SPECIFIC HEAT AND SIMULATED DRYING OF FABABEANS

by

Shyam Sunder Verma

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ABSTRACT

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S. S. Verma

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The specific heat of fababeans was determined by using the method of mixtures. The tests were conducted for four different temperature ranges between -32 and 60°C, and with four moisture contents between 11 and 32%, dry basis.

The specific heat of fababeans was a linear function of dry basis moisture content for temperature ranges of -32 to 0 °C, 0 to 20 °C, 0 to 40°C, and 0 to 60°C. The specific heat of fababeans, in general, increased with temperature but between 30 to 50°C and for higher than 20% dry basis moisture content it decreased slightly with increase in temperature. For higher than 25% dry basis moisture content and for sub-freezing temperatures, latent heat of fusion was released by the moisture in the fababeans. The heat content of the water in fababeans was greater than that of free water except at temperatures higher than 40°C.

A computer simulation model was developed for deep bed drying of fababeans. The model incorporated a few modifications over the Muir and Ingram (Muir, W.E. and G.W. Ingram. 1975. Description of a Computer Program for Optimizing Harvesting and In-bin Drying of Barley in Northern Britain. Scottish Institute of Agricultural Engineering. Bush Estate, Midlothian. 26 p.) model. The model was compared with experimental results and with the Muir and Ingram model. Experimental drying tests were carried out for 3, 5, 7, and 9 d using two different air temperature ranges.

The present model gave the best predictions of grain temperatures and moisture contents when ratio of 1.0 was used between the expected vapor pressure of exiting air to the saturation vapor pressure. For the Muir and Ingram model a simulation time increment of 180 min and a layer depth of 0.50 m gave fair predictions of grain temperatures and moisture contents. The present model gave better predictions of grain temperatures than the Muir and Ingram model. The present model also gave better predictions of grain moisture contents for long low temperature drying periods. However, the Muir and Ingram model gave better predictions for grain moisture contents for ambient air drying and for short low temperature drying periods.

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LIST OF SYMBOLS

C_{pa} = specific heat of moist air, kJ/kg °C

C_{pg} = specific heat of grain, kJ/kg °C

C_s = average specific heat of fababeans in temperature range T_g to T_m, kJ/kg °C

C_w = average specific heat of water in temperature range T_w to T_m, kJ/kg °C

D_m = mass of dry matter in a layer of grain, kg

E = water equivalent of calorimeter and accessories, kg

ln = natural logarithm

L = latent heat of vaporization of water in grain, kJ/kg water

L_s = latent heat of vaporization of free water, kJ/kg water

m_a = mass flow rate of the drying air, kg/h

m_g = mass of fababeans in a layer of grain, kg

m_i = initial moisture content of grain in a layer, decimal dry basis

m_o = final moisture content of grain at the end of simulation time increment t, decimal dry basis

M_d = moisture content of grain, % dry basis

M_s = mass of fababeans sample, kg

M_w = mass of calorimetric water, kg

P_{atm} = atmospheric pressure, Pa

P_s = saturation vapor pressure, Pa

PSAIN = saturation vapor pressure of incoming air, Pa

P_v = partial vapor pressure, Pa

PVAIN = partial vapor pressure of incoming air to a grain layer, Pa

PVAIN' = partial vapor pressure of incoming air to a grain layer when between PVAT and PVGT, Pa

PVAOUT = partial vapor pressure of outgoing air from a grain layer, Pa

PVAT = vapor pressure of air in equilibrium with grain at temperature T_i and moisture content m_i, Pa

PVEF = expected vapor pressure of air leaving the grain layer, Pa

PVGT = vapor pressure of air in equilibrium with grain at temperature T_g and moisture content m_i, Pa

PVT = partial vapor pressure of air in equilibrium with grain at temperature T_o and moisture content m_o, Pa

r = ratio of heat content of grain in a layer to the heat content of air in a simulation time increment, $m_g.C_{pg}/m_a C_{pa} t$

