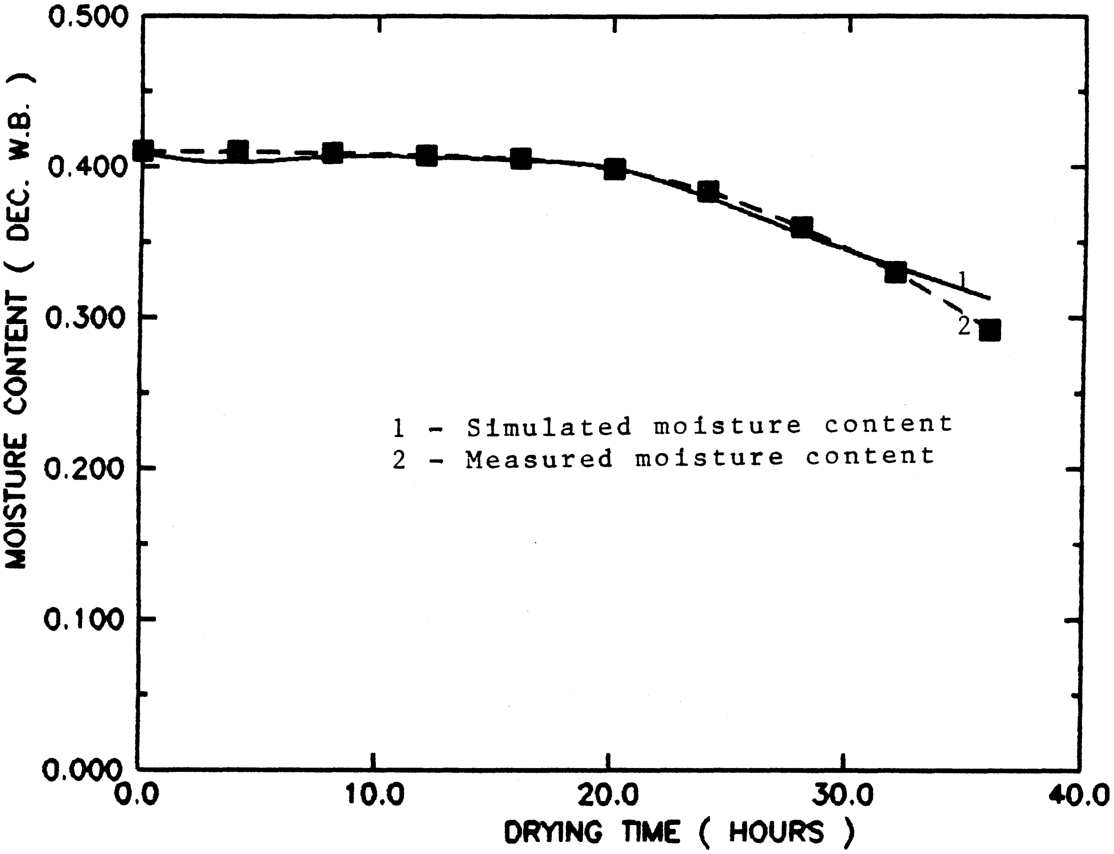

Figure 5.5. The measured and the simulated average moisture contents of the top-layer basket in the 89 T1C1 experiment.

bed (Fig. 5.6). There is reasonably good agreement between those two sets of values, as indicated by the high correlation coefficient of 0.993 for all three cases and the acceptable D_1 values of 5%, 3.7%, and 8% for the 0.3, 0.6, and 0.9 m locations, respectively. Some of the potential causes for error in measuring the air temperature inside the bed are:

1. Tips of the thermocouples are likely to be in contact with peanut surfaces which may have different temperatures than the drying air surrounding them.

2. Moisture in the air may condense on the thermocouple tips, changing the temperature experienced by the thermocouples. Such an effect is most likely to happen in the beginning of the drying period when the air humidity is closer to saturation.

3. Functional errors in the data logger may affect the readings. (Some data were lost due to malfunctioning of the printer in the data recorder during the 1989 tests.)

Even with these errors, the largest mean deviations of the air temperatures at the three locations were less than 8%; these facts increase confidence in the model.

The measured and the simulated values of variables in the 89 T2C2 experiment are given in Figs. 5.7, 5.8, 5.9, and 5.10. The air temperature at 1.0 m started from 10 C and raised to about 18 C within the first 4-5 hours and remained at approximately the same value for the next 18 hours, before beginning to increase up to

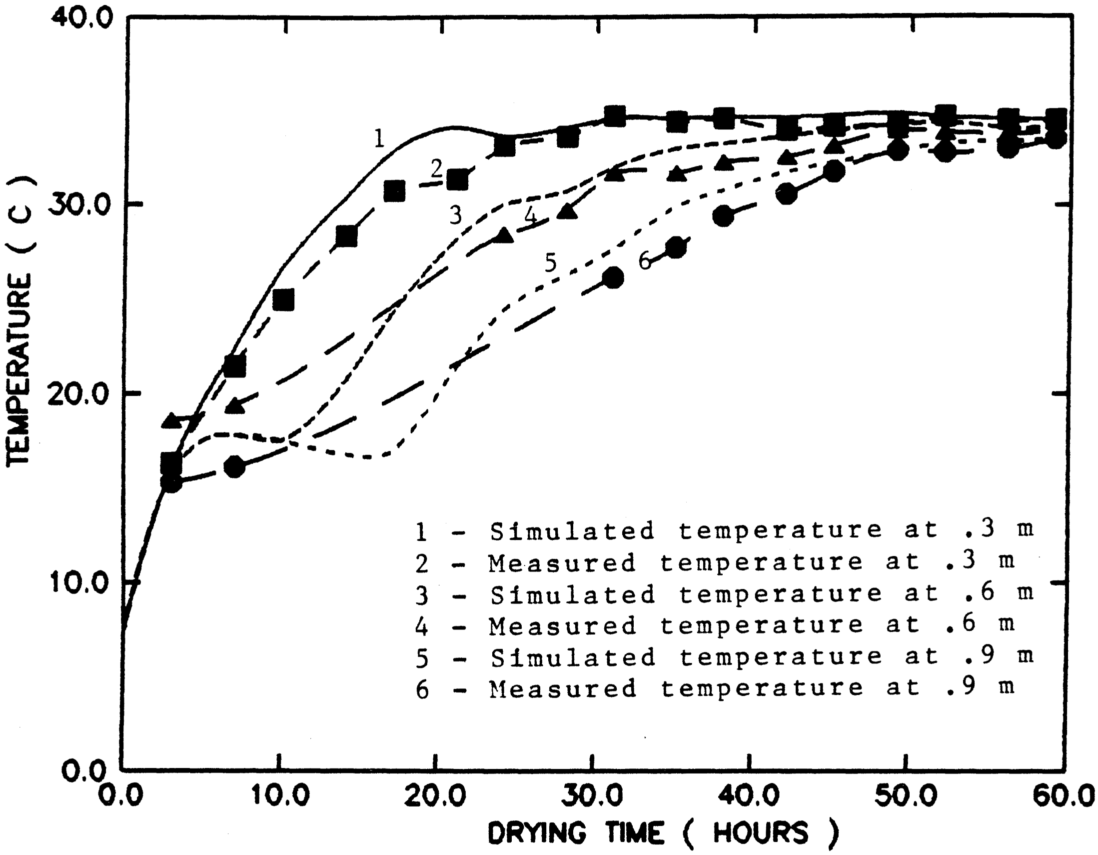

Figure 5.6. The measured and the simulated air temperatures at the 0.3, 0.6, and 0.9 m heights (89 T1C1 experiment).

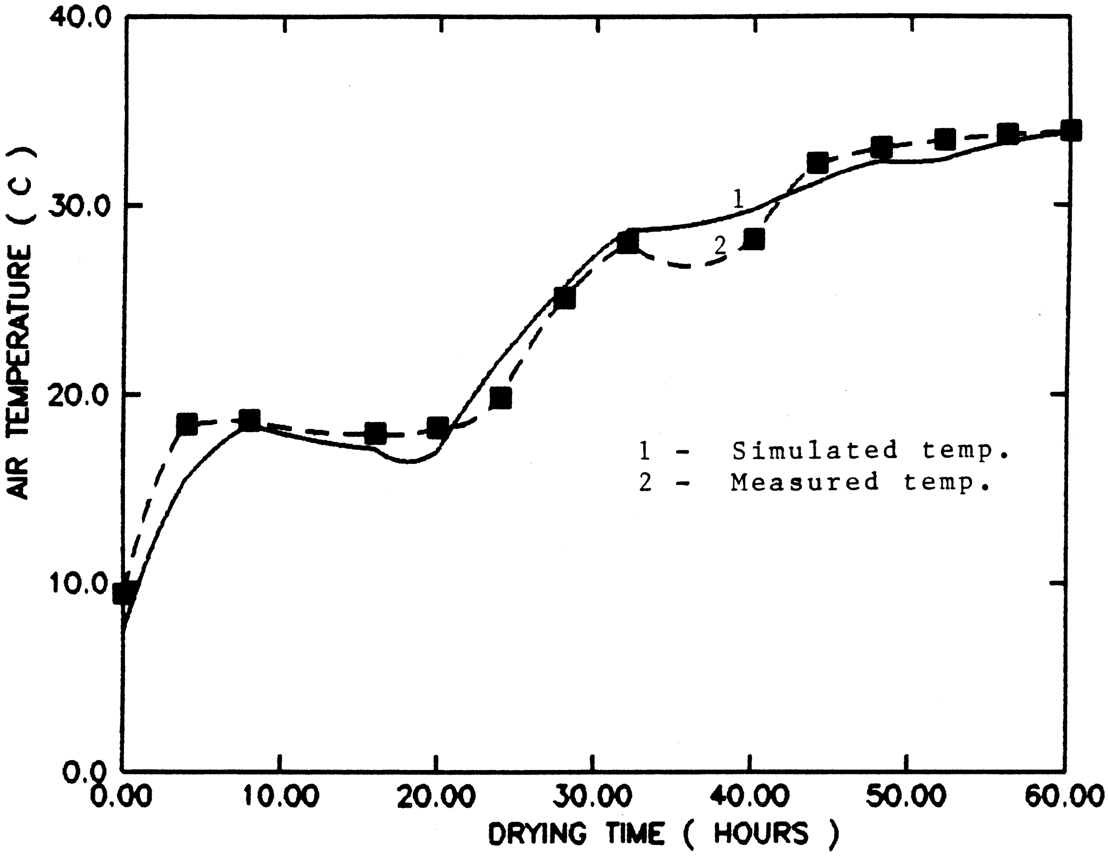

Figure 5.7. The measured and the simulated air temperatures at the 1.0 m height in the 89 T1C2 experiment.

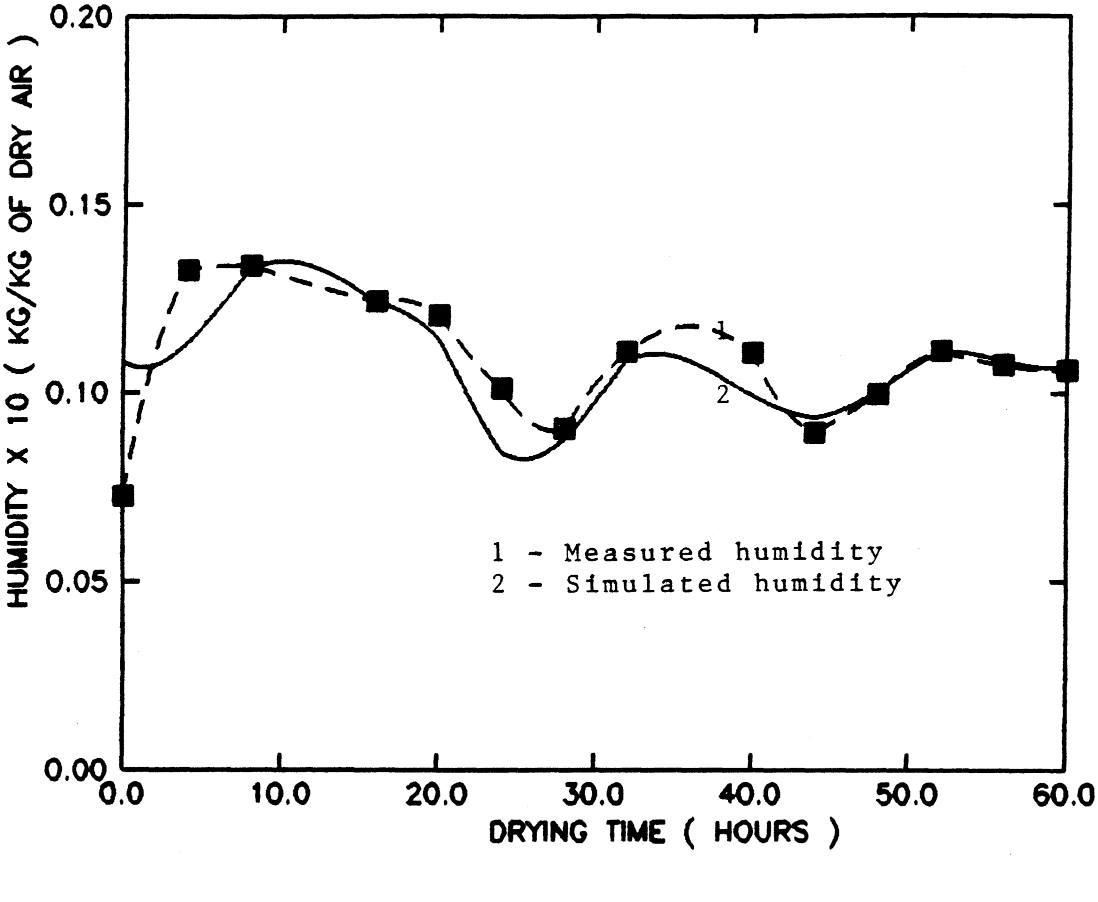

Figure 5.8. The measured and the simulated air humidities at the 1.0 m height in the 89 T1C2 experiment.

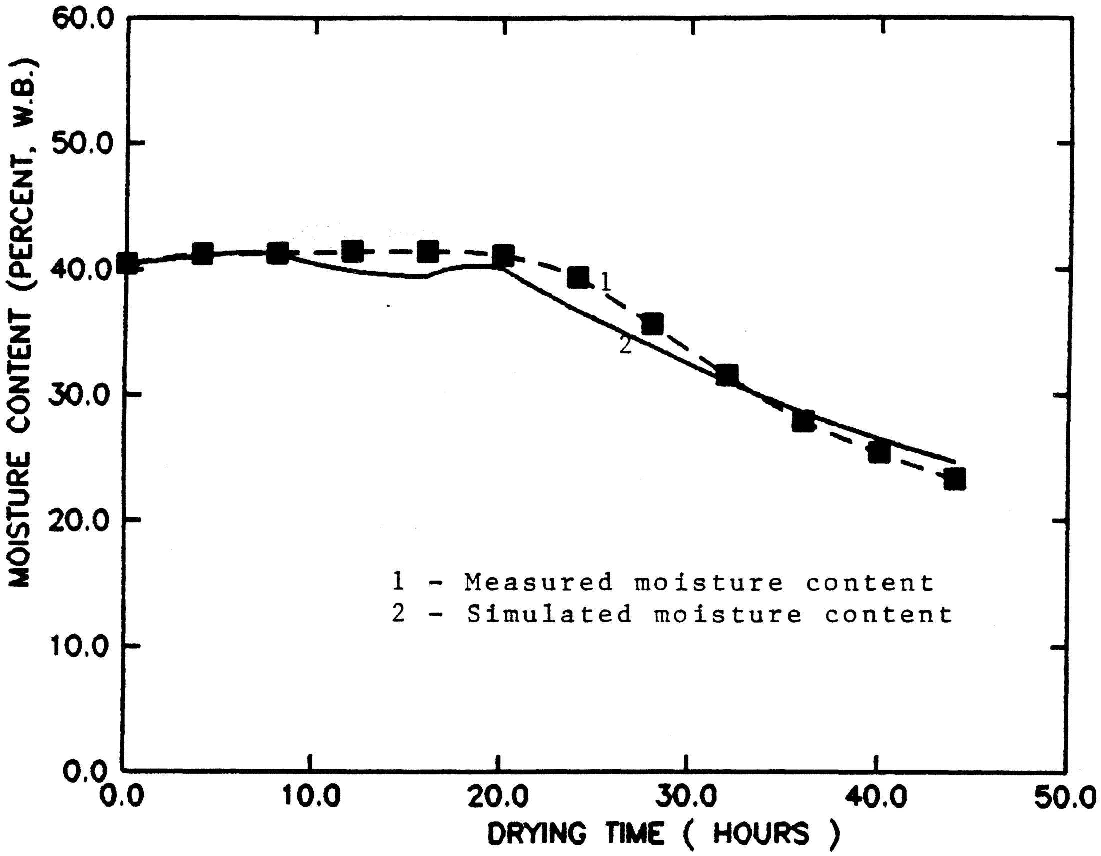

Figure 5.9. The measured and the simulated moisture contents of the top-layer basket in the 89 T1C2 experiment.

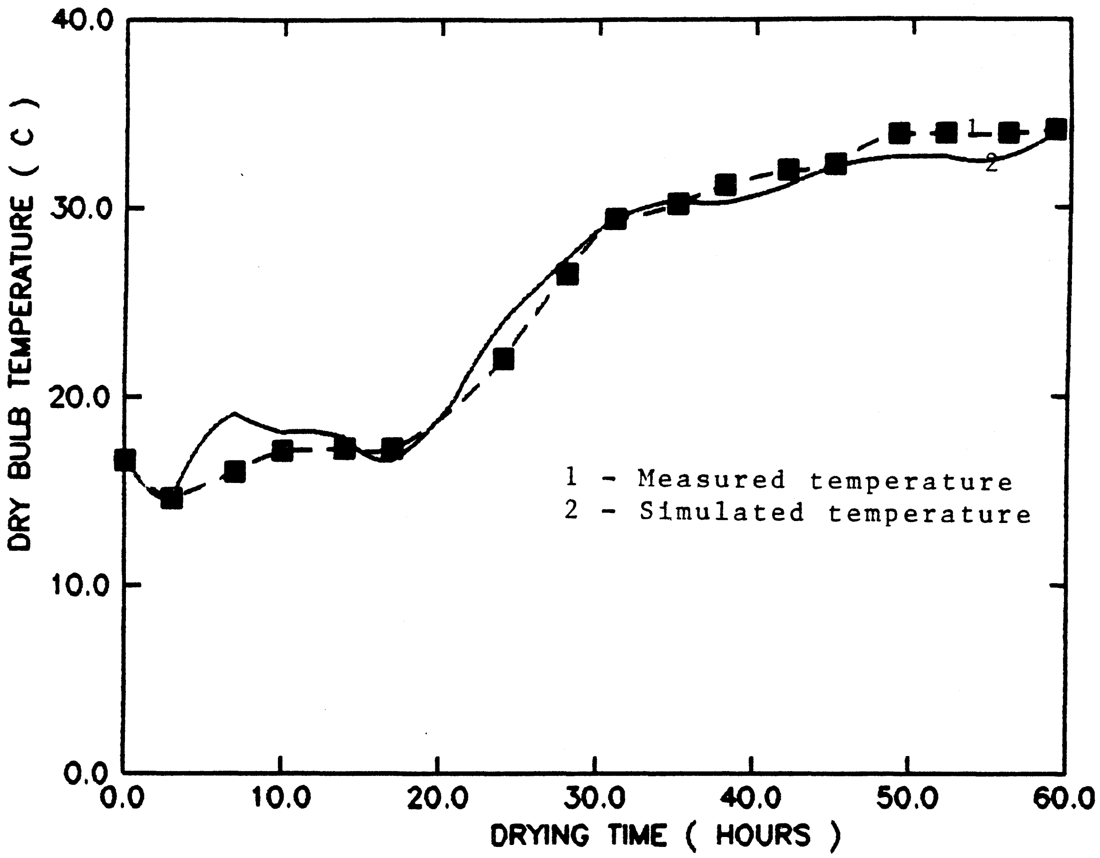

Figure 5.10. The measured and the simulated air temperatures at the 0.9 m height in the 89 T1C2 experiment.

near 35 C (Fig. 5.7). The simulated temperature also showed this pattern, and a strong relationship existed between the simulated and the measured temperatures, giving a high correlation coefficient (0.988) and low D_1 (4.5%) and D_2 (1.25%) values. As in the 89T1C1 experiment, there was a reasonably good agreement between the measured and the simulated values in air humidity at 1.0 m (Fig. 5.8). Notice that the model response during the first few hours was incompatible with the measured values in both cases. Had a smaller time increment been used, better results would have been obtained during the initial period of drying. Nevertheless, the maximum mean deviation over the entire drying period was less than 5%. The model simulated the top-layer moisture content well, with a D_1 of 3.25% and a correlation coefficient of 0.989 (Fig. 5.9), as can be deduced from Fig. 5.8. The simulated and the measured air temperatures at the 0.9 m height (Fig. 5.10) changed with time, as did the air temperature at the 1.0 m height (Fig. 5.7). The initial air temperature was higher at 0.9 m because of the local temperature rise due to respiration of the peanuts when kept in the column overnight prior to the start of the experiment. These local 'hot spots' can not be handled by the model; however, their effects was restricted to an initial period of less than two hours. For the 89 T1C2 simulation, a reasonable initial peanut temperature of 15 C was used.

The behavior of the simulated peanut temperature was examined to check whether it agreed with the theoretical understanding. One would expect the local peanut temperature to closely follow the air temperature at a given location, and the difference between the peanut and air temperatures to be governed by the past history of both air and peanut temperatures, specific heat of peanuts, airflow, convective heat transfer coefficient, specific surface area of peanuts, and relative humidity of air. (If the air is saturated, condensation of water vapor on peanut surfaces occurs, and peanut temperature is expected to remain almost constant.) The behavior of the simulated peanut and air temperatures at the 0.5 m height during the first 10 hours of the 89 T1C2 experiment is shown in Fig. 5.11. The assumed initial peanut temperature was 15 C, and while the air temperature experienced a slight drop during a 6-to-8 hour period, the peanut temperature did not decrease during that period but began to drop later. After the first hour the maximum difference between peanut and air temperatures was 2 C. The peanut temperature lagged behind the air temperature by approximately an hour during the first 10 hours. This time lag depends on the heat transfer resistance between air and peanuts, as discussed previously.

The variation in peanut temperatures in the bed can be examined by plotting the simulated peanut temperature with time at different locations (Fig. 5.12). At a location closer to the bottom, for example at 0.3 m, the peanut temperature increased steadily up to about 34 C, while at heights 0.6 and 0.9 m, a steady increase in temperature was preceded by a constant temperature period. During these periods, moisture content at the locations increased slightly, suggesting the occurrence of condensation (Fig. 5.13). Towards the end of the drying period, peanut temperatures throughout the bed approached the inlet air temperature, 35 C (Fig. 5.12).

The variation in the simulated moisture content (dry basis, decimal) over time at three different locations in the dryer is shown in Fig. 5.13 for the 89 T1C2 data. The drying front reached the peanuts at the 0.6 and 0.9 heights at about 10 and 15 hours after the drying experiment started, respectively. The rate of moisture release (gradient of the moisture curves) was lower at higher layers in the bed at a given time because the drying air gathered moisture, thus becoming closer to saturation, as

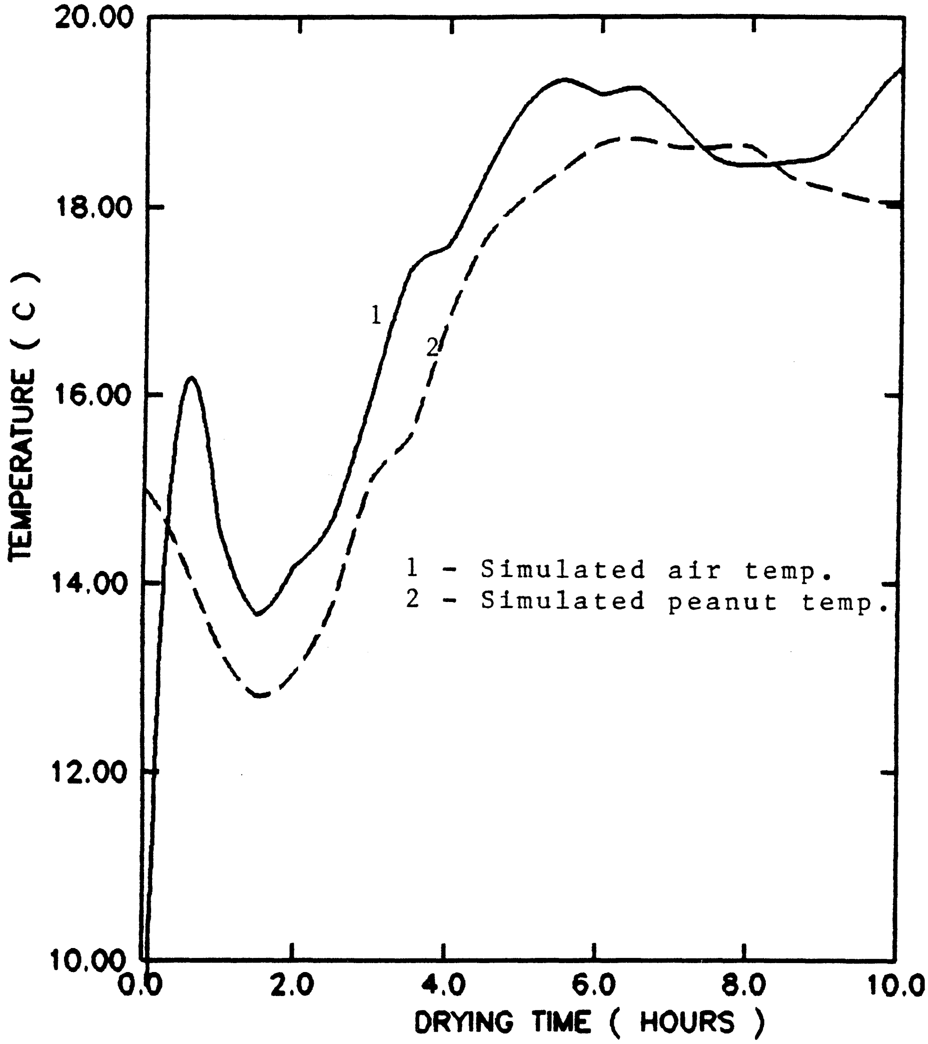

Figure 5.11. The behavior of the simulated air and the peanut temperatures at the 0.5 m height during the first 10 hours of the drying period in the 89 T1C2 experiment.