R1 = ratio of PVAOUT to PVEF

R2 = ratio of PVT to satisfactory PVAOUT

RH = relative humidity of air, decimal

RH_e = relative humidity of air that is in equilibrium with grain, decimal

RHAIN = relative humidity of the incoming air to a grain layer, decimal

s = standard deviation of specific heat, kJ/kg ^oC

t = simulation time increment, h

T_i = initial dry bulb temperature of air into a layer, ^oC

T_g = initial temperature of grain, ^oC

T_g' = temperature of air and grain at which the relative humidity of air is equal to the equilibrium relative humidity of the grain assuming that air cools at constant wet bulb temperature, ^{o}C

ΔT_g = difference between T_m and T_g, ^{o}C

T_m = final temperature of fababeans and calorimetric water mixture extrapolated graphically, ^{o}C

T_o = equilibrium air and grain temperature at the end of a simulation time increment, ^{o}C

T_w = initial temperature of the calorimetric water, ^{o}C

ΔT_w = difference between T_w and T_m, ^{o}C

V_{sa} = specific volume of air, m^3/kg

w = specific humidity of air, kg water/kg dry air

w_i = specific humidity of incoming air to a grain layer, kg water/kg dry air

w_o = specific humidity of outgoing air from a grain layer, kg water/kg dry air

ρ = bulk density of grain, kg/m^3

1. INTRODUCTION

Fababeans (Vicia faba L.) are one of the oldest cultivated field crops of Europe (Presber,1972). Presently fababeans are only grown as a protein crop to be used primarily for livestock rations and as a rotational break crop. But fababeans' good nutritional properties, good digestibility, non-toxicity, good nitrogen fixing ability, and ability to grow in shorter warm periods than its rival protein crops have made it a promising new crop for western Canada.

An important aspect of the management of any crop is its safe storage. Spoilage of stored grain occurs due to the activities of insects, mites, and fungi. To check the activities of these pests a proper combination of moisture and temperature of the grain is required. Because temperature is a major factor determining grain deterioration during storage, predicting the temperature of grain in bulks is important in the design of proper systems for temperature control. To predict temperatures the specific heat and thermal conductivity of the grain are required. The specific heat of grain is also helpful for the rational design of grain processing systems involving heat transfer e.g. cooking, heating, and drying systems.

To check the pests in the grain, a safe storage moisture can be obtained by means of drying. Conventionally fababeans are field dried and are harvested when the pods and stems dry and turn black. Under unfavorable weather conditions the beans may not field dry to a safe storage moisture or they may begin to deteriorate prior to harvest. Field drying may result in uneven drying of the crop, thereby resulting in excessive shattering of the kernels in the combine. To overcome these drawbacks of field drying, artificial drying of fababeans is required.

Drying can be accomplished by using low temperature (below 15°C), ambient (around 25°C) or high temperature (above 40°C) air. Factors affecting the operation of a drying system include: the temperature and relative humidity of the drying air, grain moisture content, grain variety and initial grain conditions, and the depth and volume of grain. To evaluate experimentally the effect of these factors on the drying characteristics of fababeans a large number of laboratory tests would be required. Such a direct approach is prohibitive in both time and funds required.

An alternative means to study the effect of these drying parameters on the drying characteristics of grain is to develop a drying simulation model on the digital computer. A simulation model, in the widest sense, duplicates the essence of a system or activity without actually attaining reality itself (Wright, 1971). The drying simulation model can be subjected to various changes in drying parameters, and the effect of these changes on the drying characteristics can be studied. The accuracy of the model can be checked by comparing its results with those obtained experimentally.

The objectives of the present study were:

1) to determine specific heat of fababeans in the temperature range -16 to 30°C and in the moisture content range 11 to 32%, dry basis

2) to develop a simulation model for low temperature and ambient air drying of fababeans.

3) to compare the results of the simulation model with those obtained experimentally.

2. REVIEW OF LITERATURE

2.1 Fababeans in Perspective

Vicia faba is one of the oldest cultivated plants. It is mentioned in early Hebrew, Greek and Roman literatures. In North America it was grown by the American Indians as far back as 5000 B.C.(Presber,1972). When the oilseed crops were relatively unknown, fababeans were one of the most important vegetable protein sources. Presently the importance of fababeans is greatly diminished and its utility as a common food item is limited. The reasons for reduced production of fababeans were its extreme yield instability, unavailability of an effective weedicide, prejudices against its color and smell, and the advent of cheaper protein sources. Today interest in fababeans is being renewed because of its scientifically recognised nutritional advantages (Table 2.1).

TABLE 2.1*

Nutritional comparison among fababeans, barley and soybeans

Nutrients	Fababeans	Barley	Soybeans
Crude protein content	27.0%	11.0%	45.0%
Carbohydrate equivalents	48.0%	66.4%	28.7%
Organic substances	82.0%	83.1%	80.5%
Lysine	1.5%	0.4%	3.3%
Methionine cystine	0.5%	0.2%	1.6%
Total nutrients	67.0%	70.0%	72.0%

* From Presber,1972

2.2 Specific Heat

A review of literature indicates that no work has been done on the specific heat of fababeans although the specific heat of many other biological materials has been found (Mohsenin,1975).

Siebel (1892, cited by Mohsenin,1975) argued that the specific heat of biological materials is equal to the specific heat of the dry matter plus that of the contained water. He gave two equations for the specific heat of biological materials - one for above freezing and one for below freezing temperatures. Obviously this is an oversimplification, because Siebel neglected the presence of bound water in biological materials. The specific heat values found experimentally are always greater than those calculated by Siebel's method (Mohsenin,1975).

For the experimental determination of specific heat of biological materials, researchers have used several different methods: the analytical method (used by Babbitt,1945 and Moote,1953), Bunsen ice calorimetry (used by Disney, 1954), method of comparison calorimeter (used by Bowers and Hanks,1962), and the method of mixtures (used by Pfalzner,1951, Kazarian, 1962, Viravanichai,1971, and Sharma and Thompson,1973). In analytical method thermal conductivity (k), thermal diffusivity (α) and density (ρ) of the grain are determined and the specific heat is calculated by the relationship $c = k/\alpha\rho$. The Bunsen ice calorimetry consists of dropping a measured amount of grain at room temperature into the ice calorimeter and measuring the amount of ice melted. Specific heat is then calculated using a heat balance equation. The method of comparison calorimeter consists of heating to a known temperature the sample and a specific heat standard in two similar cups. Then by observing their cooling curves, the sample specific heat can be calculated. The method of mixtures is described in detail in Section 4.3.2 .

Pfalzner (1951), Moote (1953), Kazarian (1962), and Sharma and Thompson (1973) found a linear relationship between the specific heat and wet basis moisture content for the particular grain they studied. Viravanichai (1971) found that for above freezing temperatures the specific heat of wheat was a linear function of its dry basis moisture content. But at freezing temperatures and at moisture contents above 25.0% dry basis the specific heat was not a linear function of moisture content. This was due to the release of latent heat of fusion by moisture in the wheat. Viravanichai found that the specific heat of wheat was not affected by dockage or by year of harvest.

While Disney (1954) found no hysteresis effect of moisture content on the specific heat, Pfalzner (1951), Kazarian (1962), and Sharma and Thompson (1973) were aware that the heat of hydration would possibly affect the calculated value of specific heat of grain. Thus, to avoid heat of hydration, Pfalzner (1951) enclosed his sample in a copper capsule. Kazarian (1962) noted that dropping the grain directly into the calorimetric water might introduce errors due to the heat of hydration and changes in the specific heat of the grain as its moisture content increases. But he found that for enclosed samples the time required to achieve thermal equilibrium was too large and hence the error caused by thermal leakage from the calorimeter would offset the benefit obtained by isolating the sample. He did not find any measurable effect of heat of hydration within 10 min of dropping the grain into the water - the time within which the specific heat readings were taken. When he coated the grain sample with paraffin to avoid an increase in moisture content of grain, he did not find any decrease in specific heat. Hence he concluded that the effect on specific heat measurements due to increase in moisture content of the grain during the time the specific heat readings were taken was insignificant. Therefore he took all his test data without isolating the sample from the calorimetric water. Sharma and Thompson (1973) used a correction factor to reduce the error due to heat of hydration. The correction factor was taken in terms of the difference between the rate of temperature rise due to heat of hydration and the rate of temperature rise due to heat transfer from the surroundings. They concluded that heat of hydration increases with a decrease in moisture content of the grain.