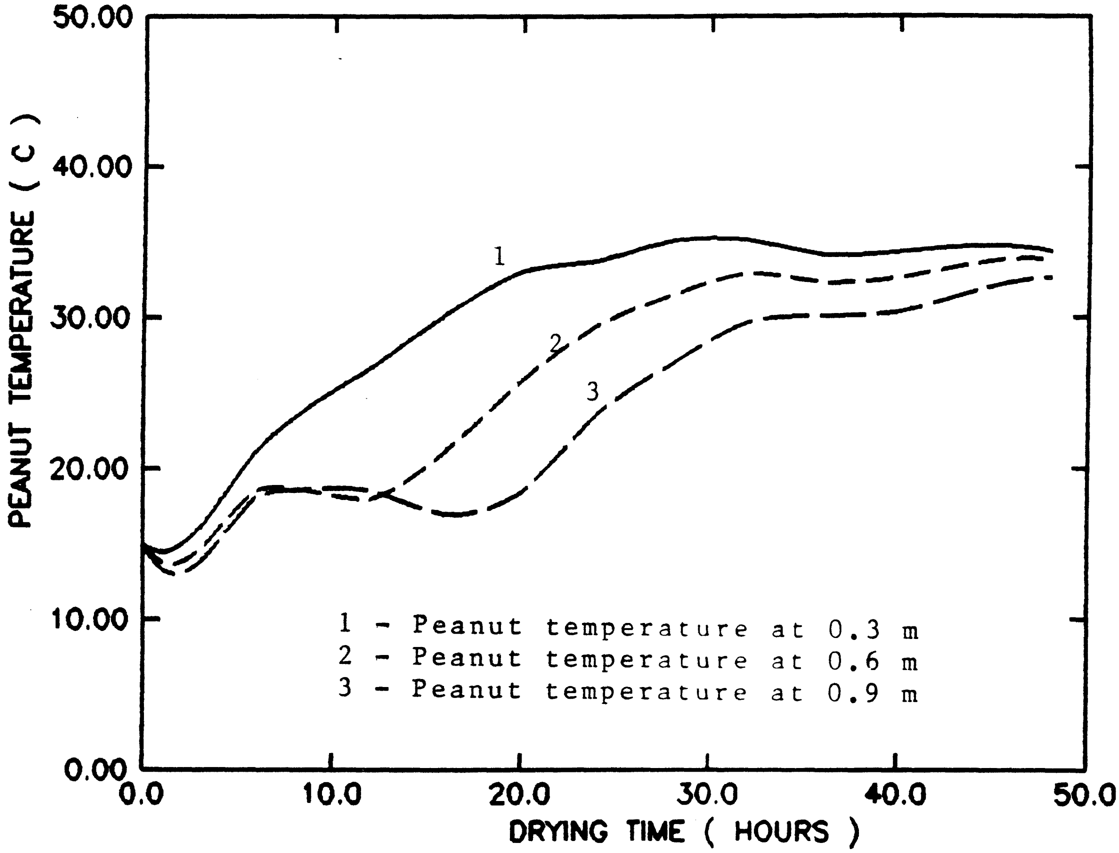

Figure 5.12. The simulated peanut temperature at three different heights, (0.3, 0.6, and 0.9 m) in the peanut bed (89 T1C2 experiment).

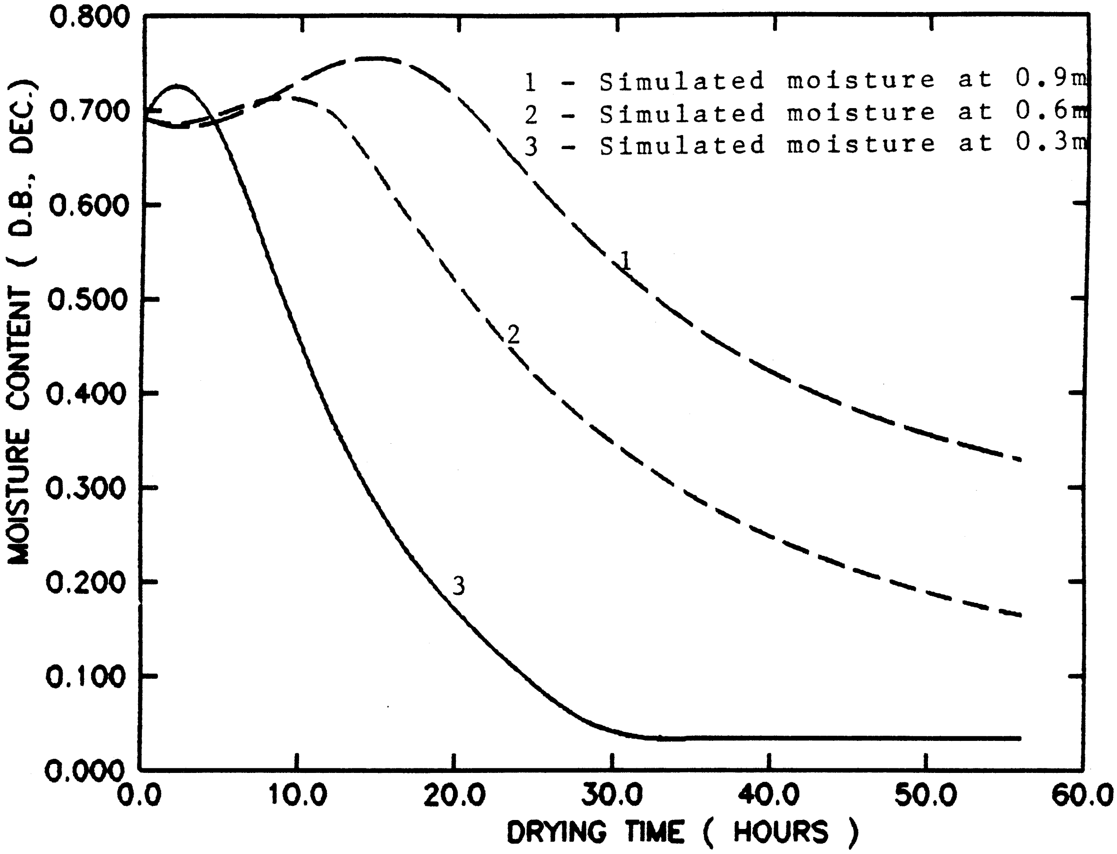

Figure 5.13. The simulated moisture content at three different heights (0.3, 0.6, and 0.9 m), showing the occurrence of condensation during the initial periods of drying (89 T1C2 experiment.)

it moved through the bed. The peanuts at the 0.3 m height dried down to a 5% moisture content (dry basis) and remained constant for the remainder of the drying period. This final moisture content was the equilibrium moisture content corresponding to the condition of the drying air. Since the air temperature at the 0.3 m height was close to 35 C, the maximum allowable drying air temperature for peanuts, after 30 hours of drying, the equilibrium moisture content could be expected to be as low as 5% dry basis (Beasley and Dickens, 1963). Accuracy of the simulated moisture content during the final hours of drying depends on the accuracy of the equilibrium moisture content model used.

As discussed previously, any discrepancy between the simulated and the measured temperatures and humidities at the 1.0 m height should be reflected in the simulated and the measured values of the moisture contents of peanuts, as shown in Figs. 5.14, 5.15, and 5.16, which are based on the 89 T1C3 experiment. The measured and the simulated air humidities had a correlation coefficient of 0.851 and a D_l of 7.3%. The model consistently predicted lower values for air humidity at the 1.0 m height throughout the drying period (Fig. 5.15), suggesting that the predicted moisture release should be lower than the actual moisture release. Thus, the predicted moisture content should be slightly higher than the actual moisture content. Fig. 5.16 gives the simulated and the measured average moisture contents of the top-layer basket; it can be seen that the simulated moisture content is slightly higher than the measured value, thereby increasing confidence in the validity of the model. Furthermore, as shown in Fig. 5.17, the measured and the simulated air temperatures at the 0.3 and 0.6 m heights in the 89 T1C3 experiment had an excellent correlation and acceptable D_l values, indicating that the transfer mechanisms were correctly formulated in the model.

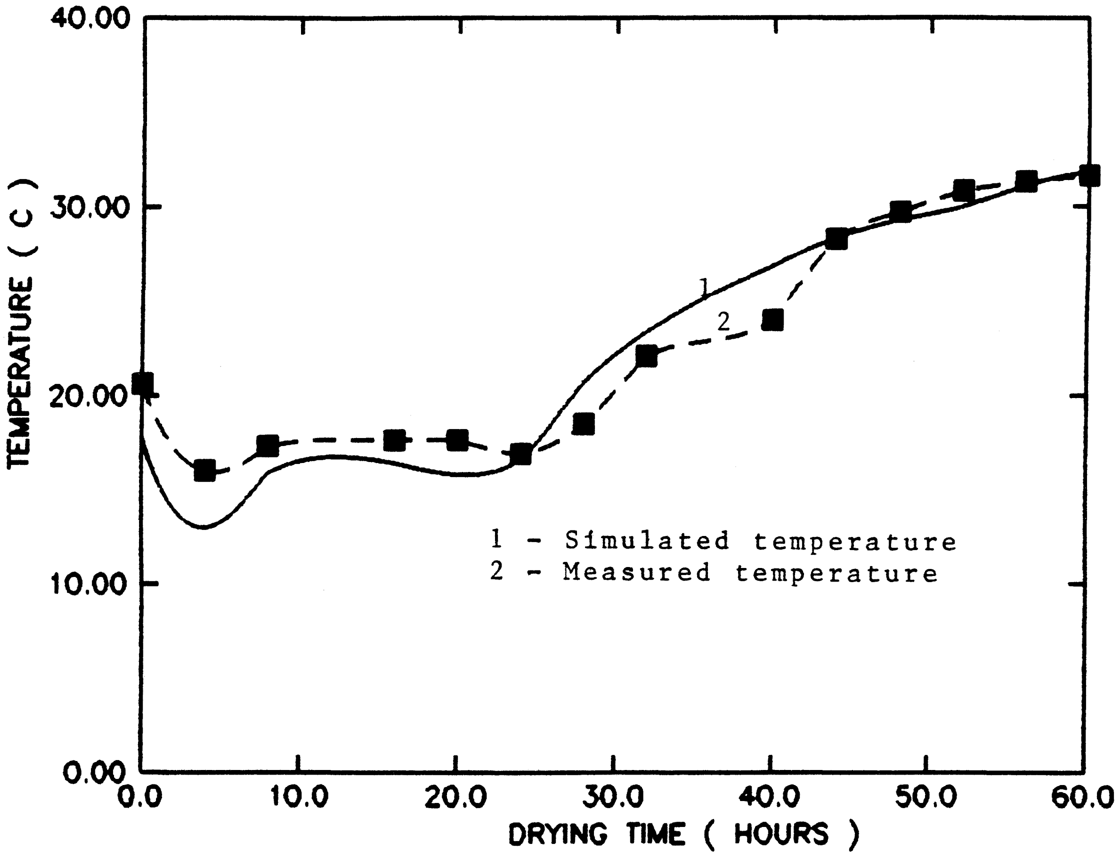

Figure 5.14. The measured and the simulated air temperatures at the 1.0 m height in the 89 T1C3 experiment.

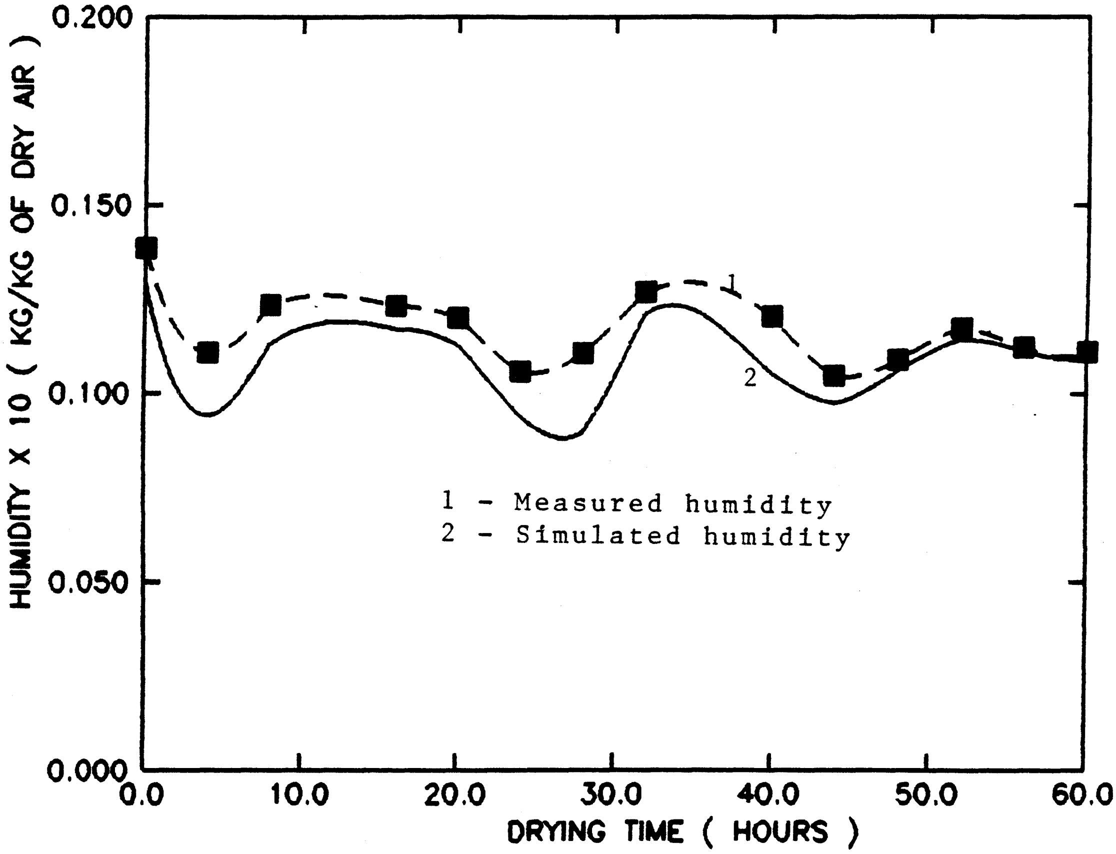

Figure 5.15. The measured and the simulated air humidities at the 1.0 m height in the 89 T1C3 experiment.

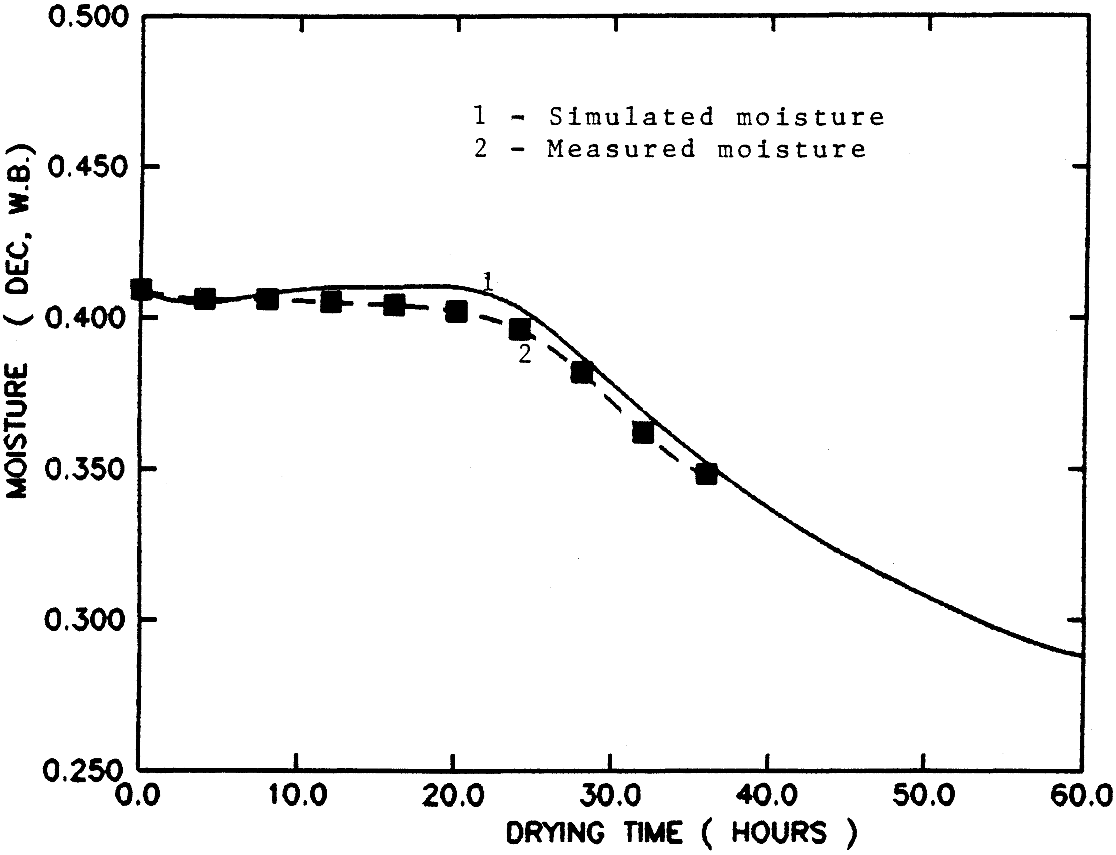

Figure 5.16. The measured and the simulated average moisture content of peanuts in the top-layer basket (89 T1C3 experiment).

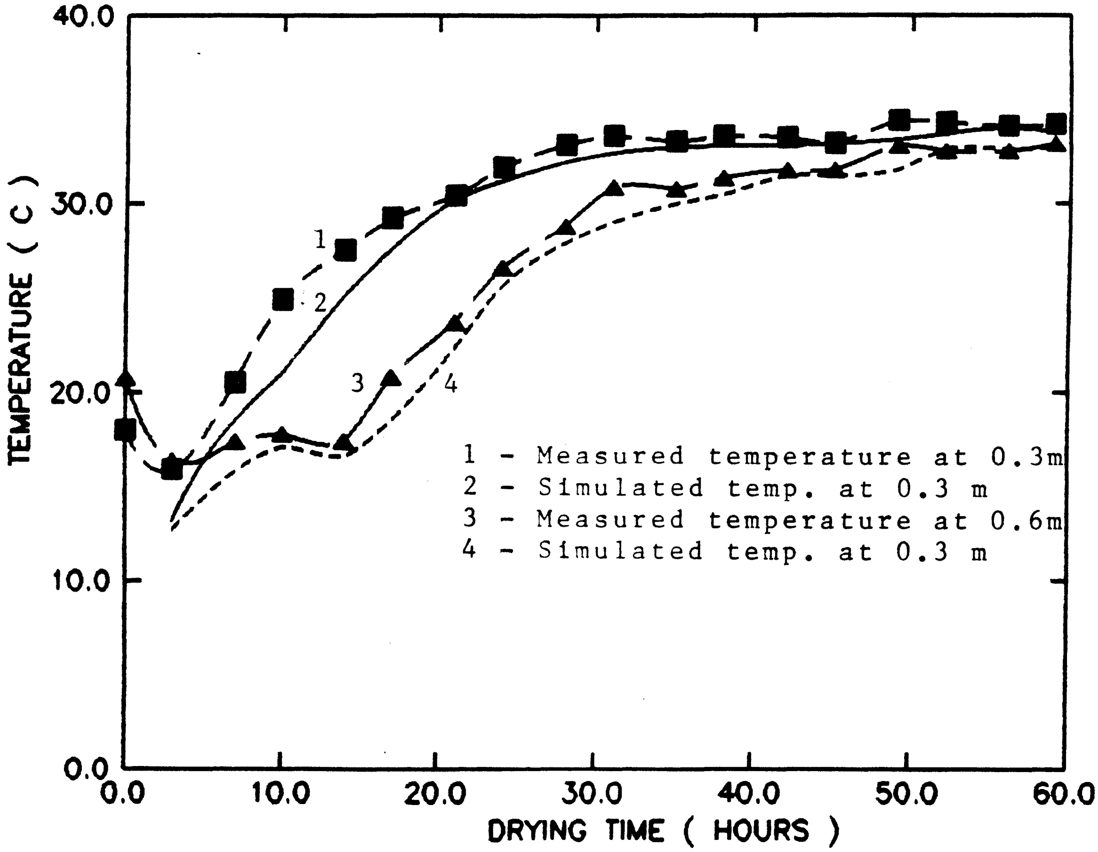

Figure 5.17. The measured and the simulated air temperatures at the 0.3 and 0.6 m heights in the 89 T1C3 experiments.

A case in which the model outputs agreed extremely well with the measured outputs for the same inputs was the 89 T2C2 experiment. The measured and the simulated air temperatures at the 1.0 m height had a correlation coefficient of 0.994 and a D_l value of 3.7%, and the measured and simulated air humidities were also in excellent agreement (Fig. 5.18, and 5.19). For the same experiment, the simulated final average moisture content agreed well with the measured final moisture content (Fig. 5.20).

The simulated moisture contents for the 89 T2C2 experiment were plotted against time for four different heights, 0.3, 0.5, 0.7, and 0.9 m (Fig. 5.21). The moisture content as a function of distance above the mesh screen was nonlinear. For example, at 30 hours the dry basis moisture contents of peanuts were approximately 5, 9, 22, and 33% at the 0.3, 0.5, 0.7, and 0.9 m heights, respectively. On the other hand, peanut temperatures were an inverse function of distance above the mesh screen (Fig. 5.22). At a given height, the time when the moisture content began to decrease was approximately equal to the time when peanut temperature started to increase, which is in accordance with heat and mass transfer theory.

The measured air temperatures inside the bed along with the corresponding simulated values for two different experiments, 89 T4C1 and 89 T4C2, are shown in Figs. 5.23 and 5.24. The model predictions compared favorably with the measured temperatures, even with the possible inaccuracies in temperature measurements inside the bed.

As mentioned above, the inlet air humidity and the dry bulb temperature were accurately measured in the 1989 tests, and, in addition, the thin layer equation used

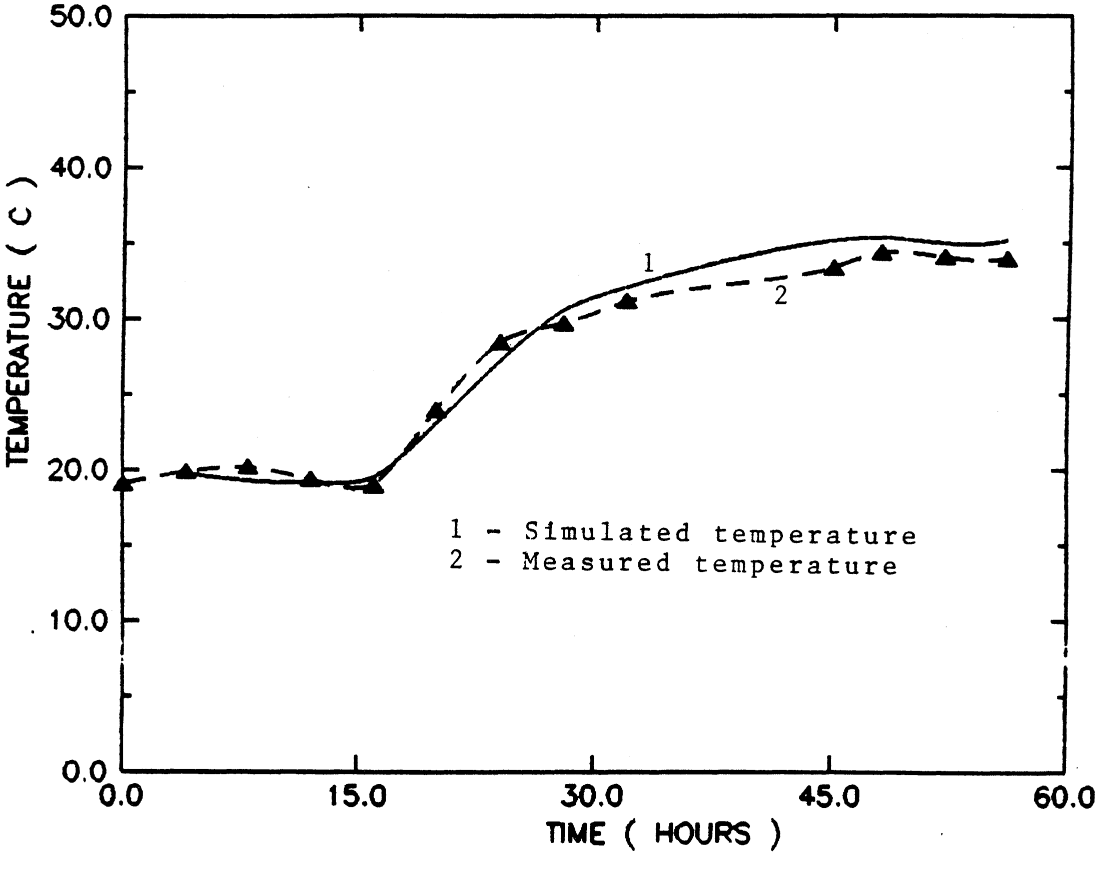

Figure 5.18. The measured and the simulated air temperatures at the 1.0 m height in the 89 T2C2 experiment.

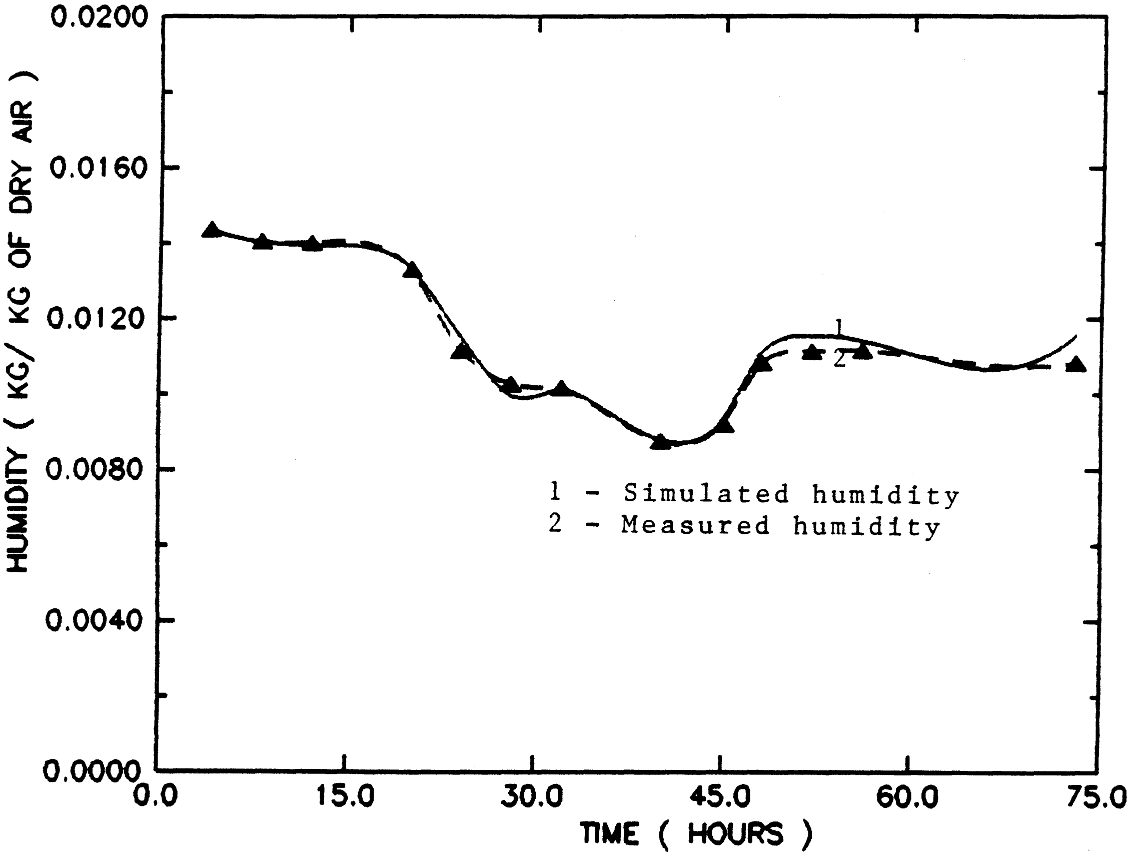

Figure 5.19. The measured and the simulated air humidities at the 1.0 m height in the 89 T2C2 experiment.

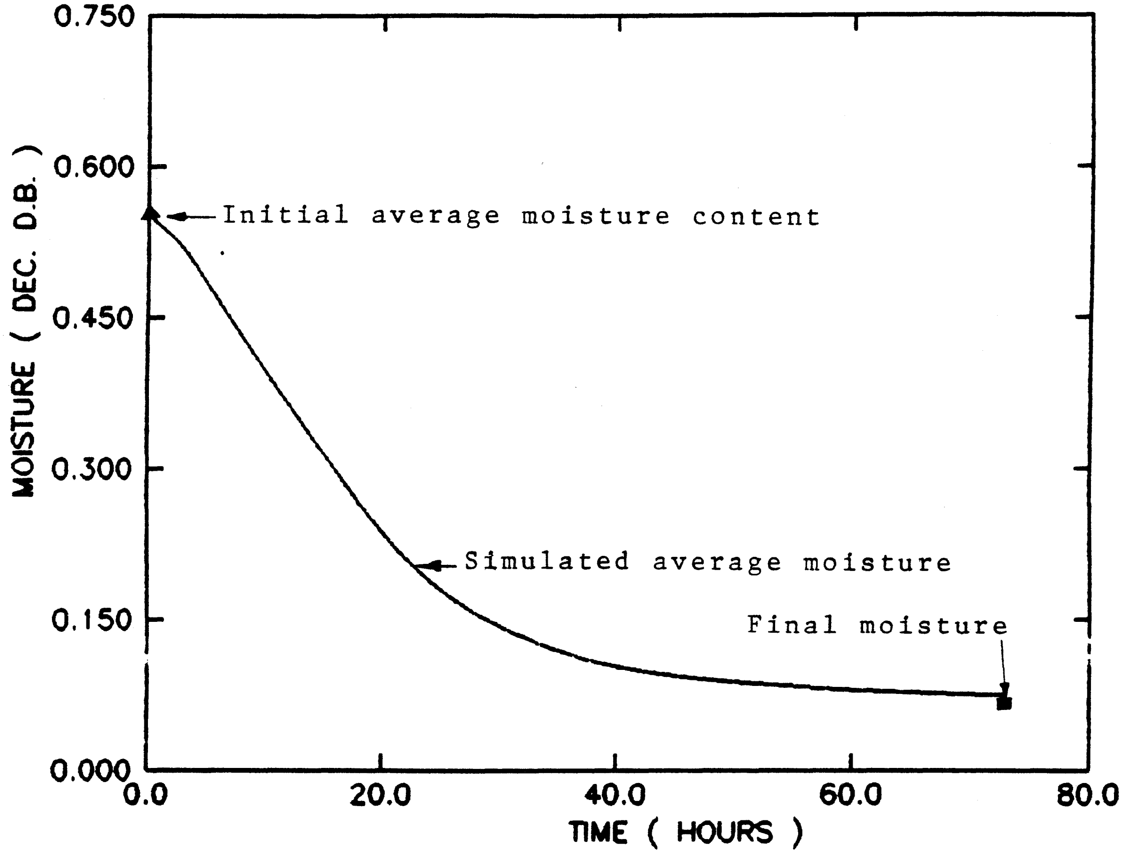

Figure 5.20. The simulated average moisture content of the dryer in the 89 T2C2 experiment.

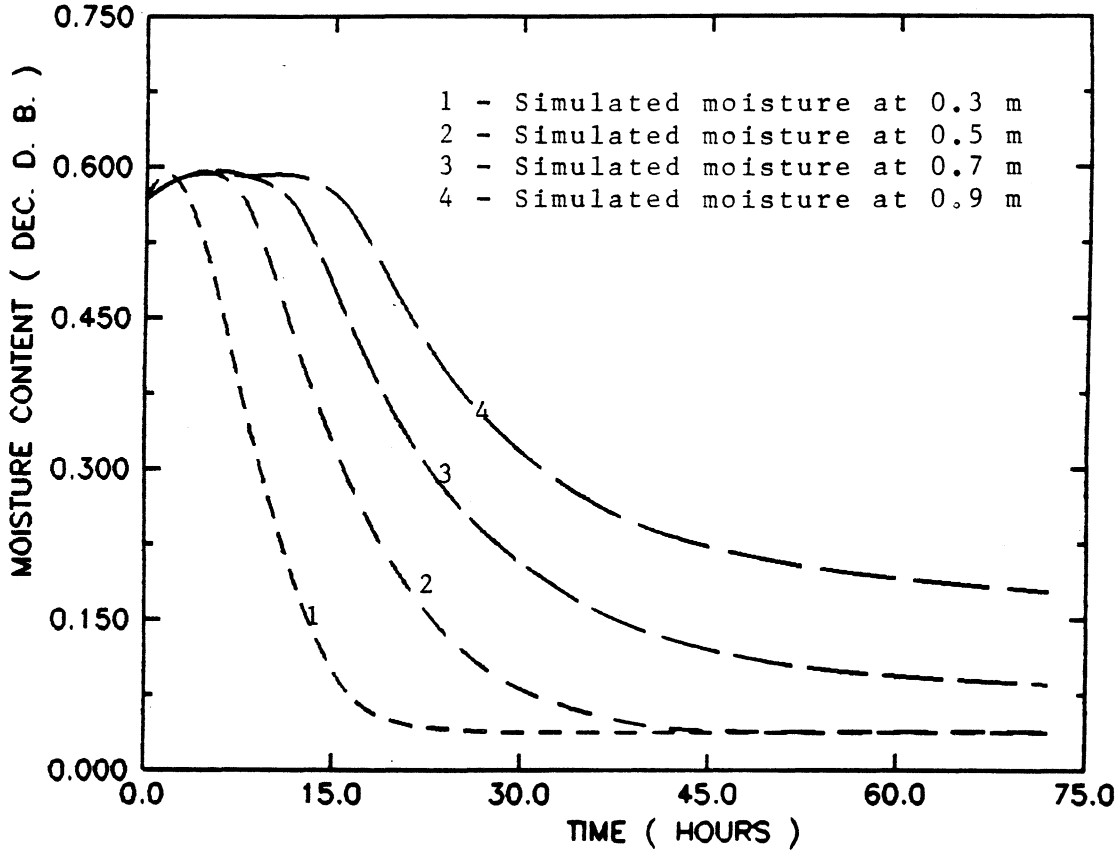

Figure 5.21. The simulated moisture contents at the 0.3, 0.5, 0.7, 0.9 m heights in the 89 T2C2 experiment.

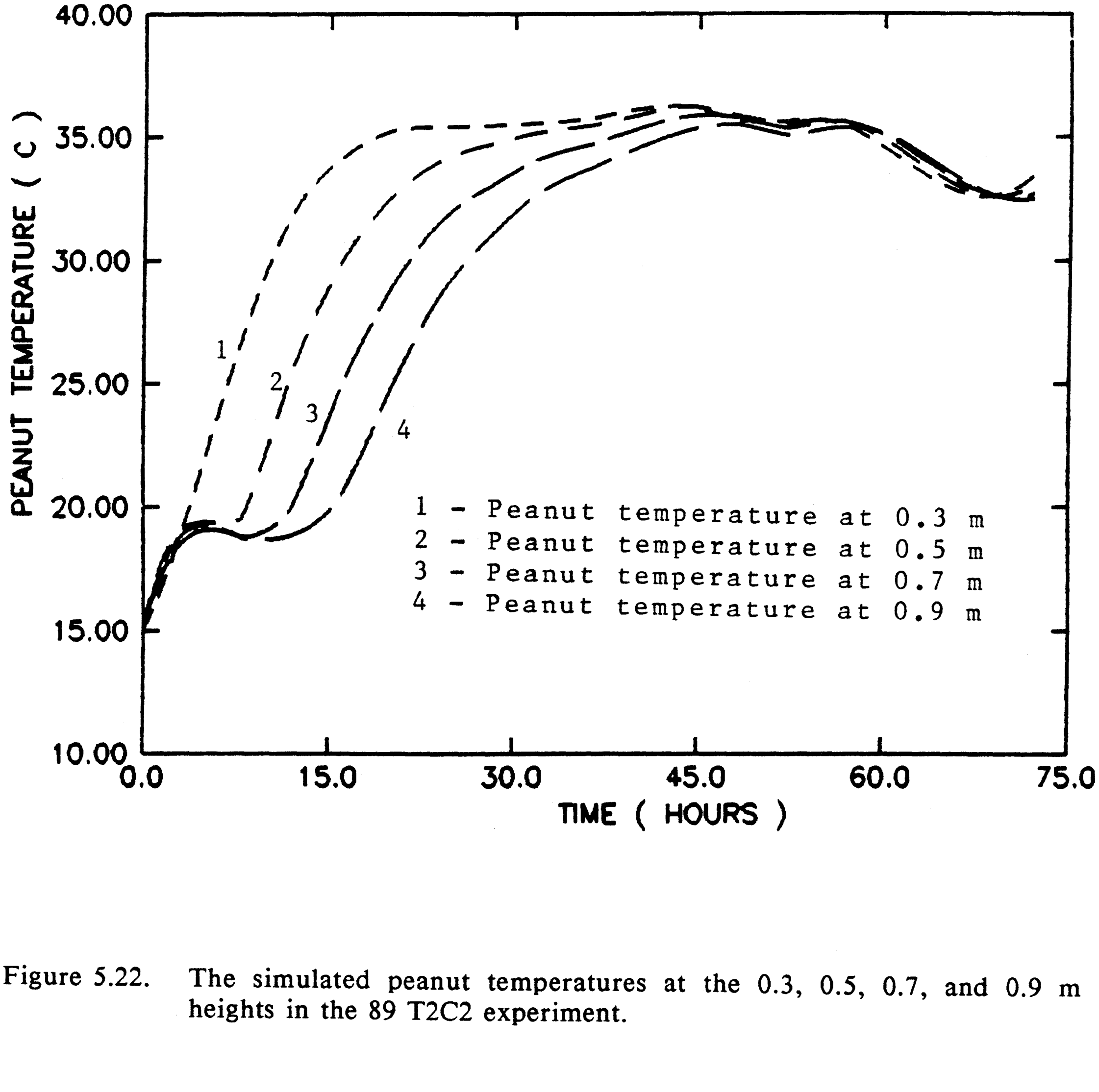

Figure 5.22. The simulated peanut temperatures at the 0.3, 0.5, 0.7, and 0.9 m heights in the 89 T2C2 experiment.

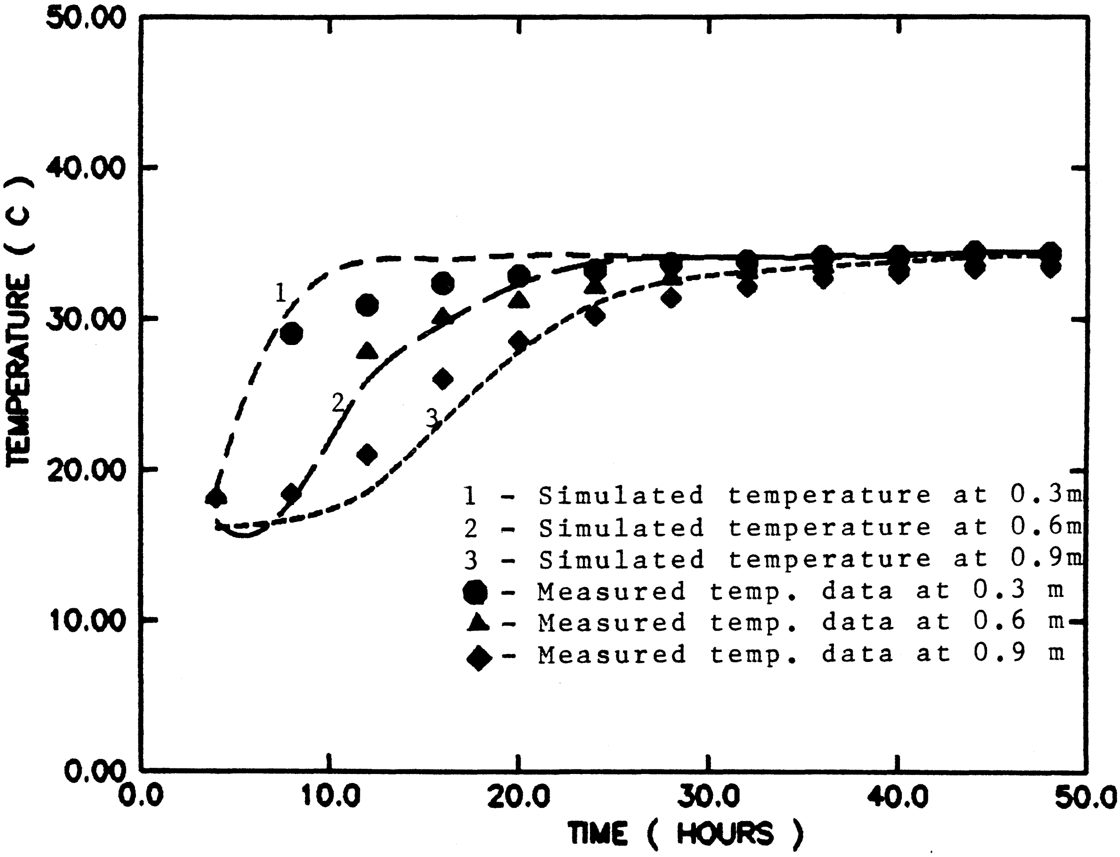

Figure 5.23. The simulated and the measured air temperatures at the 0.3, 0.6, and 0.9 m heights in the 89 T4C1 experiment.

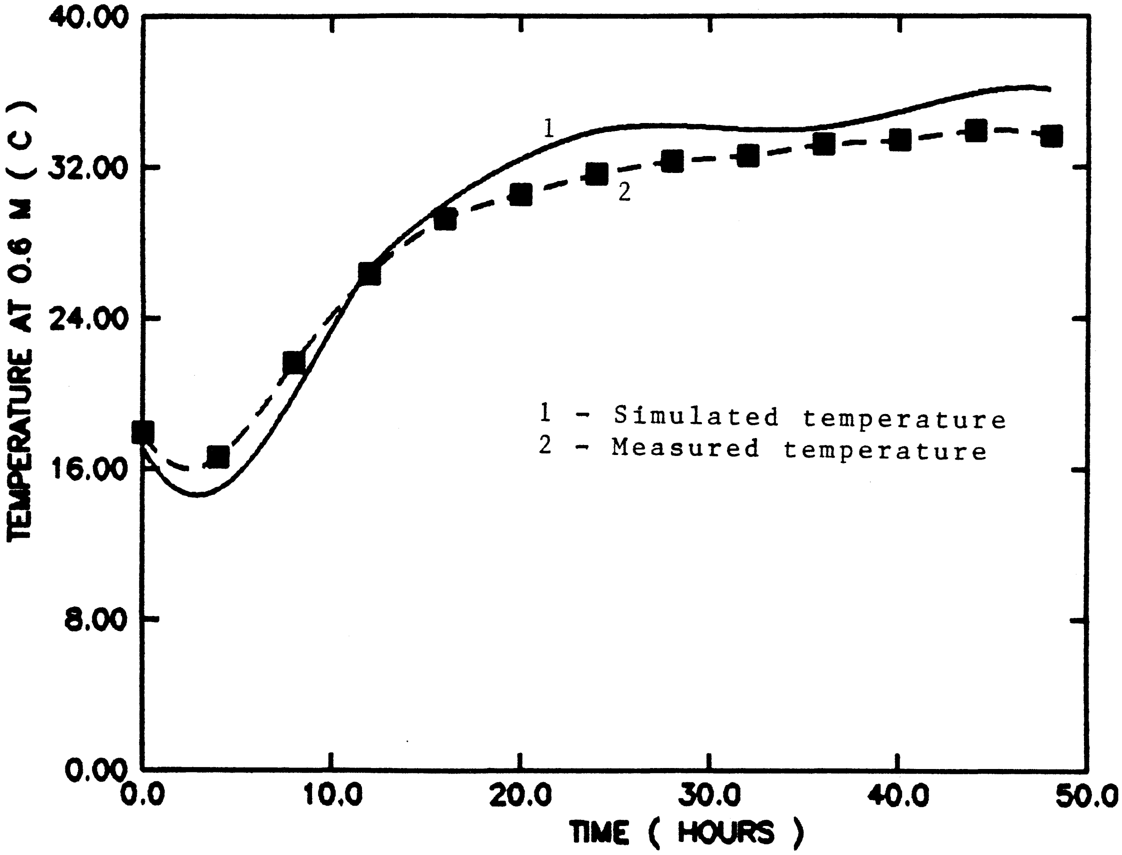

Figure 5.24. The measured and the simulated air temperatures at the 0.6 m height in the 89 T4C2 experiment.

in the model was developed using the same peanuts brought for the 1989 tests; therefore, the thin-layer equation and the model PEATECH are more likely to work well with the 1989 data. The model, however, predicted reasonably well for the experiments in 1987 and 1988. Since it is impossible to discuss each experiment individually, a fairly acceptable and an unacceptable scenario are discussed here. For example, the model simulated the humidity at 1.0 m reasonably well in the 88 T1C3 experiment, as seen in Table 5.3 and Fig. 5.25. D_1 and D_2 values for the simulated and the measured humidities, 11.5% and -5.4% respectively, were high but acceptable and the correlation coefficient, 0.974, was excellent. The high mean percentage deviations in air humidity at the 1.0 m height may be due to inaccurate inlet air humidity measurements and/or to inaccuracies introduced by the thin layer drying equation in the model.

Unacceptable agreement between simulated and measured results was found for the 88 T3C3 experiment. Inaccuracies introduced by the inputs were dominant. Fig. 5.26 shows the measured and the simulated air temperatures at the 1.0 m height for the experiment; the correlation coefficient and D_1 were 0.9 and 9%, respectively. Even though the simulated temperatures were acceptable, the simulated humidity had a D_1 of 30% and a correlation coefficient of 0.82, which are not acceptable (Fig. 5.27). (In this experiment, inlet air humidity was assumed to be equal to the ambient air humidity because there was no recirculation.) To check the accuracy of the measured air humidities, the measured air humidity at 1.0 m and the ambient air humidity (the inlet air humidity) were plotted (Fig. 5.28). As seen in Fig. 5.28, there were periods in which the measured humidity exiting the bed was less than the corresponding inlet air humidity, something that cannot happen in a drying process. Therefore, the measurements were inaccurate. When the inaccurate values were used,

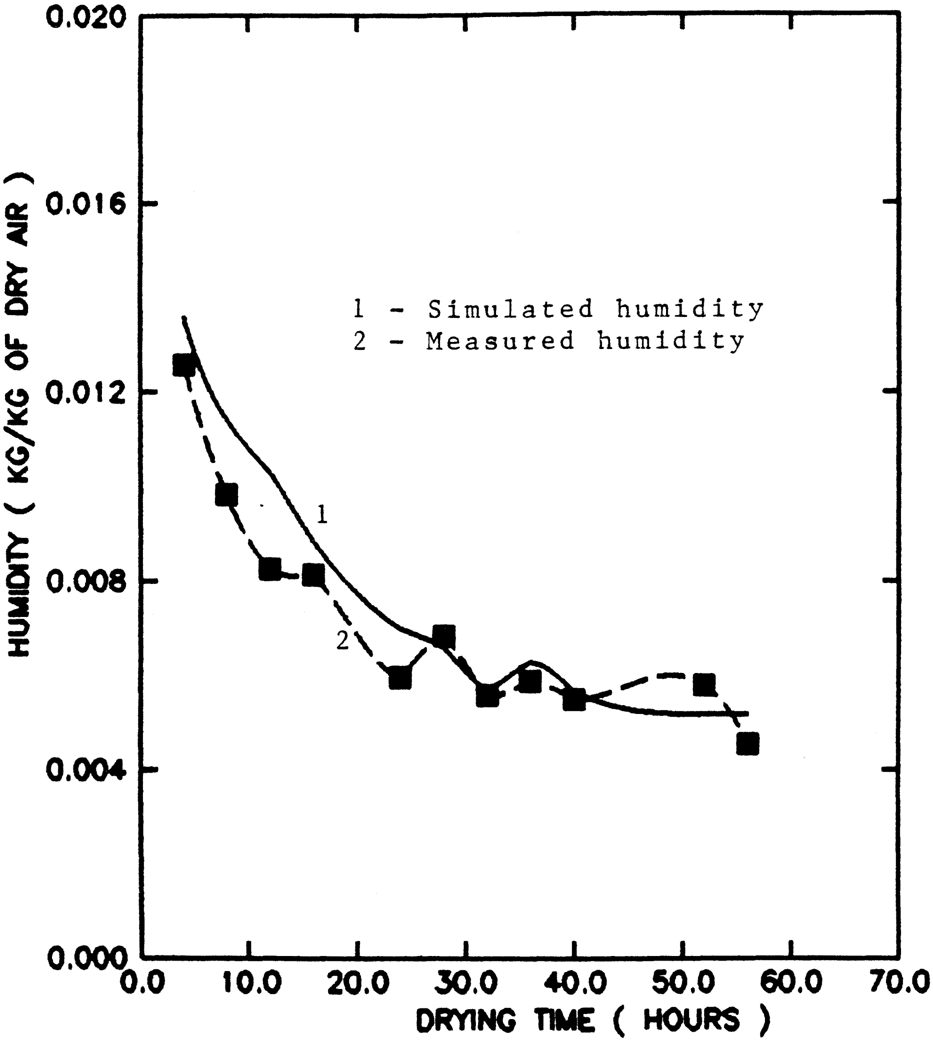

Figure 5.25. The measured and the simulated air humidities at the 1.0 m height in the 88 T1C3 experiment.

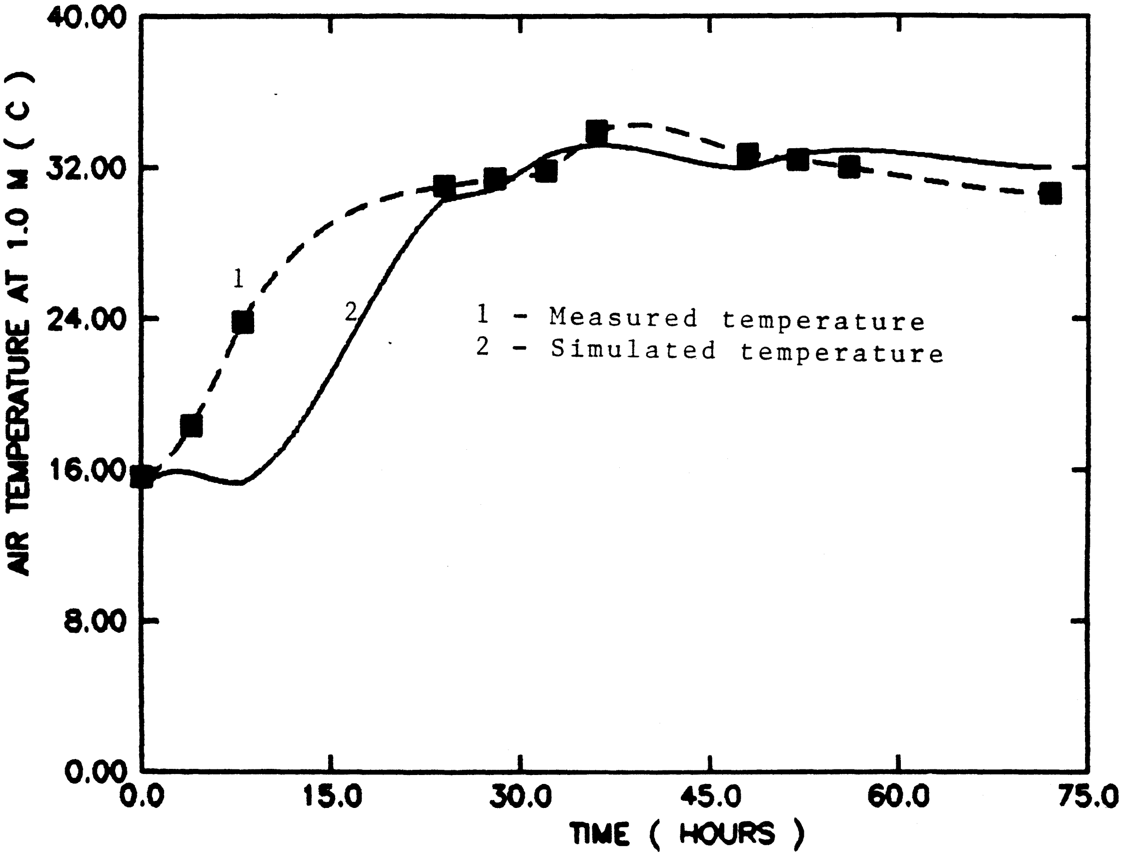

Figure 5.26. The measured and the simulated air temperatures at the 1.0 m height in the 88 T3C3 experiment.

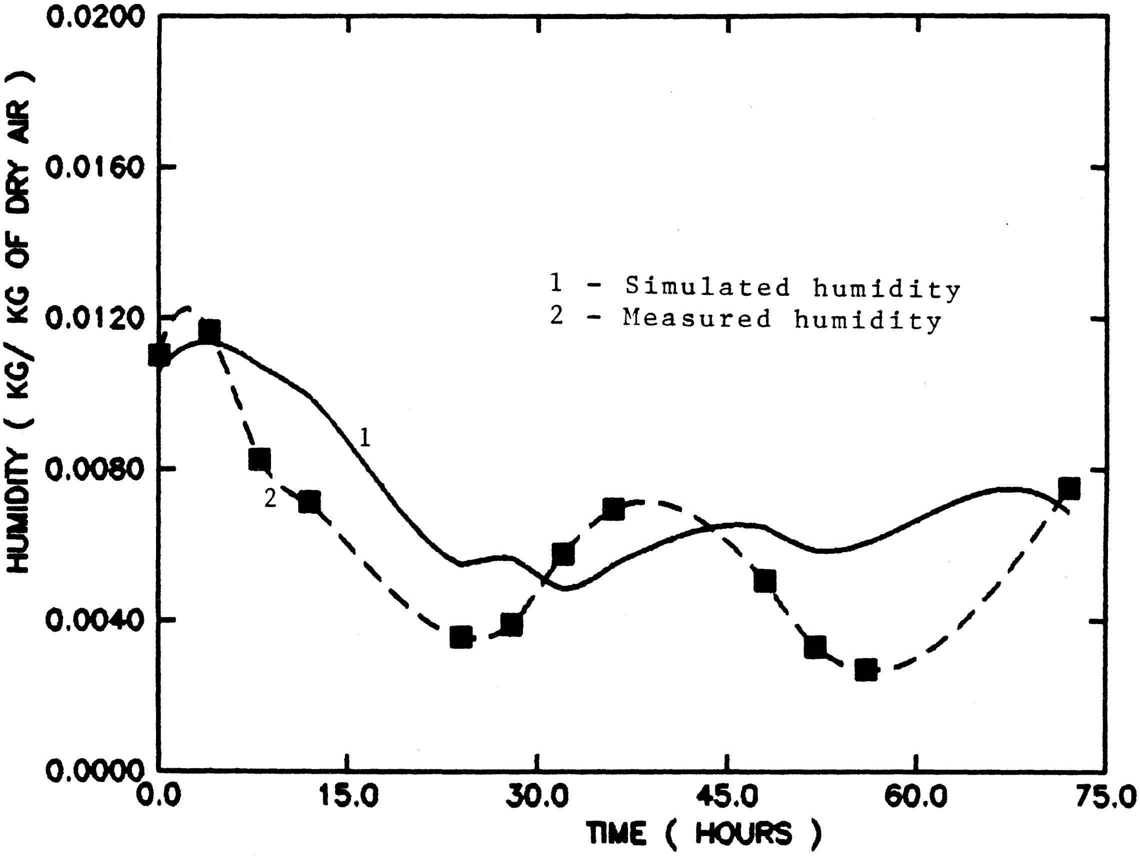

Figure 5.27. The measured and the simulated air humidities at the 1.0 m height in the 88 T3C3 experiment.