2.3 Drying Simulation

The first deep bed drying model was proposed by Hukill (1947), while the first computer simulation model was developed by Boyce (1965). Later Thompson et al. (1968) reduced Boyce's heat and mass transfer differential equations to algebraic equations. The drying model developed by Bakker-Arkema et al. (1966,1967, 1971) for simulation on digital computer, and by Hamdy and Barre (1969) for simulation on a hybrid computer are probably the most rigorous from the heat and mass transfer viewpoint. All the above mentioned models are designed for high temperature drying only and they do not simulate wetting of the grain. These models are empirical drying models where the drying rate is controlled by drying constants. Thus the accuracy of these drying models is greatly dependent on precise determination of the drying constants. Also the computer time required to execute these simulations is quite large compared to the simplified model of Bloome and Shove (1970).

Bloome and Shove (1970) predicted heat and mass transfer in deep beds of shelled corn for near equilibrium conditions. The input air conditions for their model were hourly weather data and their model could simulate both adsorption and desorption processes. Their model permitted initial temperature and moisture gradients, and they considered all the heat and mass transfer phenomena to be reversible without hysteresis. They treated the deep bed as composed of several isothermal layers and they considered the output air from one layer as the input air to the next layer.

The models by Thompson (1970), Alam and Shove (1971), Sharma (1973), Khanna (1974), and Muir and Ingram (1975) are modifications of Bloome and Shove 's model. Thompson (1970) modified Bloome and Shove 's model by incorporating heat transfer from the bin walls and the heat of respiration within the grain. He used a trial and error method to estimate a more accurate value of the relative humidity of the exiting air. The estimation was carried out until the difference between the relative humidity of the exiting air and the relative humidity in equilibrium with the grain tended to zero. A similar trial and error estimation was also used by Muir and Ingram (1975).

Alam and Shove (1971) modified Bloome and Shove 's model by assuming that for the first grain layer only 98% of the associated mass transfer takes place, whereas for the following layers it varies linearly from 98 to 100%. This assumption does not account for the loss of air specific humidity as the air passes from one layer to the next.

Sharma (1973) and Khanna (1974) used the same approach as Bloome and Shove (1970) but with small modifications. Sharma, instead of using the actual grain temperature for the simulation model, used T_g', the temperature of air and grain at which the relative humidity of air is equal to the equilibrium relative humidity of the grain, assuming that air cools at constant wet bulb temperature. He did not account for the difference in temperatures between initial grain temperature and T_g'. Khanna (1974), in accordance with the reporting by Boyce (1965), took the vapor pressure of air exiting the grain as R ($\leq$1.0) times the vapor pressure estimated from the heat and mass transfer processes. Boyce (1965) had reported that for heated air drying tests vapor pressure of air exiting the grain never exceeded 0.80 times its saturation vapor pressure.

To check if the grain was drying or wetting, Bloome and Shove (1970), and Alam and Shove (1971) compared the grain moisture content with the equilibrium grain moisture content at air temperature, while Sharma (1973) and Khanna (1974) compared the vapor pressure of incoming air, PVAIN with the vapor pressure of air in equilibrium with grain at initial temperature and moisture content, PVGT. For the same purpose Muir and Ingram (1975) compared PVAIN with the vapor pressure of air in equilibrium with grain at air temperature and initial moisture content, PVAT. Muir and Ingram reasoned that PVAIN should be compared with PVAT because air temperature was the ultimate temperature to be attained by the grain.

3. SIMULATION MODELLING

3.1 Assumptions

The simulation model for low temperature drying is based on the following assumptions:

1. A deep bed of fababeans consists of a series of isothermal layers.

2. Conductive heat transfer between the adjacent grain layers is negligible.

3. At the end of a time increment the temperature of the grain in a layer is equal to the temperature of air leaving the layer i.e. temperature equilibrium is reached at the end of each time increment.

4. Moisture equilibrium may not be achieved at the end of a time increment.

5. The final air and grain temperature may go beyond the initial temperatures of grain and air e.g. during drying the final temperature of the air and grain may be below the initial temperatures of air and grain, and vice versa for the wetting process.