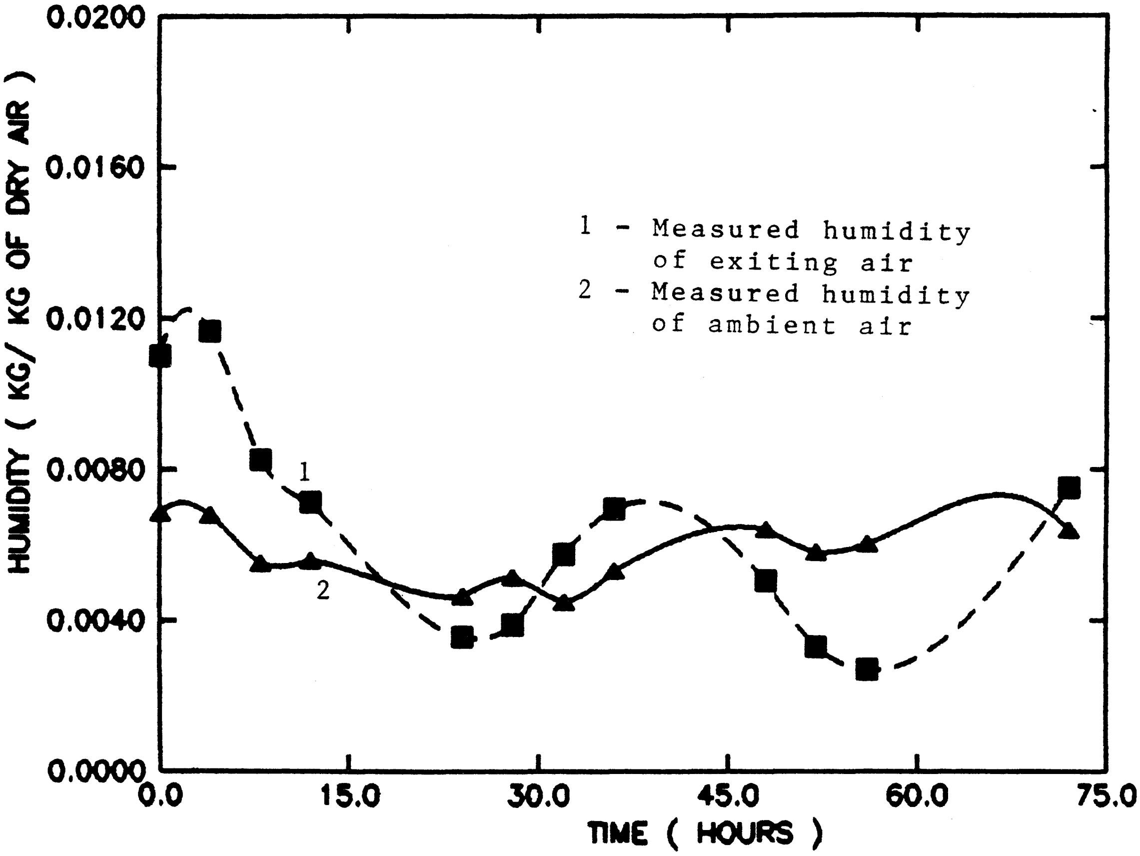

Figure 5.28. The measured air humidity at the 1.0 m and the ambient air humidity in the 88 T3C3 experiment.

the simulated top-layer moisture content also deviated from the measured average moisture content by 10%.

If input air humidity is measured as in the 1989 tests, the measured inlet, exit, and ambient air should relate properly to each other; inlet and ambient humidities should be approximately equal or lower than the exit humidity. These relationships are illustrated in Fig. 5.30, a plot of the measured humidities in the 89 T2C3 experiment. Notice that the ambient air humidity was not exactly equal to inlet air humidity, but both humidities were less than the exit humidity throughout the drying period. At 45 hours, for example, the difference between the ambient air and the inlet air humidities was 45% of the difference between the humidities of the air at the 1.0 m height and of the inlet air. Therefore, it is important to measure the humidity of the inlet air directly without assuming it to be equal to the ambient air humidity.

5.4. Conclusions and Recommendations

The following conclusions can be derived from this study:

1. The deep-bed drying model for Virginia peanuts, PEATECH, accurately simulates the drying process of Virginia peanuts in a fixed-bed dryer, provided that the inputs are accurate and an accurate thin-layer equation is used.

2. The model has a sound theoretical foundation which provides acceptable relationships among the variables in the drying process: air humidity, air temperature, peanut moisture content, and peanut temperature.

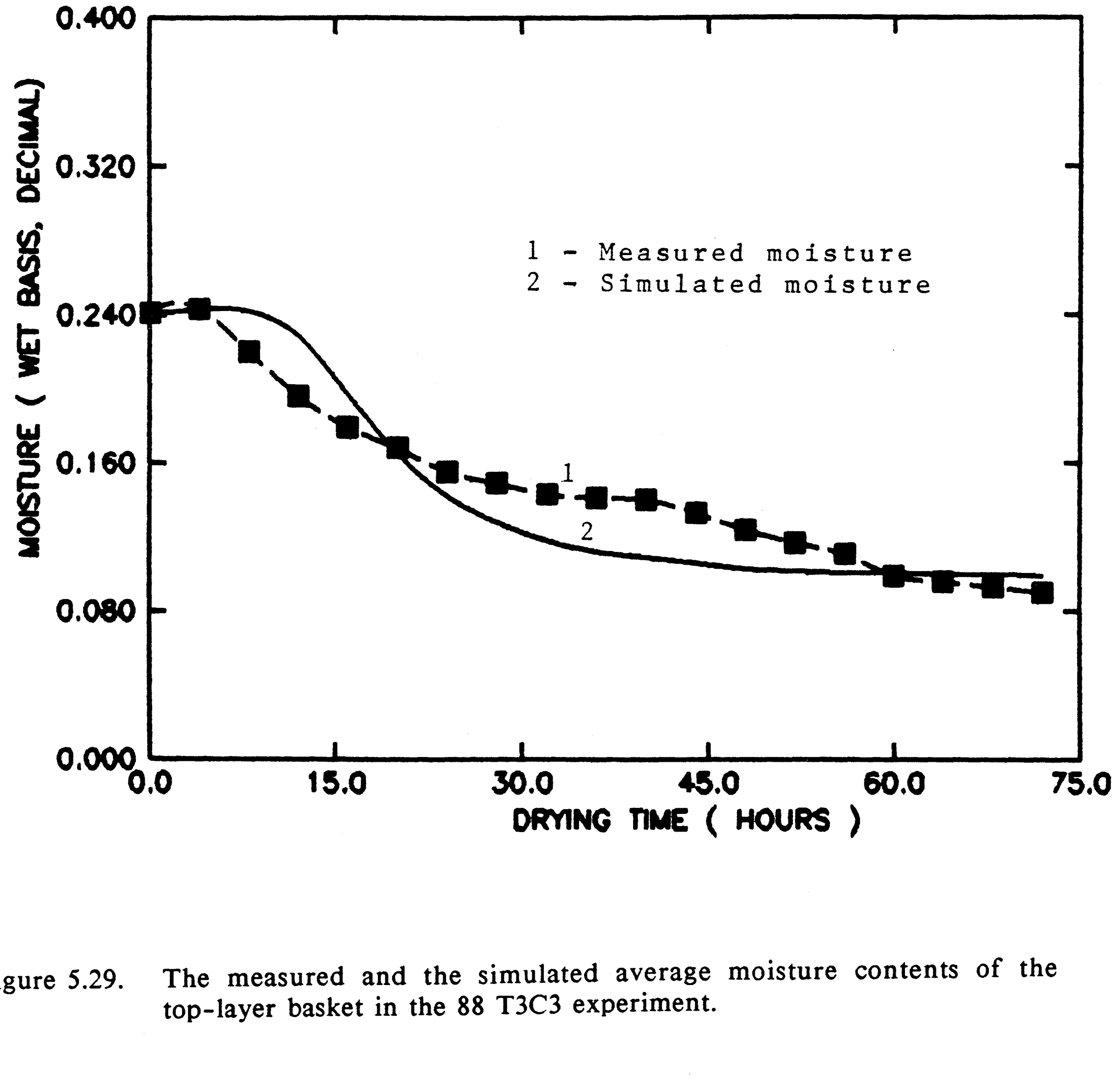

Figure 5.29. The measured and the simulated average moisture contents of the top-layer basket in the 88 T3C3 experiment.

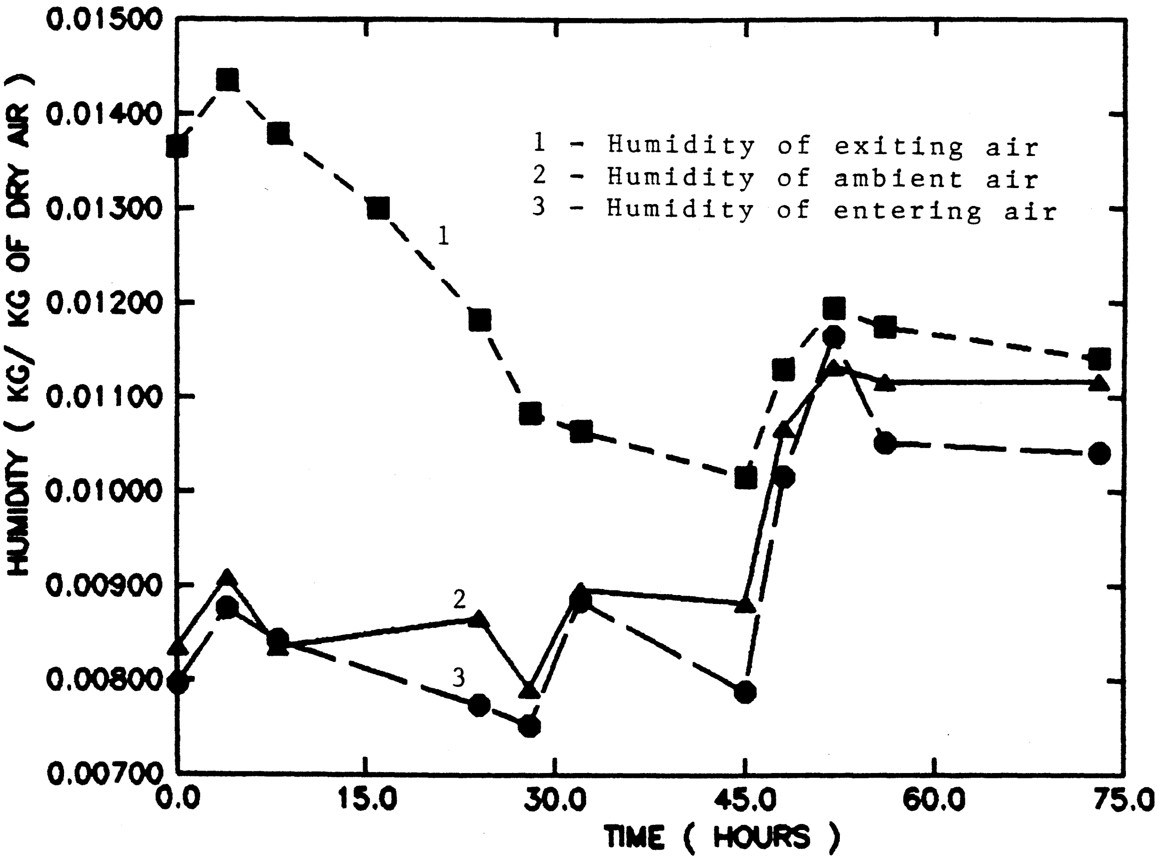

Figure 5.30. The measured humidities of air at the 1.0 m height, ambient air, and inlet air in the 89 T2C3 experiment.

3. The numerical procedure used in solving the simultaneous partial differential equations was adequate and accurate enough for engineering purposes.

The following recommendations are given for future research:

1. PEATECH gives an adequate simulation of the peanut drying process, if the thin-layer model is accurate. Therefore, serious attention should be given to developing a thin-layer model based on data from many years of tests including variabilities in initial moisture content and biological maturity at harvest; the model should be sensitive to extremely high and low air humidities. Further, the thin-layer model should be developed to accommodate the effects of airflow.

2. The peanut temperature simulated by PEATECH should be tested with experimental data.

Chapter 6

Energy Conservation in Peanut Drying

6.1 Introduction

Energy conservation in agriculture was not given prominence as a part of the energy policy of the United States during the last decade. The crisis in the Persian Gulf, with potential disruption of world oil supplies, should renew the interest in energy conservation and alternative energy sources to make the agricultural sector less dependent on imported oil. Efficient on-farm production has been the foundation of the U.S. economy. Higher on-farm production costs will increase inflation and encourage the importation of food items. Farmers should be encouraged to conserve energy in existing operations and to use locally available energy supplies as much as possible. The objective of this chapter is to show the potential for energy saving in peanut drying using exhaust-air recirculation.

6.2 Review of Literature

Energy inputs for a peanut dryer include electrical energy to operate fans and control devices, and heat energy to raise the temperature of the dry air. Blankenship and Chew (1979) determined energy consumption during peanut drying with 3.73-kW single-trailer and 7.45-kW double-trailer propane gas-fired dryers. They studied the total cost versus initial moisture content of peanuts and presented linearly regressed relationships between the two variables for two types of dryers. For peanuts with 20% initial moisture content, the total energy cost of drying in trailers was estimated to be $5 per ton. A sixty-percent increase in total energy costs can be expected if the initial moisture content is 30% (wet basis). Three main approaches for conserving energy in peanut drying are found in the literature. They are (a) using an alternate energy source such as solar heat, (b) employing an intermittent air supply, and (c) partially recirculating the drying air.

Troeger and Butler (1980a) compared the performance of prototypes of three peanut drying systems. They were (a) a solar collector-water storage supplementary LPG burner system, (b) a solar collector-air rock storage- supplementary LPG burner system, and (c) a conventional LPG burner system. They dried four metric tons of peanuts with an average initial moisture content of 17.5% (w.b.). System "a" had an 82 m^2 collector, and system "b" a 140 m^2 collector. The average solar energy contribution of the water system was 41% of the total heat energy used, and that for the air-rock-storage system was 74%. Milling quality and drying time did not significantly differ from that obtained for the conventional drying system.

Troeger and Butler (1979) presented a mathematical simulation model for a solar drying system employing a transient simulation program (TRANSYS) developed by the Solar Energy Lab at the University of Wisconsin. Troeger (1983) discussed the design parameters involved in designing a peanut-drying system using solar-heated water. Cundiff and Troeger (1981) studied the feasibility of using a solar energy system (flat plate collector- rock storage) in tobacco curing and peanut drying. Since tobacco is cured in July and August and peanuts are dried in September and October in Georgia, this arrangement is a practical way of sharing capital investment. Based on the analysis, if the solar system is designed to provide 20% of the heat energy required for five tobacco curing barns, it can supply 50% of the energy required for drying two wagons (8.4 Mg dry weight) of peanuts.

Vaughan and Lambert (1980) reported the design, construction, and testing of an integrated shed solar collector drying facility. This facility can handle six trailers and could be used for 40-50 days per year to dry peanuts. Recirculating air is solar heated while passing through the flat plate collector roof and gets mixed with outdoor air in the plenum. It was estimated that 2230 L of LPG were saved (36%) using this facility during a season.

Troeger and Butler (1980b) reported a series of tests to reduce heat and electrical energy requirement for peanut drying by shutting off dryers periodically. Peanuts were dried in 12 model bins (0.6m x 0.6m x 1.2m deep) at two different air flow rates (12.5 m^3 air per min per m^3 of peanuts and 25 m^3 of air per min per m^3 of peanuts). The four schedules they used were 15 minutes interruption per hour, 30 minutes per hour, 45 minutes per hour, and 1 hour in 4 hours. They were able to save 10% of total energy consumption using 15 minutes interruption per hour schedule and an air flow rate of 12.5 m^3 per min per m^3 of peanuts. However, heat energy consumption increased when the system was operated at 25 m^3 per min per m^3 of peanuts. No differences in milling quality were detected among these treatments. Blankenship and Chew (1979) found a reduction in electrical energy use of 32% and a reduction in LPG consumption of 21% by shutting off the dryers for one third of the operational time. The strategy of interrupting air flow can also be employed to avoid peak hours in electricity demand, thereby reducing operating costs.

Vaughan and Cundiff (1984) investigated the cost effectiveness of replacing the conventional LPG burner with a heat pump for a six-trailer peanut-drying shed in which an average of six batches of peanuts are dried annually. They visualized a system that had the heat pump evaporator installed in the exhaust air stream and the condenser located in the inlet air. The refrigerant is evaporated in the evaporator, absorbs heat from the exhaust, and is pumped into the condensor where it gives off heat to the inlet air. They concluded that the drying system with a heat pump would not be cost effective because of high capital investment for the heat pump. However, if a heat pump with a high coefficient of performance (COP) is used throughout the year for other purposes besides drying peanuts, this method could be cost competitive.

Recirculating of exhaust air and mixing it with ambient air in peanut curing facilities has two distinct advantages: (1) it allows one to exploit the remaining drying potential of exhaust air and (2) it maintains a sufficiently high humidity in incoming air to prevent the splitting damage associated with high drying rates. Harner et al. (1981) investigated energy savings from recirculation of exhaust air during peanut curing. They cured ten different batches of peanuts in a six-trailer solar peanut-drying system. The recirculated exhaust air absorbed heat while passing through a bare plate collector fitted to the roof. The recirculated air constituted two thirds of the total air flow required by the fans. The rest was drawn through a portable collector. They reported an average fuel saving of 8.71 L LPG per hour from recirculating of exhaust air and from using solar energy during 1980 and 1981. The percentage energy saving from solar and recirculation ranged from 31.0% to 34.95% during 1980.

Cook et al. (1982) presented the energy savings from different recirculation strategies along with a simulation model adapted to incorporate recirculation. They used three laboratory test dryers as described in Chapter 5. The simulation model modified by Cook et al. (1982) was used to compare the three recirculation strategies used. They reported energy saving up to 20% using these strategies, without increasing drying time.

Young (1985) compared energy consumption in dryers using partial air recirculation with conventional single pass dryers, and with dryers utilizing intermittent operation of fans and heaters. He studied five peanut-drying units for three years. He concluded that the recirculation dryers showed significant advantages over conventional and intermittent air flow dryers. Energy savings averaged around 26% in the recirculation dryers; drying time was increased by 15%; and the peanuts had slightly higher market value.

6.3 Energy Savings by Exhaust-air Recirculation

6.3.1 Experimental Results

As discussed in Chapter 5 (Section 5.3), the heat energy inputs were measured during the drying experiments. (Kulasiri (1988) described the method of calculating heat inputs to the resistance heaters by using the transducer current and voltage data collected.) The experiments in dryers 1 and 2 were done with exhaust-air recirculation, and the experiments in dryer 3 were conducted without recirculation. Since parameters such as inlet air temperature, initial moisture, initial weight of peanuts, and duration of the dryer operation were the same for all three dryers during a test, the energy inputs of dryers 1 and 2 can be compared with the energy input of dryer 3.

For each test, two different recirculation strategies were imposed on dryers 1 and 2 by positioning the hinged door (Fig. 5.2) and changing the ratio of the inlet and recirculation duct openings. The measured airflow through the vertical recirculation duct showed that the amount of air recirculated did not depend on the opening alone, but also depended upon the pressures operating in the dryers. For example, if wind speed was high outside the building, the pressure at the exhaust outlet was less and more exhaust-air flowed out instead of through the recirculation ducts. Therefore, the recirculated airflow fluctuated rapidly at times, making it impossible to maintain a schedule. Since the average air recirculation ratio (mass of air recirculated per unit mass of inlet air to the dryer) over the drying period would be misleading given the non-uniformity of recirculated airflow, recirculation ratios were not included with the energy consumption data given in Table 6.1. Nevertheless, Table 6.1 establishes the potential in exhaust-air recirculation using the experimental results.

The total heat input to a peanut dryer without air recirculation depends on the following factors:

(1) inlet air temperature

(2) airflow rate

(3) ambient air temperature

(4) ambient humidity

(5) initial moisture content of peanuts

(6) efficiency of the heater

(7) heat loss through dryer walls

(8) duration of drying

It is impossible to control all these factors; therefore, large variations in total energy, mainly due to changing weather, should be expected for tests conducted in different weather conditions.

Table 6.1. Total heat inputs and energy savings in drying experiments with inlet air temperature of 35 C and airflow of approximately 10 $m^3/min/m^3$ of peanuts.

Experiment No.	Exhaust Air Recirculation (Yes/No)	Total Heat Input (Q) MJ	Amount of Water Removed(M) kg	Duration of Drying hrs	Q/M MJ/kg	Energy Savings* (%)
89 T1C1	Y	169.6	44.96	60.0	3.77	20.5
89 T1C2	Y	179.5	44.85	60.0	4.00	15.9
89 T1C3	N	213.4	43.89	60.0	4.86	----
89 T2C1	Y	222.9	31.47	77.5	7.08	25.9
89 T2C2	Y	224.8	31.81	77.5	7.10	25.2
89 T2C3	N	300.6	32.83	77.5	9.16	----
89 T3C1	Y	184.1	31.66	69.0	5.82	40.3
89 T3C2	Y	224.2	29.82	69.0	7.10	27.3
89 T3C3	N	308.6	31.98	69.0	9.65	----
89 T4C1	Y	150.5	23.13	51.0	6.51	35.5
89 T4C2	Y	194.8	25.23	51.0	7.72	16.5
89 T4C3	N	233.4	23.36	51.0	10.0	----
88 T1C1	Y	236.8	22.94	60.0	10.3	4.1
88 T1C2	Y	226.7	22.45	60.0	10.1	8.2
88 T1C3	N	246.9	20.87	60.0	11.8	----
88 T2C1	Y	276.2	15.42	56.5	17.9	18.5
88 T2C2	Y	322.6	15.65	56.5	20.6	4.8
88 T2C3	N	339.0	13.49	56.5	25.1	----
88 T3C1	Y	364.8	39.38	76.7	9.3	17.4
88 T3C2	Y	386.3	38.63	76.7	10.0	12.5
88 T3C3	N	441.6	39.81	76.7	11.1	----

* Based on the total heat inputs

As seen in Table 6.1, the heat energy required to remove one kg of water from peanuts varied from 3.8 to 25.1 MJ. This large variation shows the importance of optimizing the drying parameters, drying time, airflow, and inlet air temperature, all of which can be controlled. Further, Table 6.1 shows that exhaust-air recirculation can save as much as 40% of the energy required to dry a batch of peanuts. To investigate the energy saving potential of different exhaust-air recirculation strategies, simulated experiments in the computer using the deep-bed drying model PEATECH are more effective because the above mentioned factors can be controlled for each experiment.

6.3 Simulated Experiments

The peanut-drying model PEATECH was modified to calculate the heat energy required to dry peanuts with exhaust-air recirculation. Total heat input is the heat energy needed to elevate the temperature of the mixture of ambient and exhaust air to the inlet temperature, accounting for the heat losses in the duct and efficiency of the heater. It was assumed that mixing of ambient and exhaust air was adiabatic, and the temperature and the humidity of the mixture were calculated by energy and mass balances. The heat energy inputs calculated using the modified model ENTECH compared favorably with measured values when ENTECH was tested with the data from drying experiments. The assumed heater efficiency was 95%.

The ambient air conditions used in the simulated experiments (Figs 6.1 and 6.2), were the measured ambient air conditions during Test 1 in 1989. Ambient relative humidity averaged around 50%, which is typical in Virginia, and ambient temperature varied from 14 C to 26 C, which is also representative of air temperatures in the Fall. The initial moisture content was assumed to be 30% wet basis, and

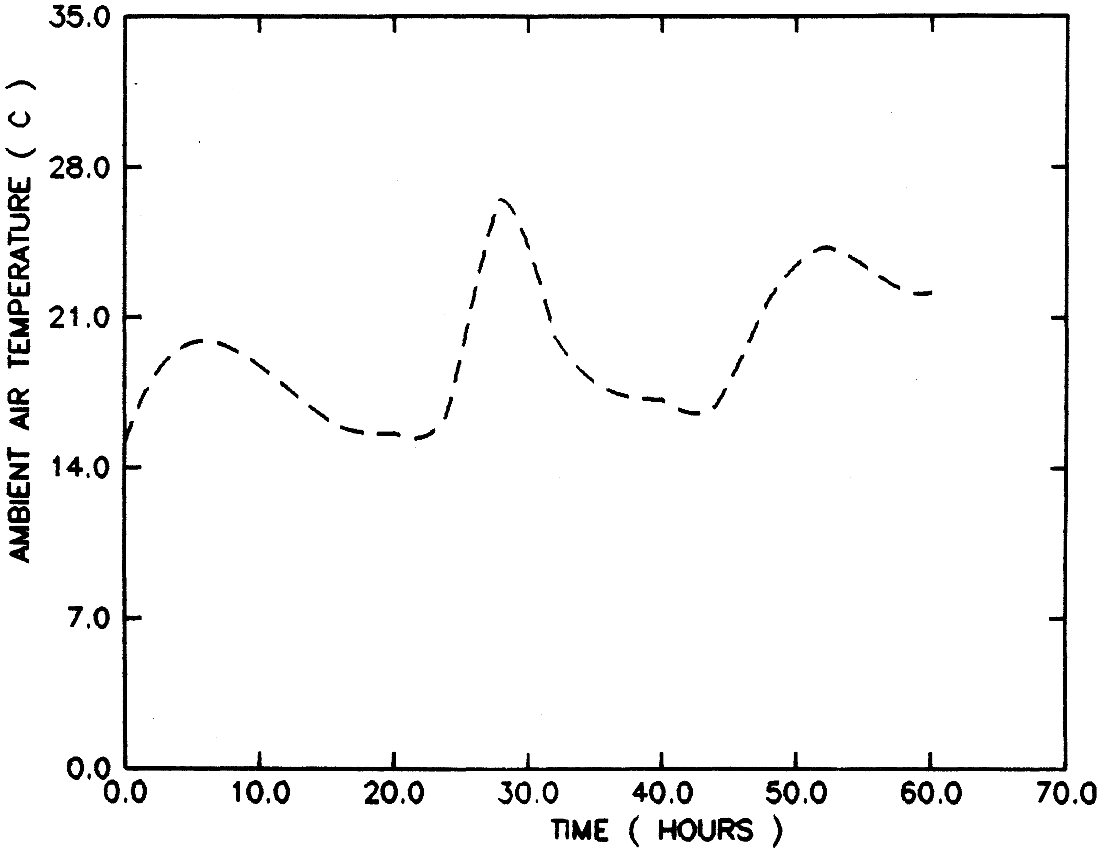

Figure 6.1. The ambient temperatures used in the simulated experiments.

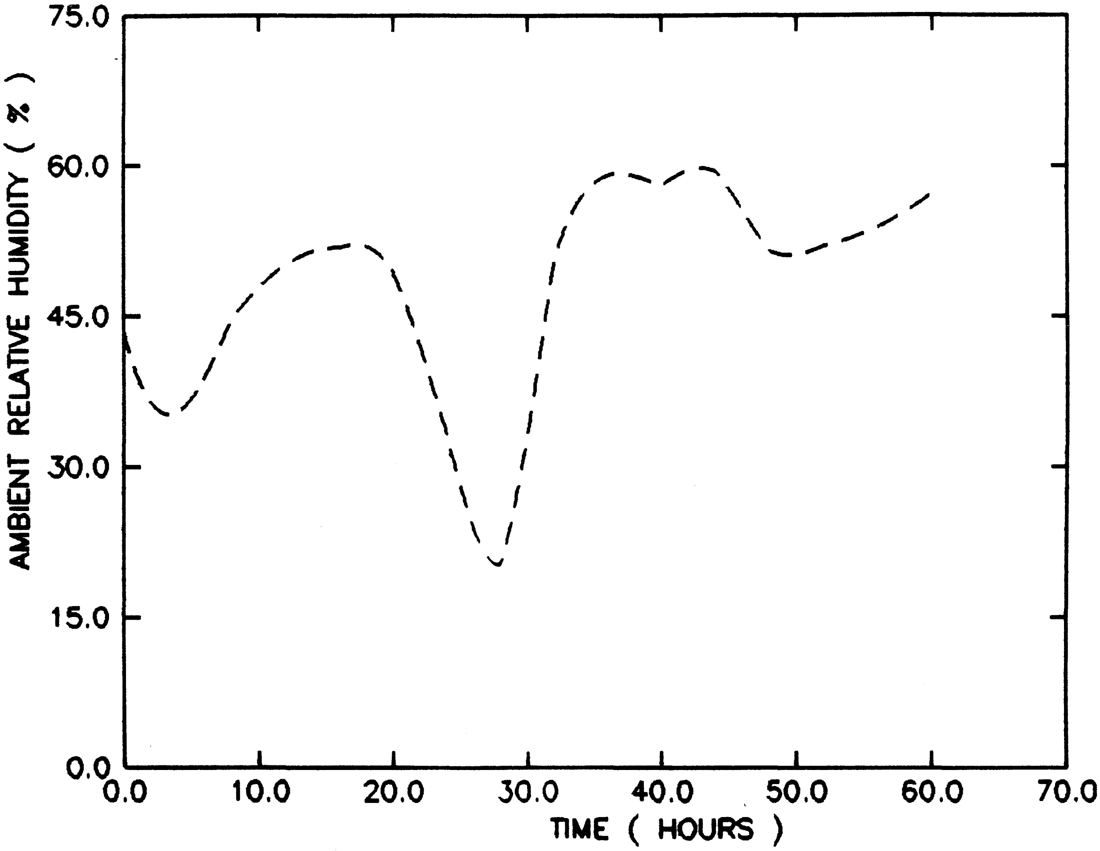

Figure 6.2. The ambient relative humidities used in the simulated experiments.

the bulk density of the solids in the peanut bed was taken as 230 kg/m^3. The height of the peanut bed was 1.1 m, and the surface area of the dryer was 0.25 m^2, as in the laboratory dryers. The duration of the drying was 60 hours for all experiments; airflow was 10 $m^3/min/m^3$ of peanuts; and the inlet air temperatures used were the measured values of the 89 T1C2 experiment, which average about 35 C. The only difference between one experiment and another was the recirculation strategies employed. The exhaust-air recirculation percentage, ERP, was defined as the kg of exhaust-air recirculated per 100 kg of inlet air to the dryer.

The following recirculation strategies were used in the experiments:

Schedule No. 1. ERP = 0 for all t
where t is the drying time (hours)

Schedule No. 2. $ERP = \begin{cases} 10.0 & 0 \le t \le 12.0 \\ 30.0 & 12.0 < t \le 36.0 \\ 50.0 & t > 36.0 \end{cases}$

Schedule No. 3 $ERP = \begin{cases} 15.0 & 0 \le t \le 12.0 \\ 45.0 & 12.0 < t \le 36.0 \\ 70.0 & t > 36.0 \end{cases}$

Schedule No. 4 $ERP = \begin{cases} 20.0 & 0 \le t \le 12.0 \\ 60.0 & 12.0 < t \le 36.0 \\ 80.0 & t > 36.0 \end{cases}$

Schedule No. 5 $ERP = \begin{cases} 30.0 & 0 \le t \le 12.0 \\ 70.0 & 12.0 < t \le 36.0 \\ 85.0 & t > 36.0 \end{cases}$

$$\text{Schedule No. 6} \quad ERP = \begin{cases} 30.0 & 0 \le t \le 6.0 \\ 40.0 & 6.0 < t \le 12.0 \\ 50.0 & 12.0 < t \le 24.0 \\ 60.0 & 24.0 < t \le 36.0 \\ 70.0 & 36.0 < t \ge 48.0 \\ 80.0 & 48.0 < t \le 60.0 \end{cases}$$

$$\text{Schedule No. 7} \quad ERP = \begin{cases} 40.0 & 0 \le t \le 6.0 \\ 50.0 & 6.0 < t \le 12.0 \\ 60.0 & 12.0 < t \le 24.0 \\ 70.0 & 24.0 < t \le 36.0 \\ 80.0 & 36.0 < t \le 48.0 \\ 85.0 & 48.0 < t \le 60.0 \end{cases}$$

$$\text{Schedule No. 8} \quad ERP = \begin{cases} 30.0 & 0.0 \le t \le 24.0 \\ 60.0 & 24.0 < t \le 48.0 \\ 70.0 & 48.0 < t \le 60.0 \end{cases}$$

$$\text{Schedule No. 9} \quad ERP = \begin{cases} 40.0 & 0.0 \le t \le 24.0 \\ 70.0 & 24.0 < t \le 48.0 \\ 80.0 & 48.0 \text{ M } t \le 60.0 \end{cases}$$

$$\text{Schedule No. 10} \quad ERP = 2.3611 \times 10^{-4}\ t^2$$

$$\text{Schedule No. 11} \quad ERP = 9.1667 \text{ X } 10^{-3}\ t + 0.30$$

$$\text{Schedule No. 12} \quad ERP = \begin{cases} 10.0 & 0.0 \le t \le 12.0 \\ 70.0 & 12.0 \le t \le 36.0 \\ 80.0 & 36.0 < t \le 60.0 \end{cases}$$

All the schedules except Nos. 1, 10, and 11 are step functions of time, and in Schedules 10 and 11 the amount of exhaust air recirculated increases continuously with time. Schedule 1 represents drying without recirculation. In all schedules, ERP was increased with drying time as the drying potential of exhaust-air also increases with time. The energy savings can be maximized by using higher amounts of exhaust-air towards the end of drying.

ENTECH was run using each of these schedules, and energy demand with time, total heat energy demand, and time to dry peanuts to an average moisture content of 10% wet basis were obtained as outputs. Table 6.2 lists the outputs for each schedule.

6.4 Results and Discussion

Even though the energy savings given in Table 6.2 are specific to ambient conditions and other drying parameters, the following observations can be made:

1. Exhaust-air recirculation can be used to save as much as 47% of the energy consumed in peanut drying provided a suitable strategy is used.

2. The drying time taken to lower average moisture content to 10% wet basis, t*, varies with the schedule, but there is no direct relationship between energy savings and t*. (Note that Schedules 6 and 9 have the same percentage savings, but t* in Schedule 9 is 4.2 hours less than t* in Schedule 6.)

3. The acceptable limits of t* depend on the extent of mold growth in the peanut bed. Since t* is within acceptable limits, schedules 4 and 12 give optimum energy savings for the drying conditions discussed.

The energy demand for Schedules 1 (without recirculation), 2, and 3 are given in Fig. 6.3. The energy demand decreased as the drying time increased for Schedules 2 and 3. The sharp drop in energy demand at 28 hours when exhaust-air was not recirculated was due to the increase in ambient temperature (Fig. 6.1).

Table 6.2. Total energy demand, time to dry peanuts to 10% wet basis, and energy savings for different exhaust-air recirculation strategies.

Schedule No.	Total Energy Demand (MJ)	Time to Dry Peanuts to 10% w.b. (hours)	Energy Savings* (%)
1	182	29.3	-----
2	137	32.5	24.7
3	117	36.0	35.7
4	104	43.6	42.9
5	96	>60.0	47.3
6	110	52.2	39.6
7	100	>60.0	45.0
8	121	39.4	33.5
9	110	48.0	39.6
10	139	29.7	23.6
11	112	45.4	38.5
12	97	46.5	46.7

* Based on the total energy demand of 182 MJ

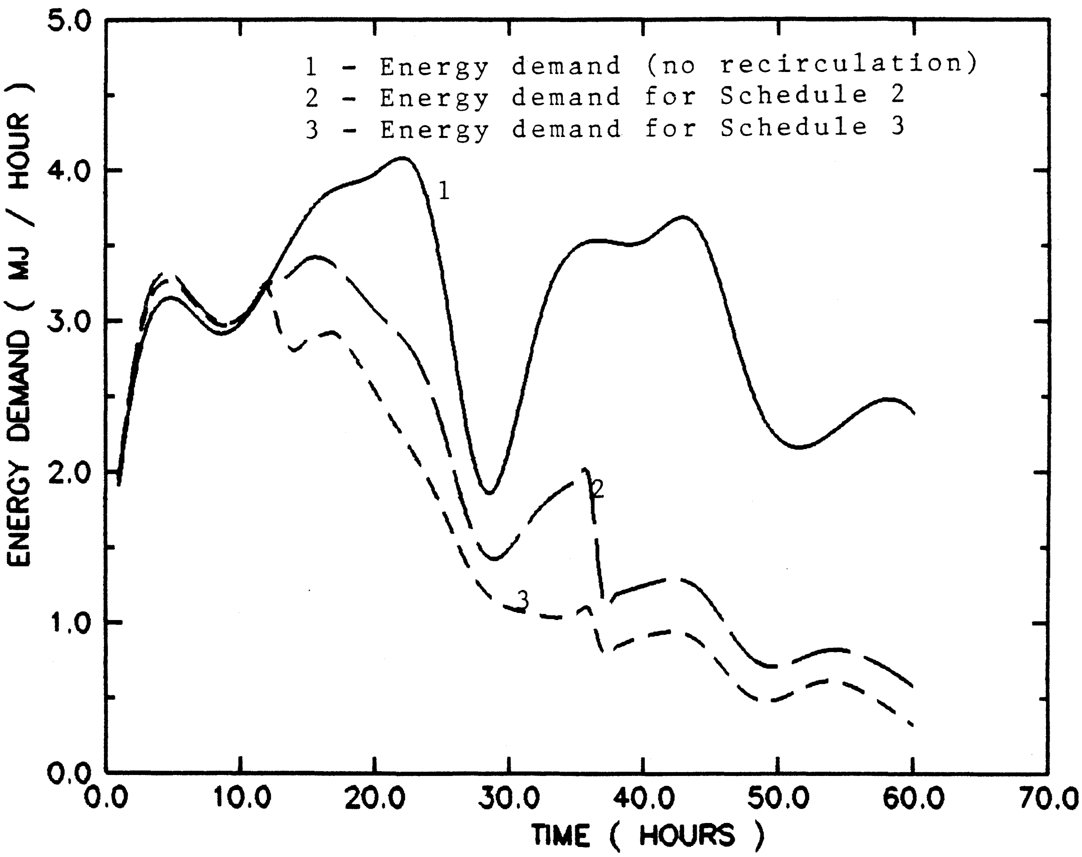

Figure 6.3. The energy demand for three simulated experiments using Schedules 1, 2, and 3.

Since the choice of the best strategy depends on the weather conditions of the area, dimensions of the dryer, initial peanut content, airflow and inlet air temperature, the model can be used to find the best schedule at a specific location. Discussion on implementation of the exhaust-air scheduling in actual dryers is beyond the scope of this work. However, given that the farmers in Virginia can save one million dollars per year by reducing energy input to dryers by 40%, redesigning of peanut dryers with sophisticated airflow controlling devices to recirculate exhaust-air according to a schedule will be a viable alternative in conserving energy in the near future.

Chapter 7

Overall Summary, Conclusions and Recommendations

In this study, thin-layer drying models and a deep-bed drying model for Virginia peanuts were developed and the potential for energy conservation using exhaust-air recirculation was established. Appropriate empirical and semi-theoretical thin-layer drying models found in the literature were fitted to the experimental data collected from the test set-up built for the purpose. The selection criteria for models based on experimental data were discussed in Chapter 3 to avoid pitfalls such as overfitting and underfitting.

Since increasing attention is being paid to theoretical models explaining drying in biological materials, such models were reviewed in Chapter 4, and a simplified model was solved for peanuts using the finite element method to illustrate the advantages of such an approach. However, solving Lukov's equations as applied to peanut drying still remains difficult given the lack of physical properties data.

The deep-bed drying model PEATECH was developed and validated in Chapter 5. The model was based on four coupled-partial differential equations consisting of four variables, air temperature, peanut temperature, air humidity, and peanut moisture content. The data collected from the drying experiments conducted using three laboratory dryers were used in the validation of the model.

Finally, in Chapter 6, the energy-saving potential of exhaust-air recirculation was established by conducting simulated experiments using a modified version of PEATECH, ENTECH, and experimental results. Twelve different recirculation strategies were examined for their energy saving potential.

The following conclusions were made from this study:

1. The experimental setup given in Chapter 3 can successfully be used to determine drying rates of peanuts for a given condition of air, provided that an accurate balance is used to measure the weight change of the tray. For the tests conducted using the experimental setup, the estimated mean square error was 1.8×10^{-5} which corresponds to a standard deviation of 0.4% dry basis.

2. The modified Page's equation in which the dynamic equilibrium moisture content corresponding to the air conditions is evaluated from the data, provides a simple but powerful tool in modeling thin-layer drying rates of Virginia peanuts. For an accurate set of data, the modified Page's equation can be fitted with an accuracy of ± 0.5% or less dry basis moisture content. Given the variability of the initial moisture content of peanuts, this accuracy is acceptable in modeling a deep-bed drying situation.

3. The multi-term exponential models can be used to model thin layer drying rates using non-linear regression techniques. However, models with a large number of parameters should be avoided because of the difficulties in relating them to the conditions of the drying air. The two-term exponential model was adequate to represent the data collected from the experiment setup.

4. The deep-bed drying model for Virginia peanuts, PEATECH, simulates the drying process within a fixed bed of peanuts accurately, provided that an accurate thin-layer drying model is incorporated.

5. PEATECH is sensitive even to small changes in the conditions of the air entering the bed and in airflow; therefore, the accuracy of the input values largely determine the accuracy of outputs.

6. The mathematical formulation of PEATECH provides the correct relationships among the variables in the drying process: air temperature, peanut temperature, air humidity, and peanut moisture content.

7. PEATECH can be used successfully to determine the energy-saving potential of exhaust-air recirculation.

8. For the weather condition tested, the Schedule No. 12 saves as much as 47% of the energy spent on heating the drying air.

The following recommendations are made for future research:

1. Thin-layer drying experiments should be conducted in every peanut season to enlarge the data base. More accurate and versatile thin layer models can be developed from such a data base to include variations in maturity at the harvest, a large range of initial moisture contents and a wide range of air conditions. PEATECH's predictions are as good as the thin-layer drying model used; therefore, efforts in developing a refined model should be continued.

2. Basic physical properties needed to solve Lukov's equations for peanut drying should be found so they can be solved using the finite element method (FEM). Once Lukov's equations are solved for a peanut pod, the coupled three dimensional partial differential equations similar to those in PEATECH can be solved using FEM to model the drying process in a bed of peanuts. However, this task is quite formidable and should be attempted only through a pooling of the expertise of various specialties such as drying of biological materials, FEM, fluid flow in porous media and physiology of peanuts.

3. PEATECH should be coupled with a weather generator to simulate energy demand in industrial peanut drying with exhaust-air recirculation for a given geographical location in the United States.

4. Means should be found to regulate exhaust-air recirculation according to a given strategy in peanut drying.

References

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Appendix A

A Sample Output of the Finite Element Method Program

HEAT TRANSFER TYPE PROBLEM

SOLUTION OF THE MOISTURE TRANSFER IN A PEANUT
ELEMENT TYPE............................ = 1
PROBLEM TYPE............................ =-1
CONVECTION (0:NO, 1:YES)................ = 1
PARAMETERS, C1, C2, C3, C4, AND C5:
C1 = 0.120E+01
C2 = 0.120E+01
C3 = 0.180E+06
C4 = 0.290E-01
C5 = 0.000E+00
ACTUAL NUMBER OF ELEMENTS IN THE MESH.... = 44
NUMBER OF NODES IN THE MESH............. = 60
TOTAL NUMBER OF EQUATIONS IN THE MODEL... = 60

CONVECTIVE BOUNDARY DATA: NBE....... = 15
ARRAY IBN: 41 42 43 44 44 40 36 32 28 24

CONVECTIVE BOUNDARY DATA: NBE....... = 20
ARRAY IBN: 16 12 8 4
COORDINATES OF THE GLOBAL NODES:

0.00000E+00	0.00000E+00	0.30000E+01	0.00000E+00	0.50000E+01	0.00000E+00
0.70000E+01	0.00000E+00	0.90000E+01	0.00000E+00	0.00000E+00	0.20000E+01
0.30000E+01	0.20000E+01	0.51000E+01	0.20000E+01	0.72000E+01	0.20000E+01
0.92000E+01	0.20000E+01	0.00000E+00	0.40000E+01	0.30000E+01	0.40000E+01
0.52000E+01	0.40000E+01	0.74000E+01	0.40000E+01	0.95000E+01	0.40000E+01
0.00000E+00	0.60000E+01	0.30000E+01	0.60000E+01	0.53000E+01	0.60000E+01
0.76000E+01	0.60000E+01	0.99000E+01	0.60000E+01	0.00000E+00	0.80000E+01
0.30000E+01	0.80000E+01	0.53000E+01	0.80000E+01	0.77000E+01	0.80000E+01
0.10000E+02	0.80000E+01	0.00000E+00	0.10000E+02	0.30000E+01	0.10000E+02
0.53000E+01	0.10000E+02	0.77000E+01	0.10000E+02	0.10100E+02	0.10000E+02
0.00000E+00	0.12000E+02	0.28000E+01	0.12000E+02	0.52000E+01	0.12000E+02
0.76000E+01	0.12000E+02	0.10000E+02	0.12000E+02	0.00000E+00	0.14000E+02
0.26000E+01	0.14000E+02	0.49000E+01	0.14000E+02	0.73000E+01	0.14000E+02
0.96000E+01	0.14000E+02	0.00000E+00	0.16000E+02	0.23000E+01	0.16000E+02
0.45000E+01	0.16000E+02	0.67000E+01	0.16000E+02	0.88000E+01	0.16000E+02
0.00000E+00	0.18000E+02	0.21000E+01	0.18000E+02	0.41000E+01	0.18000E+02
0.58000E+01	0.18000E+02	0.77000E+01	0.18000E+02	0.00000E+00	0.19000E+02
0.20000E+01	0.19000E+02	0.38000E+01	0.19000E+02	0.50000E+01	0.19000E+02
0.64000E+01	0.19000E+02	0.00000E+00	0.20000E+02	0.19000E+01	0.20000E+02
0.36000E+01	0.20000E+02	0.46000E+01	0.20000E+02	0.52000E+01	0.20000E+02

BOOLEAN (CONNECTIVITY) MATRIX NOD(I,J)

1	1	2	7	6
2	2	3	8	7
3	3	4	9	8
4	4	5	10	9
5	6	7	12	11
6	7	8	13	12
7	8	9	14	13

0.41546E+00 0.29000E-01 0.10550E+01 0.96901E+00 0.77933E+00 0.42898E+00
0.29000E-01 0.10525E+01 0.96482E+00 0.77593E+00 0.42897E+00 0.29000E-01
0.10259E+01 0.94413E+00 0.74696E+00 0.40773E+00 0.29000E-01 0.94442E+00
0.86465E+00 0.68160E+00 0.36332E+00 0.29000E-01 0.75842E+00 0.69538E+00
0.54201E+00 0.29816E+00 0.29000E-01 0.44198E+00 0.40570E+00 0.31625E+00
0.18594E+00 0.29000E-01 0.24230E+00 0.22402E+00 0.18216E+00 0.13103E+00
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.47675

TIME = 6.000

SOLUTION VECTOR:

0.10044E+01 0.87100E+00 0.67393E+00 0.37981E+00 0.29000E-01 0.10068E+01
0.87701E+00 0.67139E+00 0.36121E+00 0.29000E-01 0.10134E+01 0.89096E+00
0.68217E+00 0.36627E+00 0.29000E-01 0.10205E+01 0.90642E+00 0.69654E+00
0.37204E+00 0.29000E-01 0.10241E+01 0.91484E+00 0.71255E+00 0.38286E+00
0.29000E-01 0.10161E+01 0.90623E+00 0.70589E+00 0.38095E+00 0.29000E-01
0.97482E+00 0.87636E+00 0.67245E+00 0.35927E+00 0.29000E-01 0.87395E+00
0.78594E+00 0.60452E+00 0.31719E+00 0.29000E-01 0.68083E+00 0.61711E+00
0.47299E+00 0.25841E+00 0.29000E-01 0.38832E+00 0.35393E+00 0.27358E+00
0.16171E+00 0.29000E-01 0.21314E+00 0.19610E+00 0.15888E+00 0.11513E+00
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.43508

TIME = 7.000

SOLUTION VECTOR:

0.95588E+00 0.81526E+00 0.62087E+00 0.34643E+00 0.29000E-01 0.95903E+00
0.82129E+00 0.61806E+00 0.32910E+00 0.29000E-01 0.96734E+00 0.83544E+00
0.62755E+00 0.33286E+00 0.29000E-01 0.97617E+00 0.85086E+00 0.64001E+00
0.33704E+00 0.29000E-01 0.97912E+00 0.85788E+00 0.65338E+00 0.34553E+00
0.29000E-01 0.96532E+00 0.84477E+00 0.64368E+00 0.34201E+00 0.29000E-01
0.91293E+00 0.80789E+00 0.60732E+00 0.32027E+00 0.29000E-01 0.80145E+00
0.71243E+00 0.53938E+00 0.28067E+00 0.29000E-01 0.61068E+00 0.54964E+00
0.41707E+00 0.22752E+00 0.29000E-01 0.34358E+00 0.31193E+00 0.24024E+00
0.14312E+00 0.29000E-01 0.18933E+00 0.17382E+00 0.14084E+00 0.10296E+00
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.39845

TIME = 8.000

SOLUTION VECTOR:

0.90277E+00 0.76150E+00 0.57386E+00 0.31835E+00 0.29000E-01 0.90630E+00
0.76736E+00 0.57091E+00 0.30218E+00 0.29000E-01 0.91544E+00 0.78114E+00
0.57921E+00 0.30496E+00 0.29000E-01 0.92470E+00 0.79568E+00 0.58978E+00
0.30785E+00 0.29000E-01 0.92597E+00 0.80059E+00 0.60043E+00 0.31437E+00
0.29000E-01 0.90690E+00 0.78350E+00 0.58812E+00 0.30954E+00 0.29000E-01
0.84705E+00 0.74179E+00 0.55011E+00 0.28801E+00 0.29000E-01 0.73135E+00
0.64529E+00 0.48370E+00 0.25089E+00 0.29000E-01 0.54823E+00 0.49136E+00
0.37076E+00 0.20268E+00 0.29000E-01 0.30587E+00 0.27715E+00 0.21331E+00

SOLUTION VECTOR:

0.10368E+01	0.10576E+01	0.98896E+00	0.65376E+00	0.29000E-01	0.10352E+01
0.10590E+01	0.99057E+00	0.62952E+00	0.29000E-01	0.10326E+01	0.10602E+01
0.10031E+01	0.64763E+00	0.29000E-01	0.10298E+01	0.10608E+01	0.10179E+01
0.66588E+00	0.29000E-01	0.10284E+01	0.10602E+01	0.10322E+01	0.69012E+00
0.29000E-01	0.10281E+01	0.10602E+01	0.10340E+01	0.69689E+00	0.29000E-01
0.10309E+01	0.10624E+01	0.10263E+01	0.67986E+00	0.29000E-01	0.10398E+01
0.10609E+01	0.10041E+01	0.63327E+00	0.29000E-01	0.99114E+00	0.99362E+00
0.89723E+00	0.55011E+00	0.29000E-01	0.69185E+00	0.68188E+00	0.58674E+00
0.35302E+00	0.29000E-01	0.39420E+00	0.38698E+00	0.33801E+00	0.24325E+00
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.65381

TIME = 3.000

SOLUTION VECTOR:

0.10622E+01	0.10295E+01	0.89045E+00	0.54547E+00	0.29000E-01	0.10608E+01
0.10331E+01	0.89043E+00	0.52254E+00	0.29000E-01	0.10581E+01	0.10401E+01
0.90462E+00	0.53532E+00	0.29000E-01	0.10546E+01	0.10470E+01	0.92249E+00
0.54910E+00	0.29000E-01	0.10525E+01	0.10507E+01	0.94130E+00	0.56945E+00
0.29000E-01	0.10539E+01	0.10512E+01	0.94283E+00	0.57387E+00	0.29000E-01
0.10561E+01	0.10502E+01	0.92765E+00	0.55486E+00	0.29000E-01	0.10403E+01
0.10176E+01	0.88281E+00	0.50755E+00	0.29000E-01	0.92323E+00	0.88819E+00
0.74443E+00	0.42850E+00	0.29000E-01	0.58800E+00	0.55856E+00	0.45555E+00
0.26891E+00	0.29000E-01	0.32682E+00	0.31053E+00	0.26022E+00	0.18602E+00
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.58231

TIME = 4.000

SOLUTION VECTOR:

0.10650E+01	0.98202E+00	0.80600E+00	0.47352E+00	0.29000E-01	0.10649E+01
0.98705E+00	0.80476E+00	0.45211E+00	0.29000E-01	0.10653E+01	0.99783E+00
0.81825E+00	0.46136E+00	0.29000E-01	0.10652E+01	0.10094E+01	0.83585E+00
0.47172E+00	0.29000E-01	0.10655E+01	0.10165E+01	0.85533E+00	0.48839E+00
0.29000E-01	0.10665E+01	0.10157E+01	0.85491E+00	0.49052E+00	0.29000E-01
0.10563E+01	0.10055E+01	0.83212E+00	0.47016E+00	0.29000E-01	0.10044E+01
0.94495E+00	0.77360E+00	0.42384E+00	0.29000E-01	0.84131E+00	0.78585E+00
0.62964E+00	0.35168E+00	0.29000E-01	0.50722E+00	0.47143E+00	0.37343E+00
0.21927E+00	0.29000E-01	0.27895E+00	0.26036E+00	0.21376E+00	0.15299E+00
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.52497

TIME = 5.000

SOLUTION VECTOR:

0.10432E+01	0.92742E+00	0.73482E+00	0.42083E+00	0.29000E-01	0.10445E+01
0.93315E+00	0.73277E+00	0.40088E+00	0.29000E-01	0.10483E+01	0.94610E+00
0.74493E+00	0.40769E+00	0.29000E-01	0.10523E+01	0.96040E+00	0.76110E+00

8	9	10	15	14
9	11	12	17	16
10	12	13	18	17
11	13	14	19	18
12	14	15	20	19
13	16	17	22	21
14	17	18	23	22
15	18	19	24	23
16	19	20	25	24
17	21	22	27	26
18	22	23	28	27
19	23	24	29	28
20	24	25	30	29
21	26	27	32	31
22	27	28	33	32
23	28	29	34	33
24	29	30	35	34
25	31	32	37	36
26	32	33	38	37
27	33	34	39	38
28	34	35	40	39
29	36	37	42	41
30	37	38	43	42
31	38	39	44	43
32	39	40	45	44
33	41	42	47	46
34	42	43	48	47
35	43	44	49	48
36	44	45	50	49
37	46	47	52	51
38	47	48	53	52
39	48	49	54	53
40	49	50	55	54
41	51	52	57	56
42	52	53	58	57
43	53	54	59	58
44	54	55	60	59

HALF BAND WIDTH OF GLOBAL STIFFNESS MATRIX = 7
THETA= 0.500E-02 TIME STEP= 0.500E+00 MAX. TIME= 0.300E+02

TIME = 1.000

SOLUTION VECTOR:

0.10307E+01	0.10432E+01	0.10808E+01	0.84854E+00	0.29000E-01	0.10311E+01
0.10422E+01	0.10839E+01	0.82454E+00	0.29000E-01	0.10330E+01	0.10391E+01
0.10872E+01	0.84985E+00	0.29000E-01	0.10352E+01	0.10358E+01	0.10916E+01
0.87203E+00	0.29000E-01	0.10370E+01	0.10335E+01	0.10941E+01	0.89717E+00
0.29000E-01	0.10368E+01	0.10336E+01	0.10947E+01	0.90561E+00	0.29000E-01
0.10348E+01	0.10328E+01	0.10932E+01	0.89325E+00	0.29000E-01	0.10330E+01
0.10386E+01	0.10937E+01	0.85148E+00	0.29000E-01	0.10381E+01	0.10551E+01
0.10720E+01	0.77951E+00	0.29000E-01	0.85032E+00	0.87144E+00	0.83349E+00
0.53860E+00	0.29000E-01	0.51338E+00	0.52561E+00	0.50235E+00	0.37487E+00
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.75164