6. All processes are reversible without hysteresis.

7. Temperature and moisture gradients exist only in the direction of air flow.

8. Heat of respiration and spoilage is negligible.

3.2 Formulation of Model

The present model is, by and large, a modification of the Muir and Ingram (1975) model. The model assumes that heat transfer takes place before moisture transfer. Based on this assumption the model first estimates the equilibrium air and grain temperature depending upon the heat and mass transfer processes, and then calculates, by a trial and error procedure, the final equilibrium temperature and mass transfer. The trial and error method nullifies the error caused by the assumption that heat transfer takes place before moisture transfer. The heat and mass transfer processes are discussed by Bloome and Shove (1970), Sharma (1973) and Khanna (1974). They will be discussed here only briefly.

When the drying air interacts with the grain mass, four heat and mass transfer processes are possible:

1. Drying and Heating: If PVAIN $<$ PVGT and $T_i > T_g$
2. Drying and Cooling: If PVAIN $<$ PVGT and $T_i < T_g$
3. Wetting and Heating: If PVAIN $>$ PVGT and $T_i > T_g$
4. Wetting and Cooling: If PVAIN $>$ PVGT and $T_i < T_g$

The following heat and mass transfer equations are used for a layer of grain:

Sensible heat gained by air + Sensible heat gained by grain + Latent heat absorbed during drying of the grain = 0

$$m_a t C_{pa}(T_o - T_i) + m_g C_{pg}(T_o - T_g) + m_a t L(w_o - w_i) = 0 \quad \ldots (3.1)$$

and

Moisture gained by air + Moisture gained by grain = 0

$$(w_o - w_i)\, t m_a + (m_o - m_i) D_m = 0 \quad \ldots (3.2)$$

During drying and heating of the grain (Fig. 3.1a), the equilibrium air and grain temperature will tend towards the initial grain temperature and the expected vapor pressure of air leaving the grain layer, PVEF would be set equal to PVGT. The equilibrium temperature