TIME = 2.000

0.12832E+00 0.29000E-01 0.16954E+00 0.15557E+00 0.12635E+00 0.93271E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.36587

TIME = 9.000

SOLUTION VECTOR:

0.84827E+00 0.71033E+00 0.53164E+00 0.29411E+00 0.29000E-01 0.85192E+00
0.71590E+00 0.52865E+00 0.27902E+00 0.29000E-01 0.86118E+00 0.72892E+00
0.53584E+00 0.28103E+00 0.29000E-01 0.86991E+00 0.74202E+00 0.54459E+00
0.28286E+00 0.29000E-01 0.86897E+00 0.74457E+00 0.55263E+00 0.28769E+00
0.29000E-01 0.84556E+00 0.72424E+00 0.53824E+00 0.28184E+00 0.29000E-01
0.78135E+00 0.67957E+00 0.49957E+00 0.26076E+00 0.29000E-01 0.66577E+00
0.58466E+00 0.43563E+00 0.22604E+00 0.29000E-01 0.49302E+00 0.44080E+00
0.33173E+00 0.18220E+00 0.29000E-01 0.27377E+00 0.24790E+00 0.19105E+00
0.11620E+00 0.29000E-01 0.15287E+00 0.14035E+00 0.11442E+00 0.85347E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.33666

TIME = 10.000

SOLUTION VECTOR:

0.79438E+00 0.66203E+00 0.49337E+00 0.27275E+00 0.29000E-01 0.79795E+00
0.66723E+00 0.49037E+00 0.25867E+00 0.29000E-01 0.80679E+00 0.67921E+00
0.49652E+00 0.26006E+00 0.29000E-01 0.81438E+00 0.69060E+00 0.50356E+00
0.26101E+00 0.29000E-01 0.81109E+00 0.69079E+00 0.50921E+00 0.26442E+00
0.29000E-01 0.78438E+00 0.66802E+00 0.49327E+00 0.25781E+00 0.29000E-01
0.71820E+00 0.62188E+00 0.45471E+00 0.23733E+00 0.29000E-01 0.60550E+00
0.53021E+00 0.39377E+00 0.20492E+00 0.29000E-01 0.44430E+00 0.39677E+00
0.29839E+00 0.16497E+00 0.29000E-01 0.24623E+00 0.22300E+00 0.17232E+00
0.10607E+00 0.29000E-01 0.13868E+00 0.12748E+00 0.10442E+00 0.78730E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.31032

TIME = 11.000

SOLUTION VECTOR:

0.74221E+00 0.61668E+00 0.45841E+00 0.25364E+00 0.29000E-01 0.74557E+00
0.62144E+00 0.45543E+00 0.24050E+00 0.29000E-01 0.75365E+00 0.63224E+00
0.46059E+00 0.24137E+00 0.29000E-01 0.75976E+00 0.64180E+00 0.46607E+00
0.24160E+00 0.29000E-01 0.75424E+00 0.63981E+00 0.46961E+00 0.24382E+00
0.29000E-01 0.72520E+00 0.61534E+00 0.45259E+00 0.23667E+00 0.29000E-01
0.65880E+00 0.56887E+00 0.41470E+00 0.21693E+00 0.29000E-01 0.55067E+00
0.48142E+00 0.35705E+00 0.18673E+00 0.29000E-01 0.40132E+00 0.35824E+00
0.26962E+00 0.15026E+00 0.29000E-01 0.22243E+00 0.20160E+00 0.15635E+00
0.97466E-01 0.29000E-01 0.12648E+00 0.11646E+00 0.95923E-01 0.73120E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.28646

TIME = 12.000

SOLUTION VECTOR:

0.69241E+00	0.57423E+00	0.42630E+00	0.23636E+00	0.29000E-01	0.69546E+00
0.57853E+00	0.42336E+00	0.22409E+00	0.29000E-01	0.70257E+00	0.58808E+00
0.42761E+00	0.22453E+00	0.29000E-01	0.70708E+00	0.59582E+00	0.43166E+00
0.22415E+00	0.29000E-01	0.69957E+00	0.59194E+00	0.43339E+00	0.22539E+00
0.29000E-01	0.66906E+00	0.56640E+00	0.41571E+00	0.21789E+00	0.29000E-01
0.60368E+00	0.52044E+00	0.37889E+00	0.19898E+00	0.29000E-01	0.50110E+00
0.43774E+00	0.32465E+00	0.17087E+00	0.29000E-01	0.36335E+00	0.32439E+00
0.24458E+00	0.13755E+00	0.29000E-01	0.20175E+00	0.18306E+00	0.14259E+00
0.90074E-01	0.29000E-01	0.11593E+00	0.10695E+00	0.88617E-01	0.68306E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.26479

TIME = 13.000

SOLUTION VECTOR:

0.64527E+00	0.53458E+00	0.39671E+00	0.22060E+00	0.29000E-01	0.64796E+00
0.53841E+00	0.39380E+00	0.20913E+00	0.29000E-01	0.65401E+00	0.54672E+00
0.39721E+00	0.20921E+00	0.29000E-01	0.65694E+00	0.55274E+00	0.40000E+00
0.20833E+00	0.29000E-01	0.64775E+00	0.54725E+00	0.40020E+00	0.20877E+00
0.29000E-01	0.61646E+00	0.52119E+00	0.38221E+00	0.20109E+00	0.29000E-01
0.55297E+00	0.47635E+00	0.34675E+00	0.18306E+00	0.29000E-01	0.45640E+00
0.39864E+00	0.29594E+00	0.15694E+00	0.29000E-01	0.32974E+00	0.29455E+00
0.22264E+00	0.12646E+00	0.29000E-01	0.18367E+00	0.16689E+00	0.13063E+00
0.83662E-01	0.29000E-01	0.10674E+00	0.98692E-01	0.82284E-01	0.64137E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.24505

TIME = 14.000

SOLUTION VECTOR:

0.60090E+00	0.49760E+00	0.36936E+00	0.20614E+00	0.29000E-01	0.60321E+00
0.50097E+00	0.36649E+00	0.19543E+00	0.29000E-01	0.60819E+00	0.50808E+00
0.36914E+00	0.19520E+00	0.29000E-01	0.60963E+00	0.51252E+00	0.37083E+00
0.19392E+00	0.29000E-01	0.59909E+00	0.50574E+00	0.36977E+00	0.19370E+00
0.29000E-01	0.56760E+00	0.47959E+00	0.35174E+00	0.18596E+00	0.29000E-01
0.50655E+00	0.43627E+00	0.31782E+00	0.16885E+00	0.29000E-01	0.41616E+00
0.36360E+00	0.27039E+00	0.14462E+00	0.29000E-01	0.29993E+00	0.26815E+00
0.20330E+00	0.11673E+00	0.29000E-01	0.16780E+00	0.15272E+00	0.12018E+00
0.78058E-01	0.29000E-01	0.98686E-01	0.91467E-01	0.76756E-01	0.60500E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.22705

TIME = 15.000

SOLUTION VECTOR:

0.55930E+00 0.46314E+00 0.34404E+00 0.19283E+00 0.29000E-01 0.56124E+00
0.46607E+00 0.34121E+00 0.18282E+00 0.29000E-01 0.56519E+00 0.47207E+00
0.34318E+00 0.18233E+00 0.29000E-01 0.56528E+00 0.47510E+00 0.34393E+00
0.18073E+00 0.29000E-01 0.55371E+00 0.46731E+00 0.34184E+00 0.17999E+00
0.29000E-01 0.52246E+00 0.44141E+00 0.32400E+00 0.17230E+00 0.29000E-01
0.46422E+00 0.39990E+00 0.29175E+00 0.15612E+00 0.29000E-01 0.37995E+00
0.33217E+00 0.24758E+00 0.13366E+00 0.29000E-01 0.27342E+00 0.24472E+00
0.18619E+00 0.10812E+00 0.29000E-01 0.15381E+00 0.14024E+00 0.11098E+00
0.73130E-01 0.29000E-01 0.91606E-01 0.85118E-01 0.71902E-01 0.57307E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.21061

TIME = 16.000

SOLUTION VECTOR:

0.52041E+00 0.43105E+00 0.32056E+00 0.18053E+00 0.29000E-01 0.52200E+00
0.43358E+00 0.31779E+00 0.17118E+00 0.29000E-01 0.52498E+00 0.43855E+00
0.31915E+00 0.17048E+00 0.29000E-01 0.52390E+00 0.44036E+00 0.31910E+00
0.16862E+00 0.29000E-01 0.51159E+00 0.43181E+00 0.31620E+00 0.16747E+00
0.29000E-01 0.48091E+00 0.40642E+00 0.29873E+00 0.15991E+00 0.29000E-01
0.42568E+00 0.36689E+00 0.26820E+00 0.14467E+00 0.29000E-01 0.34736E+00
0.30394E+00 0.22716E+00 0.12387E+00 0.29000E-01 0.24981E+00 0.22387E+00
0.17099E+00 0.10049E+00 0.29000E-01 0.14143E+00 0.12921E+00 0.10286E+00
0.68776E-01 0.29000E-01 0.85354E-01 0.79513E-01 0.67620E-01 0.54490E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.19558

TIME = 17.000

SOLUTION VECTOR:

0.48412E+00 0.40120E+00 0.29879E+00 0.16915E+00 0.29000E-01 0.48538E+00
0.40336E+00 0.29607E+00 0.16043E+00 0.29000E-01 0.48750E+00 0.40741E+00
0.29691E+00 0.15955E+00 0.29000E-01 0.48542E+00 0.40817E+00 0.29620E+00
0.15750E+00 0.29000E-01 0.47262E+00 0.39907E+00 0.29267E+00 0.15603E+00
0.29000E-01 0.44278E+00 0.37441E+00 0.27570E+00 0.14866E+00 0.29000E-01
0.39064E+00 0.33694E+00 0.24691E+00 0.13434E+00 0.29000E-01 0.31802E+00
0.27856E+00 0.20883E+00 0.11510E+00 0.29000E-01 0.22872E+00 0.20526E+00
0.15744E+00 0.93690E-01 0.29000E-01 0.13044E+00 0.11942E+00 0.95651E-01
0.64913E-01 0.29000E-01 0.79812E-01 0.74547E-01 0.63828E-01 0.51994E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.18182

TIME = 18.000

SOLUTION VECTOR:

0.45030E+00 0.37344E+00 0.27858E+00 0.15862E+00 0.29000E-01 0.45126E+00
0.37526E+00 0.27593E+00 0.15047E+00 0.29000E-01 0.45262E+00 0.37849E+00
0.27632E+00 0.14946E+00 0.29000E-01 0.44972E+00 0.37837E+00 0.27506E+00
0.14727E+00 0.29000E-01 0.43665E+00 0.36893E+00 0.27107E+00 0.14556E+00

0.29000E-01	0.40783E+00	0.34513E+00	0.25469E+00	0.13843E+00	0.29000E-01
0.35879E+00	0.30977E+00	0.22763E+00	0.12500E+00	0.29000E-01	0.29157E+00
0.25571E+00	0.19236E+00	0.10723E+00	0.29000E-01	0.20986E+00	0.18862E+00
0.14533E+00	0.87613E-01	0.29000E-01	0.12066E+00	0.11070E+00	0.89238E-01
0.61473E-01	0.29000E-01	0.74885E-01	0.70132E-01	0.60458E-01	0.49775E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.16923

TIME = 19.000

SOLUTION VECTOR:

0.41882E+00	0.34763E+00	0.25983E+00	0.14885E+00	0.29000E-01	0.41953E+00
0.34916E+00	0.25725E+00	0.14125E+00	0.29000E-01	0.42023E+00	0.35168E+00
0.25726E+00	0.14013E+00	0.29000E-01	0.41667E+00	0.35082E+00	0.25557E+00
0.13785E+00	0.29000E-01	0.40351E+00	0.34121E+00	0.25124E+00	0.13597E+00
0.29000E-01	0.37584E+00	0.31837E+00	0.23552E+00	0.12911E+00	0.29000E-01
0.32985E+00	0.28510E+00	0.21015E+00	0.11655E+00	0.29000E-01	0.26771E+00
0.23511E+00	0.17752E+00	0.10014E+00	0.29000E-01	0.19295E+00	0.17371E+00
0.13448E+00	0.82167E-01	0.29000E-01	0.11192E+00	0.10292E+00	0.83515E-01
0.58401E-01	0.29000E-01	0.70492E-01	0.66197E-01	0.57453E-01	0.47796E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.15770

TIME = 20.000

SOLUTION VECTOR:

0.38955E+00	0.32367E+00	0.24243E+00	0.13979E+00	0.29000E-01	0.39003E+00
0.32493E+00	0.23993E+00	0.13271E+00	0.29000E-01	0.39017E+00	0.32683E+00
0.23963E+00	0.13151E+00	0.29000E-01	0.38609E+00	0.32538E+00	0.23759E+00
0.12917E+00	0.29000E-01	0.37300E+00	0.31572E+00	0.23304E+00	0.12718E+00
0.29000E-01	0.34657E+00	0.29391E+00	0.21803E+00	0.12061E+00	0.29000E-01
0.30355E+00	0.26270E+00	0.19429E+00	0.10889E+00	0.29000E-01	0.24617E+00
0.21651E+00	0.16413E+00	0.93739E-01	0.29000E-01	0.17777E+00	0.16032E+00
0.12474E+00	0.77275E-01	0.29000E-01	0.10411E+00	0.95967E-01	0.78395E-01
0.55651E-01	0.29000E-01	0.66567E-01	0.62680E-01	0.54767E-01	0.46026E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.14713

TIME = 21.000

SOLUTION VECTOR:

0.36236E+00	0.30141E+00	0.22628E+00	0.13140E+00	0.29000E-01	0.36264E+00
0.30244E+00	0.22387E+00	0.12479E+00	0.29000E-01	0.36231E+00	0.30381E+00
0.22331E+00	0.12354E+00	0.29000E-01	0.35785E+00	0.30189E+00	0.22102E+00
0.12119E+00	0.29000E-01	0.34495E+00	0.29230E+00	0.21633E+00	0.11912E+00
0.29000E-01	0.31980E+00	0.27155E+00	0.20205E+00	0.11286E+00	0.29000E-01
0.27965E+00	0.24235E+00	0.17990E+00	0.10194E+00	0.29000E-01	0.22671E+00
0.19971E+00	0.15203E+00	0.87959E-01	0.29000E-01	0.16412E+00	0.14827E+00
0.11598E+00	0.72874E-01	0.29000E-01	0.97111E-01	0.89729E-01	0.73803E-01
0.53183E-01	0.29000E-01	0.63051E-01	0.59530E-01	0.52361E-01	0.44440E-01

0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE = 0.13745

TIME = 22.000

SOLUTION VECTOR:

0.33711E+00 0.28075E+00 0.21130E+00 0.12361E+00 0.29000E-01 0.33723E+00
0.28159E+00 0.20899E+00 0.11746E+00 0.29000E-01 0.33651E+00 0.28251E+00
0.20822E+00 0.11618E+00 0.29000E-01 0.33178E+00 0.28023E+00 0.20574E+00
0.11383E+00 0.29000E-01 0.31917E+00 0.27078E+00 0.20100E+00 0.11172E+00
0.29000E-01 0.29533E+00 0.25113E+00 0.18747E+00 0.10578E+00 0.29000E-01
0.25791E+00 0.22385E+00 0.16681E+00 0.95618E-01 0.29000E-01 0.20909E+00
0.18451E+00 0.14109E+00 0.82731E-01 0.29000E-01 0.15182E+00 0.13743E+00
0.10808E+00 0.68906E-01 0.29000E-01 0.90822E-01 0.84126E-01 0.69678E-01
0.50965E-01 0.29000E-01 0.59895E-01 0.56703E-01 0.50201E-01 0.43016E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE = 0.12856

TIME = 23.000

SOLUTION VECTOR:

0.31368E+00 0.26160E+00 0.19742E+00 0.11640E+00 0.29000E-01 0.31366E+00
0.26226E+00 0.19519E+00 0.11067E+00 0.29000E-01 0.31264E+00 0.26281E+00
0.19427E+00 0.10937E+00 0.29000E-01 0.30773E+00 0.26025E+00 0.19166E+00
0.10705E+00 0.29000E-01 0.29548E+00 0.25103E+00 0.18693E+00 0.10494E+00
0.29000E-01 0.27295E+00 0.23246E+00 0.17414E+00 0.99323E-01 0.29000E-01
0.23813E+00 0.20702E+00 0.15491E+00 0.89872E-01 0.29000E-01 0.19315E+00
0.17074E+00 0.13118E+00 0.77995E-01 0.29000E-01 0.14072E+00 0.12764E+00
0.10096E+00 0.65324E-01 0.29000E-01 0.85164E-01 0.79085E-01 0.65965E-01
0.48967E-01 0.29000E-01 0.57058E-01 0.54160E-01 0.48258E-01 0.41735E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE = 0.12042

TIME = 24.000

SOLUTION VECTOR:

0.29195E+00 0.24383E+00 0.18454E+00 0.10971E+00 0.29000E-01 0.29183E+00
0.24435E+00 0.18242E+00 0.10439E+00 0.29000E-01 0.29056E+00 0.24459E+00
0.18137E+00 0.10309E+00 0.29000E-01 0.28556E+00 0.24184E+00 0.17869E+00
0.10081E+00 0.29000E-01 0.27373E+00 0.23289E+00 0.17401E+00 0.98725E-01
0.29000E-01 0.25250E+00 0.21539E+00 0.16196E+00 0.93420E-01 0.29000E-01
0.22013E+00 0.19170E+00 0.14408E+00 0.84643E-01 0.29000E-01 0.17869E+00
0.15827E+00 0.12220E+00 0.73700E-01 0.29000E-01 0.13070E+00 0.11880E+00
0.94525E-01 0.62086E-01 0.29000E-01 0.80065E-01 0.74541E-01 0.62618E-01
0.47165E-01 0.29000E-01 0.54503E-01 0.51871E-01 0.46508E-01 0.40580E-01
0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01 0.29000E-01

MASS AVERAGE OF THE VARIABLE = 0.11295

TIME = 25.000

SOLUTION VECTOR:

0.27182E+00	0.22737E+00	0.17262E+00	0.10352E+00	0.29000E-01	0.27160E+00
0.22777E+00	0.17060E+00	0.98572E-01	0.29000E-01	0.27014E+00	0.22775E+00
0.16945E+00	0.97282E-01	0.29000E-01	0.26512E+00	0.22487E+00	0.16674E+00
0.95070E-01	0.29000E-01	0.25375E+00	0.21624E+00	0.16216E+00	0.93019E-01
0.29000E-01	0.23379E+00	0.19978E+00	0.15082E+00	0.88024E-01	0.29000E-01
0.20374E+00	0.17775E+00	0.13422E+00	0.79881E-01	0.29000E-01	0.16558E+00
0.14695E+00	0.11405E+00	0.69802E-01	0.29000E-01	0.12164E+00	0.11081E+00
0.88702E-01	0.59155E-01	0.29000E-01	0.75464E-01	0.70441E-01	0.59596E-01
0.45538E-01	0.29000E-01	0.52199E-01	0.49806E-01	0.44929E-01	0.39538E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.10610

TIME = 26.000

SOLUTION VECTOR:

0.25316E+00	0.21212E+00	0.16157E+00	0.97786E-01	0.29000E-01	0.25287E+00
0.21241E+00	0.15965E+00	0.93188E-01	0.29000E-01	0.25128E+00	0.21219E+00
0.15845E+00	0.91922E-01	0.29000E-01	0.24629E+00	0.20923E+00	0.15573E+00
0.89782E-01	0.29000E-01	0.23542E+00	0.20096E+00	0.15128E+00	0.87783E-01
0.29000E-01	0.21668E+00	0.18551E+00	0.14064E+00	0.83091E-01	0.29000E-01
0.18881E+00	0.16504E+00	0.12524E+00	0.75542E-01	0.29000E-01	0.15367E+00
0.13668E+00	0.10666E+00	0.66261E-01	0.29000E-01	0.11343E+00	0.10357E+00
0.83429E-01	0.56500E-01	0.29000E-01	0.71307E-01	0.66736E-01	0.56865E-01
0.44066E-01	0.29000E-01	0.50117E-01	0.47940E-01	0.43503E-01	0.38596E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.09981

TIME = 27.000

SOLUTION VECTOR:

0.23588E+00	0.19801E+00	0.15135E+00	0.92477E-01	0.29000E-01	0.23554E+00
0.19821E+00	0.14953E+00	0.88209E-01	0.29000E-01	0.23386E+00	0.19783E+00
0.14828E+00	0.86974E-01	0.29000E-01	0.22894E+00	0.19484E+00	0.14560E+00
0.84914E-01	0.29000E-01	0.21858E+00	0.18693E+00	0.14130E+00	0.82979E-01
0.29000E-01	0.20103E+00	0.17246E+00	0.13133E+00	0.78579E-01	0.29000E-01
0.17519E+00	0.15346E+00	0.11705E+00	0.71586E-01	0.29000E-01	0.14286E+00
0.12734E+00	0.99931E-01	0.63042E-01	0.29000E-01	0.10600E+00	0.97007E-01
0.78649E-01	0.54091E-01	0.29000E-01	0.67546E-01	0.63384E-01	0.54394E-01
0.42733E-01	0.29000E-01	0.48236E-01	0.46253E-01	0.42213E-01	0.37744E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.09404

TIME = 28.000

SOLUTION VECTOR:

0.21989E+00	0.18494E+00	0.14188E+00	0.87565E-01	0.29000E-01	0.21951E+00
0.18507E+00	0.14016E+00	0.83605E-01	0.29000E-01	0.21777E+00	0.18456E+00
0.13890E+00	0.82408E-01	0.29000E-01	0.21296E+00	0.18158E+00	0.13627E+00
0.80433E-01	0.29000E-01	0.20312E+00	0.17405E+00	0.13213E+00	0.78570E-01
0.29000E-01	0.18671E+00	0.16052E+00	0.12281E+00	0.74452E-01	0.29000E-01
0.16278E+00	0.14290E+00	0.10958E+00	0.67978E-01	0.29000E-01	0.13302E+00
0.11885E+00	0.93815E-01	0.60113E-01	0.29000E-01	0.99256E-01	0.91056E-01
0.74312E-01	0.51905E-01	0.29000E-01	0.64141E-01	0.60348E-01	0.52155E-01
0.41526E-01	0.29000E-01	0.46532E-01	0.44726E-01	0.41045E-01	0.36972E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.08874

TIME = 29.000

SOLUTION VECTOR:

0.20510E+00	0.17285E+00	0.13313E+00	0.83021E-01	0.29000E-01	0.20468E+00
0.17292E+00	0.13150E+00	0.79349E-01	0.29000E-01	0.20291E+00	0.17231E+00
0.13025E+00	0.78195E-01	0.29000E-01	0.19825E+00	0.16937E+00	0.12768E+00
0.76309E-01	0.29000E-01	0.18893E+00	0.16222E+00	0.12372E+00	0.74524E-01
0.29000E-01	0.17360E+00	0.14959E+00	0.11502E+00	0.70675E-01	0.29000E-01
0.15146E+00	0.13326E+00	0.10277E+00	0.64685E-01	0.29000E-01	0.12407E+00
0.11113E+00	0.88249E-01	0.57447E-01	0.29000E-01	0.93135E-01	0.85653E-01
0.70372E-01	0.49919E-01	0.29000E-01	0.61053E-01	0.57596E-01	0.50125E-01
0.40430E-01	0.29000E-01	0.44989E-01	0.43343E-01	0.39986E-01	0.36272E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.08388

TIME = 30.000

SOLUTION VECTOR:

0.19141E+00	0.16167E+00	0.12504E+00	0.78819E-01	0.29000E-01	0.19098E+00
0.16169E+00	0.12350E+00	0.75417E-01	0.29000E-01	0.18921E+00	0.16102E+00
0.12226E+00	0.74308E-01	0.29000E-01	0.18471E+00	0.15814E+00	0.11977E+00
0.72515E-01	0.29000E-01	0.17590E+00	0.15137E+00	0.11600E+00	0.70810E-01
0.29000E-01	0.16161E+00	0.13958E+00	0.10788E+00	0.67218E-01	0.29000E-01
0.14112E+00	0.12446E+00	0.96547E-01	0.61679E-01	0.29000E-01	0.11593E+00
0.10409E+00	0.83181E-01	0.55018E-01	0.29000E-01	0.87573E-01	0.80744E-01
0.66792E-01	0.48113E-01	0.29000E-01	0.58252E-01	0.55098E-01	0.48282E-01
0.39435E-01	0.29000E-01	0.43589E-01	0.42087E-01	0.39026E-01	0.35637E-01
0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01	0.29000E-01

MASS AVERAGE OF THE VARIABLE= 0.07941

Appendix B

PEATECH - A Program for the Peanut Drying Model

```
C **********************************************************************
C **********************************************************************
C
C                         PEATECH
C
C           A DEEP BED DRYING MODEL FOR VIRGINIA PEANUTS
C
C
C **********************************************************************
C
C                         DON KULASIRI
C
C                AGRICULTURAL ENGINEERING DEPARTMENT
C
C        VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
C
C                  BLACKSBURG,   VIRGINIA  24060
C
C                         JULY - 1990
C
C **********************************************************************
C **********************************************************************
C     .........................................................
C   . PEATECH IS A FORTRAN PROGRAM TO MODEL THE DEEP BED DRYING
C   . OF VIRGINIA PEANUTS.  THIS PROGRAM IS FOR RESEARCH PURPOSES
C   . ONLY.  EASE OF MODIFICATION WAS A MAIN CONCERN IN
C   . THE DEVELOPMENT.
C   .
C   ...........................................................
C
C **********************************************************************
C
C                 VARIABLE LISTING
C                 ----------------
C
C  AIRTEM=TEMPERATURE OF AIR (C) AT (TIME=T,DISTANCE FROM BOTTOM=X)
C  AIRFLX=MASS FLUX OF DRY AIR, KG PER SQ. M PER HOUR
C  CAIR   =SPECIFIC HEAT OF AIR, J/KG.K
C  CPRODT=SPECIFIC HEAT OF DRY SOLIDS IN PEANUTS, J/KG.K
C  CVAPOR=SPECIFIC OF WATER VAPOR, J/KG.K
C  CWATER=SPECIFIC HEAT OF SATURATED WATER, J/KG.K
C  DBMCO  =INITIAL MOISTURE CONTENT OF PEANUTS, DRY BASIS DECIMAL
C  DBMOIS=DRY BASIS MOISTURE CONTENT OF PEANUTS (DECIMAL) AT (T,X)
C  DELT   =TIME INCREMENT, HR
C  DEPTH  =DEPTH OF THE PRODUCT, M
C  DELX   =SPACE INCREMENT, M
C  DRYTIM=DRYING TIME, HOURS
C  HUMDTY=HUMIDITY OF AIR (KG/KG) AT (T,X)
C  HUMINL=HUMIDITY OF AIR JUST BELOW THE BED, KG/KG
C  INDEX1=1 IF DRY BULB TEMPERATURE AND WET BULB TEMPERATURE
C               ARE GIVEN FOR AMBIENT AND INPUT CONDITIONS
C               USING THERMISTORS (KOHM VALUES)
C  INDEX1=2 IF DRY BULB AND RELATIVE HUMIDITY ARE GIVEN
C              USING HYGROMETER (C VALUES AND DECIMAL VALUES
```

```
C               RESPECTIVELY) FOR AMBIENT AND INPUT CONDITIONS
C IQ     =  COUNTER
C JTIME  =DRYING TIMES AT WHICH THE MANUAL TEMPERATURE, RELATIVE
C            HUMIDITY WERE MEASURED
C KTIME  =DRYING TIMES AT WHICH THE STATIC PRESSURES WERE TAKEN
C KTTIME=INTERMEDIATE INTEGER VARIABLE
C   NCOL=COLUMN NUMBER
C  NHR   =NO OF HOURS IN THE DRYING TEST
C  NREAD=NO. OF THERMISTER/RH READINGS
C   NREC=1 TEST INCLUDES RECIRCULATION, NREC=2 TEST DOES NOT
C             INCLUDE RECIRCULATION
C  NRESP=NO. OF STATIC PRESSURE READINGS
C  NTEST=TEST NUMBER
C  NYEAR=YEAR OF THE TEST
C PROTEM=TEMPERATURE OF PEANUTS (C) AT (T,X)
C   RHAR  =RELATIVE HUMIDITY OF AMBIENT AIR,
C  RHOAIR=AIR DENSITY, KG/CU. M
C   RHER  =RELATIVE HUMIDITY OF AIR ENTERING THE PEANUT BED,
C   RHOP=BULK DENSITY AT ZERO MOISTURE CONTENT, KG/ CUBIC M
C SAREA  =SPECIFIC AREA, SQ. M/CU. M
C SHTC   =SURFACE HEAT TRANSFER COEFFICIENT, J/SQ. M. K. HR
C  SPJ   =STATIC PRESSURE READING JUST BELOW THE PEANUT BED
C  TDBXR=DRY BULB TEMPERATURE READINGS OF AIR EXITING THE
C            PEANUT BED, UNITS: KOHMS   IF INDEX1=1
C                           CELSIUS IF INDEX1=2
C  TWBXR=WET BULB TEMPERATURE READINGS OF AIR EXITING THE
C            PEANUT BED, UNITS: KOHMS (INDEX1=1)
C  TDBER=DRY BULB TEMPERATURE READINGS OF AIR ENTERING THE
C           PEANUT BED, UNITS: KOHMS    IF INDEX1=1
C                           CELCIUS  IF INDEX1=2
C  TWBER=WET BULB TEMPERATURE READINGS OF AIR ENTERING THE
C            PEANUT BED, UNITS: KOHMS (INDEX1=1) (OPTIONAL)
C                     UNITS: DECIMAL (INDEX1=2)
C   TDBAR=DRY BULB TEMPERATURE READINGS OF AMBIENT AIR
C                     UNITS: KOHMS    IF INDEX1=1
C                           CELCIUS  IF INDEX1=2
C   TWBAR=WET BULB TEMPERATURE READINGS OF AMBIENT AIR
C                     UNITS: KOHMS (INDEX1=1)
C                     UNITS: DECIMAL (INDEX1=2)
C                     UNITS: INCHES OF WATER
C  TEMINL=AIR TEMPERATURE JUST BELOW THE BED, C
C  TLRATE=FUNCTION TO CALCULATE THIN LAYER DRYING RATE
C  TPO    =INITIAL PEANUT TEMPERATURE, C
C   WBMCO=INITIAL MOISTURE CONTENT OF PRODUCT, WET BASIS DECIMAL
C  WEIGHT=INITIAL WEIGHT OF THE PRODUCT, KG
C
C ***********************************************************************
C
C              VARIABLE DECLARATIONS
C              ---------------------
      REAL AIRTEM(721,111),HUMDTY(721,111),PROTEM(721,111)
      REAL DBMOIS(721,111),TEMINL(721),HUMINL(721)
      REAL TLRATE, AIRFLX,FRH,PI,RHOP,RHOAIR,CAIR,CVAPOR,CWATER
      REAL CPRODT,POUT(9),WBMCO,DBMCO,TPO,DEPTH,WEIGHT
      REAL TDBXR(30),TWBXR(30),TDBER(30),TWBER(30),RHER(30)
      REAL TDBAR(30),TWBAR(30),RHAR(30),SPJ(721),REST
      REAL HUMA(30),HUME(30),HUMX(30),FLOW,B(721),DRYTIM(721)
      REAL COEF(4,721),TIME(721),EMC,ERH
      INTEGER NTEST,NCOL,NYEAR,NRESP,NREAD,NHR,NREC,INDEX1,IL
      INTEGER JTIME(100),KTIME(100),KTTIME,IR
C
C SOME VARIABLES ARE TREATED AS CONSTANTS
```

```
      PARAMETER (PI=3.1415927,RHOAIR=1.1614,CAIR=1.007E3,
     $CVAPOR=1.877E3,CWATER=4.178E3,CPRODT=2.9308E3,PATM=101325.)
      DATA DELT/0.10/,DELX/0.01/,AREA/0.25/
C *****************************************************************
C *****************************************************************
C
C             DATA PROCESSING SECTION  (PREPROCESSING)
C             ----------------------
C *****************************************************************
C *****************************************************************
C
C    IN THIS SECTION,
C       1. DATA ARE READ FROM AN EXTERNAL FILE AND WRITTEN IN THE
C          OUTPUT FILE,
C       2. INTERPOLATION IS DONE USING HERMITE CUBIC INTERPOLATION,
C  AND  3. NECESSARY INPUTS ARE CALCULATED FOR THE WORKING SECTION.
C
C*****************************************************************
C *****************************************************************
C
C  INPUT DATA READING (DEVICE NO.=5)  AND WRITING (DEVICE NO.=6)
C *****************************************************************
C  VARIABLE DEFINITIONS FOR RECORD 1
C        NTEST=TEST NUMBER
C        NCOL=COLUMN NUMBER
C        NYEAR=YEAR
C *****************************************************************
      READ(5,1000)NTEST,NCOL,NYEAR
 1000 FORMAT(2I2,I5)
      WRITE(6,2000)NTEST,NCOL,NYEAR
 2000 FORMAT(/2X,'TEST NO.',I2,2X,'COLUMN NO.',I2,2X,I4)
C *****************************************************************
C  VARIABLE DEFINITIONS FOR RECORD 2
C        NRESP=NO. OF STATIC PRESSURE READINGS
C        NREAD=NO. OF THERMISTER/RH READINGS
C        NHR  =NO OF HOURS IN THE DRYING TEST
C        NREC=1 TEST INCLUDES RECIRCULATION, NREC=2 TEST DOES NOT
C             INCLUDE RECIRCULATION
C        INDEX1=1 IF DRY BULB TEMPERATURE AND WET BULB TEMPERATURE
C                 ARE GIVEN FOR AMBIENT AND INPUT CONDITIONS
C                 USING THERMISTORS (KOHM VALUES)
C         INDEX1=2 IF DRY BULB AND RELATIVE HUMIDITY ARE GIVEN
C                USING HYGROMETER (C VALUES AND DECIMAL VALUES
C                RESPECTIVELY) FOR AMBIENT AND INPUT CONDITIONS
C *****************************************************************
      READ(5,1010)NRESP,NREAD,NHR,NREC,INDEX1
 1010 FORMAT(2I3,I4,I2,I2)
C *****************************************************************
C  VARIABLE DEFINITIONS FOR RECORD 3
C        WBMCO=INITIAL MOISTURE CONTENT OF PRODUCT, WET BASIS DECIMAL
C        TPO = INITIAL PRODUCT TEMPERATURE, C
C       RHOP=BULK DENSITY AT ZERO MOISTURE CONTENT, KG/ CUBIC M
C        DEPTH= DEPTH OF THE PRODUCT, M
C        WEIGHT=INITIAL WEIGHT OF THE PRODUCT, KG
C *****************************************************************
      READ(5,1020)WBMCO,TPO,RHOP,DEPTH,WEIGHT
 1020 FORMAT(5F8.3)
      WRITE(6,2010)WBMCO
 2010 FORMAT(/2X,'INITIAL MOISTURE CONTENT OF PRODUCT',F8.4,'(W.B.)')
      WRITE(6,2020)TPO,RHOP
 2020 FORMAT(/2X,'INITIAL PEANUT TEMPERATURE',F8.4,1X,'C',2X,
     $'BULK DENSITY ', F8.4,'(KG/C. M)')
```

```
      WRITE(6,2030)DEPTH,WEIGHT
 2030 FORMAT(/2X,'PRODUCT DEPTH',F8.4,1X,'M',2X,'INITIAL WEIGHT',F8.4,
     $1X,'(KG)')
C *******************************************************************
C
C INPUT OF MANUALLY TAKEN DATA
C
C *******************************************************************
C VARIABLE DEFINITIONS
C
C        TDBXR=DRY BULB TEMPERATURE READINGS OF AIR EXITING THE
C             PEANUT BED, UNITS: KOHMS   IF INDEX1=1
C                          CELSIUS IF INDEX1=2
C        TWBXR=WET BULB TEMPERATURE READINGS OF AIR EXITING THE
C             PEANUT BED, UNITS: KOHMS (INDEX1=1)
C        TDBER=DRY BULB TEMPERATURE READINGS OF AIR ENTERING THE
C             PEANUT BED, UNITS: KOHMS    IF INDEX1=1
C                          CELCIUS  IF INDEX1=2
C        TWBER=WET BULB TEMPERATURE READINGS OF AIR ENTERING THE
C             PEANUT BED, UNITS: KOHMS (INDEX1=1) (OPTIONAL)
C        RHER  =RELATIVE HUMIDITY OF AIR ENTERING THE PEANUT BED,
C                    UNITS: DECIMAL (INDEX1=2)
C        TDBAR=DRY BULB TEMPERATURE READINGS OF AMBIENT AIR
C                    UNITS: KOHMS    IF INDEX1=1
C                          CELCIUS  IF INDEX1=2
C        TWBAR=WET BULB TEMPERATURE READINGS OF AMBIENT AIR
C                    UNITS: KOHMS (INDEX1=1)
C        RHAR  =RELATIVE HUMIDITY OF AMBIENT AIR,
C                    UNITS: DECIMAL (INDEX1=2)
C        SPJ   =STATIC PRESSURE READING JUST BELOW THE PEANUT BED
C                    UNITS: INCHES OF WATER
C        JTIME=DRYING TIMES AT WHICH THE MANUAL TEMPERATURE, RELATIVE
C             HUMIDITY WERE MEASURED
C        KTIME=DRYING TIMES AT WHICH THE STATIC PRESSURES WERE TAKEN
C
C *******************************************************************
C  READ AND WRITE MEASURED STATIC PRESSURE
C *******************************************************************
C
      READ(5,1030)(KTIME(IQ),SPJ(IQ),IQ=1,NRESP)
 1030 FORMAT(I4,F6.3)
      WRITE(6,2040)
 2040 FORMAT(/1X,'TIME',2X,'MEA. STATIC PRESS. (IN. W.C.)',/)
      WRITE(6,2050)(KTIME(IQ),SPJ(IQ),IQ=1,NRESP)
 2050 FORMAT(I5,5X,F6.3)
C *******************************************************************
C   READ MEASURED DATA
C *******************************************************************
C IF INDEX1=2 THEN GO TO 2 AND READ TEM AND REL. HUMIDITY VALUES
C
      IF (INDEX1 .EQ. 2) GO TO 2
      WRITE(6,2060)
 2060 FORMAT(/2X,' MEASURED TEMPERATURE VALUES (KOHMS)')
      WRITE(6,2070)
 2070 FORMAT(/5X,'AMBIENT',4X,'INLET',4X,'EXIT')
      WRITE(6,2080)
 2080 FORMAT(/1X,'TIME',1X,'TDB',3X,'TWB',3X,'TDB',3X,'TDB',
     $3X,'TWB',/)
      DO 1 IQ=1,NREAD
       READ(5,1040)JTIME(IQ),TDBAR(IQ),TWBAR(IQ),TDBER(IQ),TDBXR(IQ),
     $TWBXR(IQ)
 1040  FORMAT(I4,5F6.3)
```

```
      WRITE(6,2090)JTIME(IQ),TDBAR(IQ),TWBAR(IQ),TDBER(IQ),TDBXR(IQ),
     $TWBXR(IQ)
 2090 FORMAT(I5,5F6.3)
C CONVERT RESISTANCE DATA TO TEMPERATURES (DEG. C)
C AMBIENT AIR CONDITIONS
      TDBAR(IQ)=REST(TDBAR(IQ))
      TWBAR(IQ)=REST(TWBAR(IQ))
      CALL PSYC(1,TDBAR(IQ),TWBAR(IQ),POUT)
      HUMA(IQ)=POUT(4)
      RHAR(IQ)=POUT(1)
C ENTERING AIR CONDITIONS
      TDBER(IQ)=REST(TDBER(IQ))
C FOR CASE OF NO RECIRCULATION
      HUME(IQ)=HUMA(IQ)
C EXITING AIR CONDITIONS
      TDBXR(IQ)=REST(TDBXR(IQ))
      TWBXR(IQ)=REST(TWBXR(IQ))
      CALL PSYC(1,TDBXR(IQ),TWBXR(IQ),POUT)
      HUMX(IQ)=POUT(4)
    1 CONTINUE
C
C  IF TEMPERATURE AND RELATIVE HUMIDITY ARE MEASURED, READ AND WRITE
    2 IF (INDEX1 .EQ. 1) GO TO 4
      WRITE(6,2100)
 2100 FORMAT(/2X,' MEASURED TEMPERATURE (C) AND REL. HUMIDITY (DEC.)')
      WRITE(6,2110)
 2110 FORMAT(/10X,'AMBIENT',12X,'INLET',12X,'EXIT')
      WRITE(6,2120)
 2120 FORMAT(/1X,'TIME',4X,'TDB',6X,'RHA',6X,'TDB',5X,'RHI',6X,'TDB',
     $6X,'TWB',/)
      DO 3 IQ=1,NREAD
      READ(5,1050)JTIME(IQ),TDBAR(IQ),RHAR(IQ),TDBER(IQ),RHER(IQ),
     $TDBXR(IQ),TWBXR(IQ)
 1050 FORMAT(I4,6F9.3)
      WRITE(6,2130)JTIME(IQ),TDBAR(IQ),RHAR(IQ),TDBER(IQ),RHER(IQ),
     $TDBXR(IQ),TWBXR(IQ)
 2130 FORMAT(I4,6F9.3)
C HUMIDITY OF AMBIENT AIR
       PSA=PWS(TDBAR(IQ))
       PVA=PSA*RHAR(IQ)
       HUMA(IQ)=0.6219*PVA/(PATM-PVA)
       CALL PSYC(2,TDBAR(IQ),HUMA(IQ),POUT)
       TWBAR(IQ)=POUT(3)
C HUMIDITY OF ENTERING AIR
       PSE=PWS(TDBER(IQ))
       PVE=PSE*RHER(IQ)
       HUME(IQ)=0.6219*PVE/(PATM-PVE)
C CONVERT RESISTANCE DATA TO TEMPERATURES (DEG. C)
      TDBXR(IQ)=REST(TDBXR(IQ))
      TWBXR(IQ)=REST(TWBXR(IQ))
      CALL PSYC(1,TDBXR(IQ),TWBXR(IQ),POUT)
      HUMX(IQ)=POUT(4)
    3 CONTINUE
C *****************************************************************
C *****************************************************************
C
C           INTERPOLATION OF INPUT VALUES
C
C *****************************************************************
C
C      INTERPOLATION OF STATIC PRESSURE VALUES
C *****************************************************************
```

```
C
C FIRST CLOCK TIME VALUES ARE CONVERTED TO DRYING TIME VALUES
C ********************************************************************
C VARIABLE DEFINITIONS
C         DRYTIM=DRYING TIME, HOURS
C         IQ    =COUNTER
C         KTTIME=INTERMEDIATE INTEGER VARIABLE
C ********************************************************************
C
 4      DRYTIM(1)=0.0
        KTIME(1)=KTIME(1)/100
        ND=0
      DO 5 IQ=2,NRESP
          KTIME(IQ)=KTIME(IQ)/100
       IF (KTIME(IQ-1) .GT. KTIME(IQ))  THEN
          ND=ND+1
       END IF
          KTTIME=24*ND+KTIME(IQ)
        DRYTIM(IQ)=  FLOAT(KTTIME-KTIME(1))
 5    CONTINUE
C
C********************************************************************
C INTERPOLATION OF STATIC PRESSURE VALUES
C
C IMSL SUBROUTINE CSDEC AND FUNCTION CSVAL ARE CALLED FOR
C CUBIC SPLINE INTERPOLATION.
C********************************************************************
C       ********************************************
       CALL CSDEC(NRESP,DRYTIM,SPJ,0,0,0,0,B,COEF)
C       ********************************************
C
         NINTV=NRESP-1
         DO 6 I=1,721
          TIME(I)=FLOAT(I-1)*DELT
          SPJ(I)=CSVAL(TIME(I),NINTV,B,COEF)
 6       CONTINUE
C
C
C ********************************************************************
C
C ENTERING AIR CONDITIONS TO THE BED ARE INTERPOLATED
C
C ********************************************************************
C
C DRYING TIME VALUES ARE CALCULATED USING JTIME DATA
C ********************************************************************
        DRYTIM(1)=0.0
        JTIME(1)=JTIME(1)/100
        ND=0
      DO 9 IQ=2,NREAD
          JTIME(IQ)=JTIME(IQ)/100
       IF (JTIME(IQ-1) .GT. JTIME(IQ))  THEN
          ND=ND+1
        END IF
          KTTIME=24*ND+JTIME(IQ)
        DRYTIM(IQ)=  FLOAT(KTTIME-JTIME(1))
 9    CONTINUE
C********************************************************************
C WRITE OUT MEASURED AMBIENT, ENTERING AND EXITING AIR CONDITIONS
C
     WRITE(6,2160)
 2160  FORMAT(/,2X,' MEASURED AIR CONDITIONS',/)
```

```
      WRITE(6,2170)
2170  FORMAT(/,2X,'TIME',2X,'TDBA',2X,'TWBA',2X,' RHA ',2X,' HUMA  ',/
       DO 10 IQ=1,NREAD
       WRITE(6,2180)DRYTIM(IQ),TDBAR(IQ),TWBAR(IQ),RHAR(IQ),HUMA(IQ)
2180    FORMAT(2X,F4.1,2X,F4.1,2X,F4.1,2X,F5.3,2X,F6.5)
 10    CONTINUE
      IF (INDEX1 .EQ. 1) THEN
       WRITE(6,2171)
2171  FORMAT(/,2X,'TIME',2X,'TDBE',2X,/)
       DO 11 IQ=1,NREAD
       WRITE(6,2181)DRYTIM(IQ),TDBER(IQ)
2181    FORMAT(2X,F4.1,2X,F4.1)
 11    CONTINUE
      ELSE
       WRITE(6,2172)
2172  FORMAT(/,2X,'TIME',2X,'TDBE',2X,' RHE ',2X,' HUME  ',/)
       DO 12 IQ=1,NREAD
       WRITE(6,2182)DRYTIM(IQ),TDBER(IQ),RHER(IQ),HUME(IQ)
2182    FORMAT(2X,F4.1,2X,F4.1,2X,F5.3,2X,F6.5)
 12    CONTINUE
      END IF
       WRITE(6,2173)
2173  FORMAT(/,2X,'TIME',2X,'TDBX',2X,'TWBX',2X,' HUMX  ',/)
       DO 13 IQ=1,NREAD
       WRITE(6,2183)DRYTIM(IQ),TDBXR(IQ),TWBXR(IQ),HUMX(IQ)
2183    FORMAT(2X,F4.1,2X,F4.1,2X,F4.1,2X,F6.5)
 13    CONTINUE
C***********************************************************************
C INTERPOLATION CONTINUES......
C
C INTERPOLATION OF ENTERING TEMPERATURE, TDBER
C IMSL SUBROUTINE CSDEC AND FUNCTION CSVAL ARE CALLED FOR
C CUBIC SPLINE INTERPOLATION.
C***********************************************************************
C        *******************************************
       CALL CSDEC(NREAD,DRYTIM,TDBER,0,0,0,0,B,COEF)
C        *******************************************
C
         NINTV=NREAD-1
        DO 14 I=1,721
         TIME(I)=FLOAT(I-1)*DELT
         TEMINL(I)=CSVAL(TIME(I),NINTV,B,COEF)
 14      CONTINUE
C
C
C***********************************************************************
C INTERPOLATION CONTINUES FURTHER .............
C
C INTERPOLATION OF ENTERING HUMIDITY, HUME
C IMSL SUBROUTINE CSDEC AND FUNCTION CSVAL ARE CALLED FOR
C CUBIC SPLINE INTERPOLATION.
C***********************************************************************
C        *******************************************
       CALL CSDEC(NREAD,DRYTIM,HUME,0,0,0,0,B,COEF)
C        *******************************************
C
         NINTV=NREAD-1
        DO 15 I=1,721
         TIME(I)=FLOAT(I-1)*DELT
         HUMINL(I)=CSVAL(TIME(I),NINTV,B,COEF)
 15      CONTINUE
C
```

```
C END OF PREPROCESSING SECTION
C*******************************************************************
C
C ARRAYS TEMINL AND HUMINL ARE PASSED TO THE PROCESSING SECTION
C OF THE DRYER.  REST OF THE PROCESS CALCULATIONS ARE DONE
C IN THE PROCESSING SECTION OF THE PROGRAM.
C   TEMINL CONTAINS DB TEMPERATURE OF THE ENTERING AIR.
C   HUMINL CONTAINS HUMIDITY OF ENTERING AIR IN THE CASE OF DIRECT
C   DRYING, AND IT CONTAINS HUMIDITY OF AMBIENT AIR IN THE CASE
C   OF DRYING WITH RECIRCULATION OF EXHAUST AIR.
C
C ******************************************************************
C ******************************************************************
C ******************************************************************
C        WORKING SECTION OF THE DRYER
C
C THIS SECTION OF THE MAIN PROGRAM MODELS THE DRYING MECHANISM OF THE
C DRYER.  TWO DIMENSIONAL ARRAYS ARE USED TO IMPROVE THE FLEXIBILITY
C OF THE PROGRAM EVEN THOUGH IT IS POSSIBLE TO USE ONE DIMENSIONAL
C ARRAYS TO SOLVE A SYSTEM OF FIRST ORDER DIFFERENTIAL EQUATIONS.
C (REF. FINITE DIFFERENCE SCHEMES AND PARTIAL DIFFERENCE EQUATIONS
C      JOHN C. STRIKWERDA, 1989
C  WADSWORTH AND BROOKS/COLE MATHEMATICS SERIES)
C  LEAP FROG SCHEME WAS EMPLOYED.
C
C*******************************************************************
C VARIABLE DESCRIPTION
C
C  AIRTEM=TEMPERATURE OF AIR (C) AT (TIME=T,DISTANCE FROM BOTTOM=X)
C  PROTEM=TEMPERATURE OF PEANUTS (C) AT (T,X)
C  HUMDTY=HUMIDITY OF AIR (KG/KG) AT (T,X)
C  DBMOIS=DRY BASIS MOISTURE CONTENT OF PEANUTS (DECIMAL) AT (T,X)
C  DELT=TIME INCREMENT, HR
C  DELX=SPACE INCREMENT, M
C  TEMINL=AIR TEMPERATURE JUST BELOW THE BED, C
C  HUMINL=HUMIDITY OF AIR JUST BELOW THE BED, KG/KG
C  AIRFLX=MASS FLUX OF DRY AIR, KG PER SQ. M PER HOUR
C  TLRATE=FUNCTION TO CALCULATE THIN LAYER DRYING RATE
C  RHOP   =PRODUCT DENSITY, KG/CU. M
C  RHOAIR=AIR DENSITY, KG/CU. M
C  CAIR   =SPECIFIC HEAT OF AIR, J/KG.K
C  CVAPOR=SPECIFIC OF WATER VAPOR, J/KG.K
C  CWATER=SPECIFIC HEAT OF SATURATED WATER, J/KG.K
C  CPRODT=SPECIFIC HEAT OF DRY SOLIDS IN PEANUTS, J/KG.K
C  TPO    =INITIAL PEANUT TEMPERATURE, C
C  DBMCO  =INITIAL MOISTURE CONTENT OF PEANUTS, DRY BASIS DECIMAL
C  SHTC   =SURFACE HEAT TRANSFER COEFFICIENT, J/SQ. M. K. HR
C  SAREA  =SPECIFIC AREA, SQ. M/CU. M
C ******************************************************************
C ******************************************************************
C
C                 INITIALIZATION PROCESS
C
C ******************************************************************
C
C IN THIS SECTION, FINITE DIFFERENCE SCHEME IS INITIALIZED.
C FOR EACH TIME INCREMENT, AIR CONDITIONS AT THE BOTTOM ARE COMPUTED.
C INLET AIR TEMPERATURE AND HUMIDITY ARE GIVEN BY ARRAYS
C TEMINL AND HUMINL. THESE ARRAYS ARE COMPUTED IN PREPROCESSING SECTION
C BEFORE STARTING THE FINITE DIFFERENCE COMPUTATIONS, LEAF FROG
C SCHEMES  REQUIRE SETTING UP  OF A STARTING PROCEDURE.
C*******************************************************************
```

```
C
C
C
C INITIAL MOISTURE CONTENT AND PEANUT TEMPERATURE ARE GIVEN.
C WET BASIS MOISTURE CONTENT IS CONVERTED TO DRY BASIS MOISTURE CONTENT
      DBMCO=WBMCO/(1.-WBMCO)
     DO 20 M=1,111
      DBMOIS(1,M)=DBMCO
      PROTEM(1,M)=TPO
 20   CONTINUE
      DO 22 N=1,721
        AIRTEM(N,1)=TEMINL(N)
        HUMDTY(N,1)=HUMINL(N)
C MOISTURE CONTENT OF PEANUTS AT THE INLET IS COMPUTED
       DBMOIS(N+1,1)=DBMOIS(N,1)+DELT*TLRATE(N,DELT,AREA,SPJ(N),
     $AIRTEM(N,1),HUMDTY(N,1),DBMOIS(1,1))

  22  CONTINUE
C INITIAL MOISTURE GRADIENT AND TEMPERATURE GRADIENTS ARE ESTABLISHED
      DO 25 N=1,2
      H0=1.006*AIRTEM(N,1)+HUMDTY(N,1)*(2501.+1.775*AIRTEM(N,1))
C AIRFLX=MASS FLUX OF DRY AIR, KG PER SQ. M PER HOUR
      AIRFLX=FLOW(AIRTEM(N,1),HUMDTY(N,1),AREA,SPJ(N))
C
      DO 23 M=2,111
       DBMOIS(N+1,M)=DBMOIS(N,M)+DELT*TLRATE(N,DELT,AREA,SPJ(N),
     $AIRTEM(N,M-1),HUMDTY(N,M-1),DBMOIS(1,M))
       HUMDTY(N,M)=HUMDTY(N,M-1)-(RHOP*DELX/AIRFLX)*(DBMOIS(N+1,
     $M)-DBMOIS(N,M))/(DELT)
       AIRTEM(N,M)=(H0-2505.0*HUMDTY(N,M))/(1.006+1.775*
     $HUMDTY(N,M))
  23 CONTINUE
  25 CONTINUE
C
C*******************************************************************
C             CORE SECTION
C
C*******************************************************************
C TIME LOOP STARTS HERE
C
C
     DO 40 N=2,721
C
C  CONDITIONS ARE CALCULATED FOR ALL THE POSITIONS OF THE BED.
C
     DO 35 M=2,110
C *******************************************************************
C  SPACE DEPENDENT CONSTANTS ARE COMPUTED
C TIME DEPENDENT CONSTANTS ARE CALCULATED.