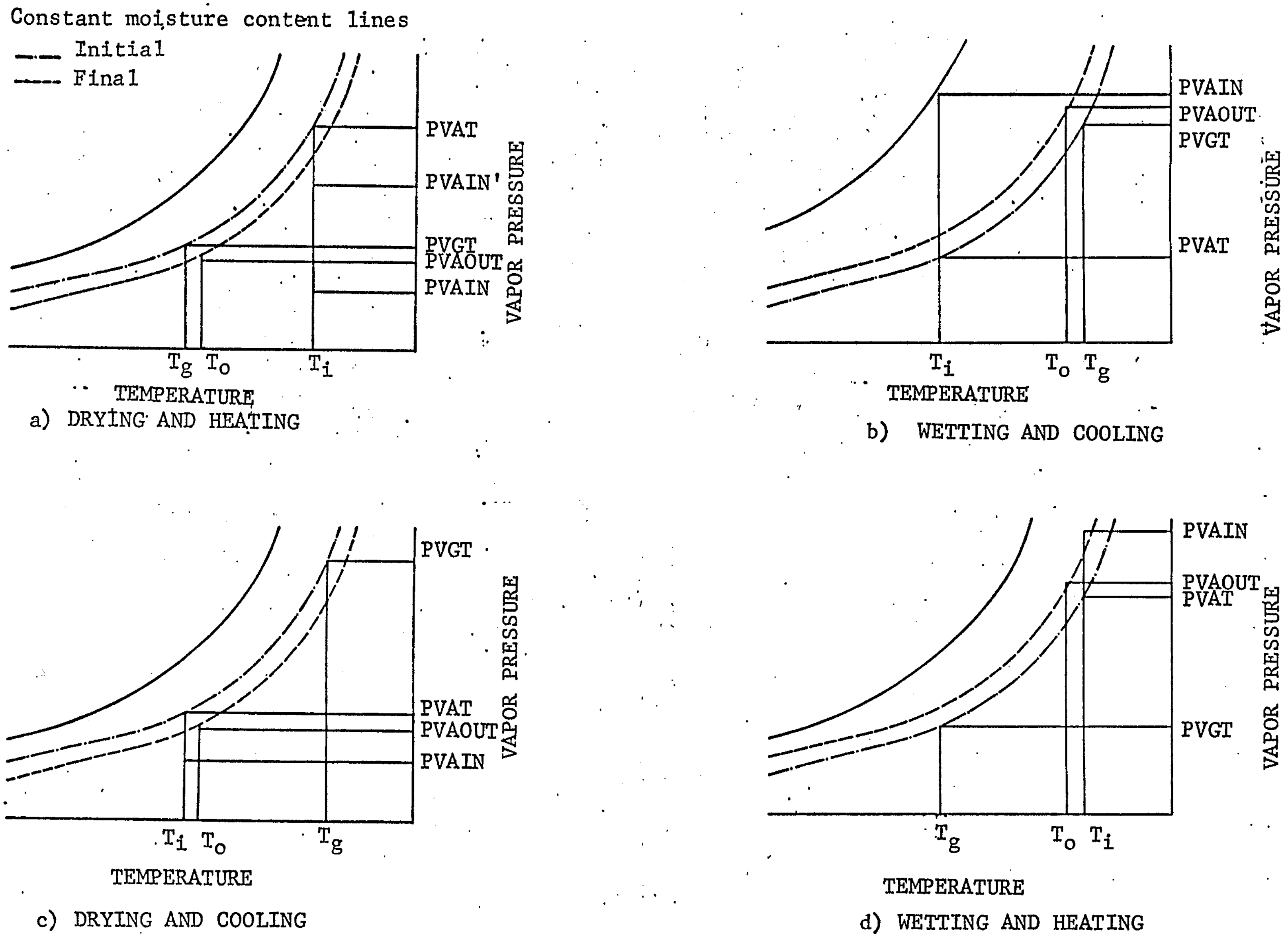

FIGURE 3.1 Skeleton psychrometric charts illustrating the heat and mass transfer processes.

would reach T_g if heat gained from cooling the air from T_i to T_g is not sufficient to increase the vapor pressure of air from PVAIN to PVGT. How close the equilibrium temperature comes to T_g depends upon the differences between T_i and T_g, and between PVAIN and PVGT. However, if the simulation time increment and the grain layer depth are chosen such that the ratio of heat content of the grain to the heat content of the air, r is greater than unity then the grain would be dried only slightly and the equilibrium temperature would be nearer to T_g. Hence for the case of drying and heating a small simulation time increment (60 min) and a large grain layer depth (1.0 m) are selected so that r is greater than unity to bring the equilibrium air and grain temperature near T_g.

Similarly, for the case of wetting and cooling (Fig. 3.1b) where the equilibrium temperature tends towards the initial grain temperature a small simulation time increment and a large grain layer depth are selected.

During drying and cooling of the grain (Fig. 3.1c), the equilibrium air and grain temperature tends towards the initial air temperature and PVEF is set equal to PVAT. The equilibrium temperature would reach T_i if the heat gained from cooling the grain from T_g to T_i is not sufficient to increase the vapor pressure of the incoming air from PVAIN to PVAT. However, if the ratio r is less than unity, the equilibrium air and grain temperature would be nearer to T_i. Hence for drying and cooling, a large simulation time increment (720 min) and a small grain layer depth (0.10 m) are selected.

For the case of wetting and heating (Fig. 3.1d) the equilibrium air and grain temperature tends towards T_i and PVEF is set equal to PVAT. The equilibrium temperature would reach T_i if the heat of condensation from decreasing the vapor pressure of the incoming air from PVAIN to PVAT is more than sufficient to heat the grain from T_g to T_i. Hence to bring the equilibrium temperature near T_i a large simulation time increment (720 min) and a small grain layer depth (0.10 m) are selected.

Thus the present model selects a simulation time increment and grain layer depth depending upon the heat and mass transfer processes which is an improvement over the Muir and Ingram (1970) model. The present model incorporates the following additional modifications over the Muir and Ingram model:

1. To check if the grain is drying or wetting, PVAIN is compared with PVGT instead of PVAT. Muir and Ingram (1975) used PVAT for comparison with PVAIN because they argued that air temperature was the final temperature to be attained by the grain. Their argument was unreasonable because to check if, at any instant, the grain is drying or wetting we must compare PVAIN with the vapor pressure of the air in equilibrium with the grain at the grain temperature (PVGT).

2. When PVAIN is between PVAT and PVGT the expected vapor pressure of air leaving the grain layer, PVEF is set midway between PVAIN and PVGT. In Fig. 3.1a, because PVAIN' is lower than PVAT and because T_i is greater than T_g, the Muir and Ingram model would term the process as that of drying and heating and would set PVEF as PVGT.