C
      AIRFLX=FLOW(AIRTEM(N-1,M-1),HUMDTY(N-1,M-1),AREA,SPJ(N))
C
      SHTC  =3.6E5*(AIRFLX/3600.)**0.49
      SAREA=188.0
C *******************************************************************
C  MOISTURE CONTENT IS CALCULATED
C  IF PREVIOUS MOISTURE CONTENT IS EQUAL OR LESS THAN EQUILIBRIUM
C  MOISTURE CONTENT FOR THE AIR CONDITION THEN THE MOISTURE CONTENT
C  DOES NOT CHANGE.
C CONDENSATION IS MODELED THROUGH A SUBROUTINE  (CONDEN)
C
```

```
      PWC=(PATM*HUMDTY(N,M-1))/(1000.0*(0.62198+HUMDTY(N,M-1)))
      PWCS=PWS(AIRTEM(N,M-1))/1000.0
      ALPH=LOG(PWC)
      RH1=PWC/PWCS
      IF (RH1 .GT. 0.99999999) RH1=0.99999999
      TDP1=6.983+14.38*ALPH+1.079*ALPH**2

C
C CALCULATION OF LATENT HEAT OF VAPORIZATION AT DEW POINT TEMPERATURE
C
      HFG  =(2502.535-2.385764*TDP1)*1000.
C
C MODELING THE CONDENSATION
C
      IF (RH1 .EQ. .99999999) THEN
        CALL CONDEN(AIRFLX,HFG,RHOP,DELT,DELX,
     $AIRTEM(N,M-1),HUMDTY(N,M-1),DBMOIS(N-1,M),
     $PROTEM(N-1,M),AIRTEM(N,M+1),HUMDTY(N,M+1),DBMOIS(N+1,M),PROTEM
     $(N+1,M), AIRTEM(N,M),HUMDTY(N,M),DBMOIS(N,M),PROTEM(N,M))
        GO TO 34
      END IF
C
C IF THE MOISTURE CONTENT OF THE PRODUCT IS LESS THAN OR EQUAL TO THE
C EQUALIBRIUM MOISTURE CONTENT FOR THAT TEMPERATURE, AND REL. HUMIDITY
C THEN THE MOISTURE CONTENT DOES NOT CHANGE.
C
      DBEMC=EMC(AIRTEM(N,M-1),RH1)
      IF (DBMOIS(N-1,M) .GT. DBEMC) THEN
       DBMOIS(N+1,M)=DBMOIS(N-1,M)+2.0*DELT*TLRATE(N,DELT,AREA,SPJ(N)
     $AIRTEM(N,M-1),HUMDTY(N,M-1),DBMOIS(1,M-1))
       ELSE
         DBMOIS(N+1,M)=DBMOIS(N-1,M)
      END IF
C
       DBMOIS(N,M)=(DBMOIS(N+1,M)+DBMOIS(N-1,M))/2.0
C
C HUMIDITY IS CALCULATED
       HUMDTY(N,M+1)=HUMDTY(N,M-1)-(2.0*RHOP*DELX/AIRFLX)*(DBMOIS(N+1
     $M)-DBMOIS(N-1,M))/(2.0*DELT)
       HUMDTY(N,M)=(HUMDTY(N,M+1)+HUMDTY(N,M-1))/2.0
C
C AIR TEMPERATURE IS CALCULATED
     AIRTEM(N,M+1)=AIRTEM(N,M-1)*((AIRFLX*CAIR+AIRFLX*CVAPOR*HUMDTY
     $(N,M)-DELX*SHTC*SAREA)/(AIRFLX*CAIR+AIRFLX*CVAPOR*HUMDTY(N,M)
     $+DELX*SHTC*SAREA))+(2.*DELX*SHTC*SAREA*PROTEM(N-1,M))/(AIRFLX*CAI
     $+AIRFLX*CVAPOR*HUMDTY(N,M)+DELX*SHTC*SAREA)
     AIRTEM(N,M)=(AIRTEM(N,M+1)+AIRTEM(N,M-1))/2.
C
C
C PRODUCT TEMPERATURE IS CALCULATED
C
C AN INTERMEDIATE CONSTANT IS CALCULATED
C
     F1=0.5*(-2.*DELT*SHTC*SAREA/(RHOP*CPRODT+RHOP*CWATER*DBMOIS(N,M)
     $+(CVAPOR*AIRFLX*DELT*(HUMDTY(N,M+1)-HUMDTY(N,M-1)))/(DELX*(RHOP*
     $CPRODT+RHOP*CWATER*DBMOIS(N,M))))
C
     PROTEM(N+1,M)=PROTEM(N-1,M)*(1.+F1)/(1.-F1)  +AIRTEM(N,M)*2.*DELT*
     $SHTC*SAREA/((1.-F1)*(RHOP*CPRODT+RHOP*CWATER*DBMOIS(N,M)))-
     $(HFG+CVAPOR*AIRTEM(N,M))*AIRFLX*DELT*(HUMDTY(N,M+1)-HUMDTY(N,M-1)
     $/((1.-F1)*(RHOP*CPRODT+RHOP*CWATER*DBMOIS(N,M))*DELX)
C
```

```
      PROTEM(N,M)=(PROTEM(N+1,M)+PROTEM(N-1,M))/2.0
C
 34   PROTEM(N,1)=(PROTEM(N+1,2)-PROTEM(N-1,1))/2. +PROTEM(N-1,1)
 35   CONTINUE
 40   CONTINUE
C
C**********************************************************************
C
C                    OUTPUT SECTION
C
C**********************************************************************
C  THIS SECTION CALCULATES THE NECESSARY OUTPUTS AND WRITE THEM
C  ON A SEPARATE DISK.  THIS SECTION CAN EASILY BE INTEGRATED INTO
C  THE PREVIOUS SECTION BY INSERTING  IN THE LOOP.  BUT, OUTPUT SECTION
C   WAS PROGRAMMED SEPARATELY TO INCREASE THE FLEXIBLITY OF THE
C  PROGRAM.
C**********************************************************************
C**********************************************************************
C AVERAGE MOISTURE CONTENT OF THE WHOLE BED WITH TIME IS WRITTEN OUT.
C
C THE GRID POINT AT WHICH THE TOP LAYER BEGINS SHOULD BE GIVEN.
C
          MTOT=111
          NTOT=721
          MGAP=05
C EVERY HALF HOUR
          INTER=10
        WRITE(6,2203)
 2203   FORMAT(//,30X,'SIMULATION RESULTS',//,15X,'TIME',5X,'AVE. MOIS
     $(D.B.)')

        DO 41 N=1,NTOT
          SUMDBM=0.0
          TOPDBM=0.0
        DRTIME=FLOAT(N-1)*DELT
         DO 42 M=1,MTOT-1
          SUMDBM=SUMDBM+DBMOIS(N,M)
 42       CONTINUE
          AVEDBM=SUMDBM/FLOAT(MTOT-1)
C
C IF THE AVERAGE MOISTURE CONTENT OF THE BED IS LESS THAN 0.111 D. BASI
C DRYING TIME IS WRITTEN OUT.
          IF (AVEDBM .LT. 0.115 .AND. AVEDBM .GT. 0.111) FTIME=DRTIME
        WRITE(6,2205)DRTIME,AVEDBM
 2205     FORMAT(13X,F5.2,4X,F8.3)
 41     CONTINUE
       WRITE(6,2206)FTIME
 2206   FORMAT(/,2X,'TIME TAKEN TO DRY PEANUTS TO 10% MC (W.B.)=',F8.2)
C *********************************************************************
C *********************************************************************
C THIS SECTION WRITE OUT AIR CONDITION AT DIFFERENT POINTS IN THE
C BED ALONG WITH THE PRODUCT TEMPERATURE.
C
       DO 43 M=1,MTOT,MGAP
         IF (M .EQ. 1) GOTO 43
         IF (M .EQ. MTOT) GOTO 43
         DIST=DELX*FLOAT(M-1)
         WRITE(6,2207)DIST
 2207   FORMAT(/,5X,'VERTICAL DISTANCE FROM BOTTOM IN METERS =',F5.3,/)
         WRITE(6,2208)
 2208   FORMAT(/,5X,'TIME',2X,'TEM (D.B.)',2X,'TEM. (W.B.)',2X,
     $'HUMIDITY',2X,'PROD. TEM',2X,'MOISTURE D.B' /)
```

```
      DO 44 N=1,NTOT,INTER
      IF (N .EQ. NTOT) GOTO 44
      DRTIME=DELT*FLOAT(N-1)
        CALL PSYC(2,AIRTEM(N,M),HUMDTY(N,M),POUT)
C AVERAGE THE MOISTURE CONTENT AROUND THE POINT
      DBMOIS(N,M)=ABS((DBMOIS(N,M-4)+DBMOIS(N,M-3)+DBMOIS(N,M-2)
     $+DBMOIS(N,M-1)+DBMOIS(N,M)+DBMOIS(N,M+1)+DBMOIS(N,M+2)
     $+DBMOIS(N,M+3)+DBMOIS(N,M+4))/9.0)
      WRITE(6,2209)DRTIME, AIRTEM(N,M),POUT(3),HUMDTY(N,M),
     $PROTEM(N,M),DBMOIS(N,M)
 2209  FORMAT(3X,F5.2,2F12.3,F12.6,F13.3,F13.5)
  44   CONTINUE
  43   CONTINUE
      STOP
      END
C*********************************************************************
C END OF MAIN PROGRAM
C*********************************************************************
C
C            FUNCTION TLRATE(N,DELT,AREA,SPJ,TEM,HUM,DBMI)
C*********************************************************************
C
C THIS FUNCTION CALCULATED THE THIN LAYER DRYING RATES FOR A GIVEN TIME
C AIR TEMPERATURE AND HUMIDITY
C
C VARIABLES
C        TEM=TEMPERATURE,C                          ......INPUT
C        HUM=HUMIDITY,KG/KG                         ......INPUT
C        AREA=CROSS SECTIONAL AREA, SQ. M           ......INPUT
C        SPJ=STATIC PRESSURE, INCH WATER            ......INPUT
C        RME=EQUILIBRIUM MOISTURE CONTENT, D.B. .....COMPUTED
C        RK=DRYING CONSTANT                         .......COMPUTED
C        RN=DRYING EXPONENT                         .......COMPUTED
C        N=TIME INDEX                               .......INPUT
C        DELT=TIME INTERVAL,HR                      .......INPUT
C        RH=RELATIVE HUMIDITY,DEC                   .......COMPUTED
C
      FUNCTION TLRATE(N,DELT,AREA,SPJ,TEM,HUM,DBMI)
       REAL DELT,AREA,SPJ,TEM,HUM,DBMI,TIME,RH,RK,RN,POUT(9)
       REAL VELFAC,A,B,C,TREF
       INTEGER N
        TIME=FLOAT(N)*DELT
        CALL PSYC(2,TEM,HUM,POUT)
         RH=POUT(1)
        RME=((-LOG(1.-RH))**0.7)*(111./(TEM+273.))**2.4
        RK=EXP(-0.780523-0.144026*TEM+0.00358*TEM**2+2.13914*RH
     $+0.715991*DBMI-0.137131*TEM*RH)
        RN=0.98867+0.019836*TEM-0.000608*TEM**2-1.033613*RH-0.63824017*
     $DBMI+0.0499769*TEM*RH
C VELOCITY FACTOR IS CALCULATED (COLSON & YOUNG, 1988)
          A= 1119.99061201
          B=-10234.18560008
          C=24281.40000027
         TREF=REST(5.220)
        FLOW=((TEM+273.16)/(TREF+273.16))*(A+B*SPJ+C*SPJ**2)/AREA
        VELFAC=(FLOW/(2.51*60.))**0.70
C
        TLRATE=-(DBMI-RME)*VELFAC*RK*RN*((TIME)**(RN-1.))
     $*EXP(-RK*(TIME)**RN)
        IF (TLRATE .GT. 0.0) TLRATE=0.0
      RETURN
      END
```

```
C
C*******************************************************************
C *******************************************************************
C
C               FUNCTION FLOW(TEMP,HUM,AREA,PRESS)
C
C *******************************************************************
C THIS FUNCTION CALCULATES THE AIR FLUX THROUGH THE BED.
C *******************************************************************
C VARIABLE DEFINITION:
C           TEMP=TEMPERATURE OF AIR, C
C           HUM =HUMIDITY OF AIR, DECIMAL
C           AREA=AREA OF THE DRYER CROSS SECTION, SQ. M
C          PRESS=STATIC PRESSURE DOWNSTREAM OF THE FAN, INCHES WATER
C           FLOW=MASS FLUX OF AIR, KG PER SQ. M PER HOUR
C *******************************************************************
C
      FUNCTION FLOW(TEMP,HUM,AREA,PRESS)
      REAL TEMP,HUM,AREA,POUT(9),VSA,PRESS,A,B,C,TREF
        CALL PSYC(2,TEM,HUM,POUT)
          VSA=POUT(9)
          A= 1119.99061201
          B=-10234.18560008
          C=24281.40000027
        TREF=REST(5.220)
       FLOW=((TEM+273.16)/(TREF+273.16))*(A+B*PRESS+C*PRESS**2)/
     $(VSA*AREA)
      RETURN
      END
C *******************************************************************
C
C               FUNCTION EMC
C
C *******************************************************************
C
C  THIS FUNCTION GIVES THE EQUILIBRIUM MOISTURE CONTENT OF PEANUTS
C  CALCULATED BY A CHUNG-FOST TYPE EQUATION.
C *******************************************************************
C VARIABLE DIFINITIONS:
C
C   EMC=EQUILIBRIUM MOISTURE CONTENT OF PEANUTS, D.B. DECIMAL
C   TEM=TEMPERATURE, C
C   RH=RELATIVE HUMIDITY, DECIMAL
C
       FUNCTION EMC(TEM,RH)
       REAL TEM,EMC,A,B,C,POUT(9),RH
        A=0.25200673
        B=-0.04290912
        C=60.0249
        EMC=A+B*LOG(-(TEM+C)*LOG(RH))
       RETURN
       END
C
C *******************************************************************
C
C               SUBROUTINE CONDEN
C
C *******************************************************************
C  THIS SUBROUTINE MODELS THE CONDENSATION THAT OCCURS WHEN
C  RELATIVE HUMIDITY OF AIR EXCEEDS 0.99999999.  PRODUCT TEMPERATURE
C  CHANGE IS CONSIDERED NEGLIGIBLE.  DURING CONDENSATION
C  AIR TEMPERATURE AND DBMC INCREASES AND HUMIDITY DROPS.
```

```
C
C ********************************************************************
C
C VARIABLE DEFINITIONS ARE SAME AS IN THE MAIN PROGRAM
C ********************************************************************
C
C  INPUTS-AIRFLX,HFG,DELT,DELX,RHOP,ATEM1,HUM1,DBM1,PTEM1
C  OUTPUTS-ATEM2,HUM2,DBM2,PTEM2,ATEM3,HUM3,DBM3,PTEM3
C
C ********************************************************************
      SUBROUTINE CONDEN(AIRFLX,HFG,RHOP,DELT,DELX,ATEM1,HUM1,
     $DBM1,PTEM1,ATEM3,HUM3,DBM3,PTEM3,ATEM2,
     $HUM2,DBM2,PTEM2)
      REAL AIRFLX,RHOP,DLEX,DELT,HFG,ATEM1,HUM1
      REAL DBM1,PTEM1,ATEM2,HUM2,DBM2,PTEM2,ATEM3,HUM3,DBM3,PTEM3
      REAL WBTEM
      INTEGER MODE
      DATA CAIR/1.007E3/,CVAPOR/1.877E3/
        WBTEM=ATEM1
         PWWB=PWS(WBTEM)
         HUM3=0.62198*PWWB/(101325.-PWWB)
         HUM2=(HUM1+HUM3)/2.0
         DBM3=DBM1+(AIRFLX*DELT/(RHOP*DELX))*(HUM1-HUM3)
         DBM2=(DBM1+DBM3)/2.0
       ATEM3=(ATEM1*(CAIR+CVAPOR*HUM1)-HFG*(HUM3-HUM1))/
     $(CAIR+CVAPOR*HUM3)
       ATEM2=(ATEM1+ATEM3)/2.0
       PTEM2=PTEM1
       PTEM3=PTEM1
      RETURN
      END
C********************************************************************
C ********************************************************************
C***              SUBROUTINE PSYC
C********************************************************************
C
C********************************************************************
C***    SUBROUTINE PSYC CALCULATES THE PSYCHROMETRIC PROPERTIES OF
C***    THE DRYING AIR BASED ON THE ASAE DATA SHEET D271.2 IN THE
C***    AGRICULTURAL ENGINEERING YEARBOOK.
C********************************************************************
C***
C***    RECEIVES:
C***
C***        1. MODE = FLAG TO SIGNAL WHICH VALUES ARE TO BE EN-
C***          TERED.
C***
C***            = 1 THEN DRY BULB AND WET BULB TEMPERATURES
C***             ARE TO BE INPUT.
C***
C***            = 2 THEN DRY BULB TEMPERATURE AND HUMIDITY RATIO
C***             ARE TO BE INPUT.
C***
C***        2. P1 = ENTERING DRY BULB TEMPERATURE (C).
C***
C***        3. P2 = WET BULB TEMPERATURE (C) OR HUMIDITY RATIO
C***          DEPENDING ON THE MODE (MODE).
C***
C***    RETURNS:
C***
C***          POUT AN ARRAY CONSISTING OF:
C***
```

```
C***        1. RH = RELATIVE HUMIDITY (DEC).
C***
C***        2. TDP = DEW POINT TEMPERATURE (C).
C***
C *        3. TWB = WET BULB TEMPERATURE (C).
C**
C***
C***        5. HS = SATURATION PRESSURE (PA).
C***
C***        6. PV = PARTIAL VAPOR PRESSURE (PA).
C***
C***        7. PS = SATURATION PRESSURE (PA).
C***
C***        8. SH = ENTHALPY (J/KG).
C***
C***        9. VSA = SPECIFIC VOLUME (CUBIC M/KG).
C***
C*********************************************************************
C
      SUBROUTINE PSYC   (MODE,P1,P2,POUT)
      LOGICAL ERROR
      DIMENSION POUT(9)
      DATA PATM/101325./
      ERROR=.FALSE.
      TE=P1
      PS=PWS(TE)
      HS=0.6219*PS/(PATM-PS)
      GOTO(10,20),MODE
C
C*********************************************************************
C**    MODE 1   TA,TWBA ---> RH,TDP,TWB,H,HS,PV,PS,SH,VSA
C*********************************************************************
C
   10 CONTINUE
      TWBA=P2
      TWB=TWBA
      PSWB=PWS(TWBA)
      PV=PVWBDB(TE,TWBA,PSWB)
      H=0.6219*PV/(PATM-PV)
   14 PV=H*PATM/(H+.6219)
C
C*********************************************************************
C***    IF THE PARTIAL VAPOR PRESSURE IS LESS THAN ZERO AN ERROR
C***    MESSAGE IS GENERATED.
C*********************************************************************
C
      IF (PV.LE.0) GOTO 96
      TDP=DEW(PV)-273.16
   16 RH=PV/PS
   17 SH=ENTHAL(H,TDP,TE)
      VSA=287*(TE+273.16)/(PATM-PV)
      GOTO (90,24,24,24),MODE
C
C*********************************************************************
C***    MODE 2   TE,HE ---> RH,TDP,TWB,H,HS,PV,PS,SH,VSA
C*********************************************************************
C
C*********************************************************************
C***    IF MODE = 2 THEN P2 = H (HUMIDITY RATIO)
C*********************************************************************
C***        5. H = HUMIDITY RATIO (DEC).
C
```

```
  20 CONTINUE
     H=P2
     GOTO14
C
C*********************************************************************
C***    AN ITERATIVE PROCEDURE IS USED TO CALCULATE THE WET BULB
C***    TEMPERATURE.
C*********************************************************************
C
  24 JN=0
     TWB=(TE+2*TDP)/3
  26 CONTINUE
     PSWB=PWS(TWB)
     B=BP(PSWB,PATM,PV,TWB)
     TWB1=TE+(PSWB-PV)/B
C
C*********************************************************************
C***    A DIFFERENCE OF LESS THAN 0.012 BETWEEN THE PREVIOUS WET
C***    BULB TEMPERATURE AND THE ONE BEING CALCULATED MUST BE OB-
C***    TAINED TO SATISFY THE CONVERGENCE CRITERIA.
C*********************************************************************
C
     TWCV=ABS(TWB-TWB1)/TWB
     IF(TWCV.LT..012)GOTO 28
     TWB=(TWB1+2*TWB)/3
C*********************************************************************
C***    IF THE NUMBER OF ITERATIONS IS GREATER THAN 10 AN ERROR
C***    MESSAGE IS GENERATED.
C*********************************************************************
C
     JN=JN+1
     IF(JN.LT.10) GOTO 26
     GOTO 96
  28 TWB=TWB1
     GOTO 90
  96 CONTINUE
     ERROR=.TRUE.
  90 CONTINUE
C
C*********************************************************************
C***    IF THE RELATIVE HUMIDITY IS GREATER THAN 1.00  IT IS
C***    SET EQUAL TO 0.999.
C*********************************************************************
C
     IF(RH.GE..999) RH=.999
     POUT(1)=RH
     POUT(2)=TDP
     POUT(3)=TWB
     POUT(4)=H
     POUT(5)=HS
     POUT(6)=PV
     POUT(7)=PS
     POUT(8)=SH
     POUT(9)=VSA
     IF(ERROR) GOTO 98
     RETURN
C
C*********************************************************************
C***    ERROR MESSAGE IS GENERATED IF THE PARTIAL VAPOR PRESSURE
C***    IS LESS THAN 0 OR THE NUMBER OF ITERATIONS REQUIRED TO
C***    CALCULATE THE WET BULB TEMPERATURE IS GREATER THAN 10.
C*********************************************************************
```

```
C
  98 WRITE(6,500) MODE,JN,P1,P2
 500 FORMAT(1H0,'**ERROR**PSYC**',2X,'MODE=',I2,2X,'ITER. NO.=',I2,2X,
    &'P1=',F8.4,2X,'P2=',F8.4)
     WRITE(MOUT,501) TWB,TWB1,TWCV
 501 FORMAT(2X,'TWB=',F6.2,2X,'TWB1=',F6.2,2X,'TWCV=',F8.4)
     RETURN
     END
C
C*******************************************************************
C***        BP
C*******************************************************************
C
C*******************************************************************
C***     AN EQUATION REPRESENTING THE WET BULB LINE
C***     (ASAE D271.2).
C*******************************************************************
C
C*******************************************************************
C***
C***        1. HFGP = LATENT HEAT OF VAPORIZATION AT WET BULB
C**            TEMPERATURE (J/KG).
C***
C***        2. PSWB = SATURATION VAPOR PRESSURE (PA).
C***
C***        3. PATM = ATMOSPHERIC PRESSURE (PA).
C***
C***        4. PV = VAPOR PRESSURE (PA).
C***
C***        5. TWB = WET BULB TEMPERATURE (C).
C***
C***        6. BP = WET BULB LINE ON PSYCHROMETRIC CHART.
C***
C*******************************************************************
C
     FUNCTION BP(PSWB,PATM,PV,TWB)
     B1=1006.9254*(PSWB-PATM)*(1.+0.15577*PV/PATM)
     HFGP=2.502553E6-2.385764E3*TWB
     BP=B1/(0.62194*HFGP)
     RETURN
     END
C
C*******************************************************************
C**         DEW
C*******************************************************************
C
C*******************************************************************
C***     DEW POINT TEMPERATURE CALCULATED (ASAE D271.2)
C*******************************************************************
C
C*******************************************************************
C***
C***        1. PS = SATURATION VAPOR PRESSURE (PA).
C***
C***        2. DEW = DEW POINT TEMPERATURE (K).
C***
C*******************************************************************
C
     FUNCTION DEW(PS)
     X=ALOG(0.00145*PS)
     ARG1=13.6626*X+1.17678*X**2-0.189693*X**3
     ARG2=0.087453*X**4-0.0174053*X**5+2.14768E-3*X**6
```

```
      ARG3=-0.138343E-3*X**7+0.38E-5*X**8
      DEW=255.38+19.5322+ARG1+ARG2+ARG3
      RETURN
      END
C
C*********************************************************************
C***        ENTHAL
C*********************************************************************
C
C*********************************************************************
C***    ENTHALPY OF AIR CALCULATED (ASAE D271.2)
C*********************************************************************
C
C*********************************************************************
C***
C***        1. HFGDP = LATENT HEAT OF VAPORIZATION AT DEW POINT
C***           TEMPERATURE (J/KG).
C***
C***        2. HR = HUMIDITY RATIO (DEC).
C***
C***        3. TDP = DEW POINT TEMPERATURE (C).
C***
C***        4. TDB = DRY BULB TEMPERATURE (C).
C***
C***        5. ENTHALPY = ENTHALPY (J/KG).
C***
C*********************************************************************
C
      FUNCTION ENTHAL(HR,TDP,TDB)
      HFG2P=2.502535E6-2.385764E3*TDP
      ARG1=1.006925E3*TDB+4.1868E3*HR*TDP+HFG2P*HR
      ENTHAL=ARG1+1.875686E3*HR*(TDB-TDP)
      RETURN
      END
C
C*********************************************************************
C***        PVWBDB
C*********************************************************************
C
C*********************************************************************
C***    PARTIAL VAPOR PRESSURE OF AIR IS CALCULATED (ASAE D271.2)
C*********************************************************************
C
C*********************************************************************
C***
C***        1. HFGP = LATENT HEAT OF VAPORIZATION (J/KG).
C***
C***        2. TDB = DRY BULB TEMPERATURE (C).
C***
C***        3. TWB = WET BULB TEMPERATURE (C).
C***
C***        4. PSWB = SATURATION VAPOR PRESSURE (PA).
C***
C***        5. PVWBDB = PARTIAL VAPOR PRESSURE OF AIR (PA).
C***
C*********************************************************************
C
      FUNCTION PVWBDB(TDB,TWB,PSWB)
      HFGP=2.502553E6-2.385764E3*TWB
      ARG1=0.62194*HFGP*PSWB-1.006925E3*(PSWB-101325.0)*(TWB-TDB)
      ARG2=0.62194*HFGP+156.8488*(PSWB-101325.)*(TWB-TDB)/101325.
      PVWBDB=ARG1/ARG2
```

```
      RETURN
      END
C
C*********************************************************************
C***    PWS
C*********************************************************************
C
C*********************************************************************
C***    SATURATION VAPOR PRESSURE IS CALCULATED (ASAE D271.2)
C*********************************************************************
C
C*********************************************************************
C***
C***        1. TC = DRY BULB AIR TEMPERATURE (C).
C***
C***        2. PWS = SATURATION VAPOR PRESSURE (PA).
C***
C*********************************************************************
C
      FUNCTION PWS(TC)
      T=TC+273.16
      ARG1=-27405.53+97.5413*T-0.146244*T**2
      ARG2=0.12558E-3*T**3-0.48502E-7*T**4
      ARG3=4.34903*T-0.39381E-2*T**2
      PWS=22105650.*EXP((ARG1+ARG2)/ARG3)
      RETURN
      END
C
C*********************************************************************
C
C           FUNCTION REST
C*********************************************************************
C  FUNCTION REST USES THE THERMISTER PROBE RESISTANCES AND CALCULATES
C  THE TEMPERATURES (C)
C*********************************************************************
      FUNCTION REST(R)
      REAL A,B,C,D,E
      A=-2077.423
      B=4681.344
      C=498.4451
      D=21.7356
      E=100.1315
      S=-1.0
      ARG=A+B*R+C*R**2
      IF(ARG .GT. 0.0) GO TO 10
      REST=100.0
      GO TO 20
 10   REST=D*R+E+S*SQRT(ARG)
 20   RETURN
      END
C*********************************************************************
C*********************************************************************
```

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