

SIMULATION OF HEAT AND MASS TRANSFER DURING
AERATION OF WHEAT AND RAPESEED BULKS

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ABSTRACT

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SIMULATION OF HEAT AND MASS TRANSFER DURING AERATION OF WHEAT AND RAPESEED BULKS

Digital computer models were developed for wheat and rapeseed which use the finite-difference method to predict the changes in grain temperature and moisture content resulting from aeration with ambient air. The models can be used in establishing the limits of low-temperature, low-airflow drying systems as well as evaluating the effect of parameters, leading to system optimization.

An improvement over previous models has been incorporated into these models by taking into account the wet-bulb depression of the entering air. When the air passing through the grain has a relative humidity lower than the equilibrium relative humidity of the grain, the dry-bulb temperature of the air drops to near its wet-bulb temperature, during the early hours of aeration. This equilibrium temperature of the air and grain during the early hours of aeration is taken as the initial grain temperature for the simulation of the aeration process.

The accuracy of the models was verified by experimental

tests in the laboratory. The model for wheat predicted the location of the drying front within ± 3.0 centimeters of the measured drying front for an apparent air velocity of 2.44 meters per minute, and within ± 7.1 centimeters for an apparent air velocity of 4.36 meters per minute. A better agreement between experimental and simulated moisture gradients was noticed for rapeseed than for wheat.

The computer models developed during this investigation may simulate the drying with ambient air for the following approximate ranges of air and grain conditions: (i) dry-bulb temperature of the incoming air - 10.0 to 37.5 degrees Celsius for wheat and 20.0 to 37.5 degrees Celsius for rapeseed; (ii) relative humidity of the incoming air - 30 percent to 90 percent for wheat and 50 to 90 percent for rapeseed; (iii) initial moisture content (dry basis) of the grain - 10 percent to 25 percent for wheat and 5 percent to 20 percent for rapeseed; (iv) initial temperature of the grain - 10.0 to 37.5 degrees Celsius for wheat and 20.0 to 37.5 degrees Celsius for rapeseed.

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LIST OF SYMBOLS

C_{pa}	=	specific heat of the moist air, kcal/kg C
C_{pg}	=	specific heat of the grain, kcal/kg C
C_{pr}	=	specific heat of rapeseed, kcal/kg C
C_{pw}	=	specific heat of wheat, kcal/kg C
$f_1(m), f_2(m)$	=	parameters used in determination of equilibrium moisture content equation for rapeseed
L	=	latent heat of vaporization of water in grain, kcal/kg water
$\ln$	=	natural logarithm
L_s	=	latent heat of vaporization of water in grain, kcal/kg water
m_a	=	mass flow rate of the air, kg dry air/h
m_d	=	mass of solids in a layer of grain, kg
m_g	=	mass of the grain in the layer, recalculated as moisture content changes, kg
m	=	moisture content of the grain, % dry basis
m_i	=	initial moisture content of the grain in a layer, % dry basis
m_o	=	moisture content of the grain subsequent to simulation for the time increment, Δt , % dry basis

M_o	=	initial moisture content of the grain in aeration column, % dry basis
M_{exp}	=	experimental equilibrium moisture content, % dry basis
M_{sim}	=	simulated equilibrium moisture content, % dry basis
P_{atm}	=	atmospheric pressure, g/cm^2
P_g	=	vapour pressure of the moisture in grain, g/cm^2
P_s	=	saturation vapour pressure, g/cm^2
P_v	=	partial vapour pressure, g/cm^2
P_{vi}	=	partial vapour pressure of the incoming air, g/cm^2
Q_a	=	flow rate of the air, m^3/h
RH	=	relative humidity, decimal fraction
RH_a	=	relative humidity of the incoming air, %
RH_e	=	relative humidity of the air that is in equilibrium with the grain, decimal fraction
T	=	temperature of the water, C

T_{db}	=	dry-bulb temperature of the incoming air, C
T_g	=	temperature of the air and grain at which the relative humidity of the air is equal to the equilibrium relative humidity of the grain assuming that air cools at constant wet-bulb temperature, C
T_i	=	air temperature into the layer, C
T_o	=	air temperature out of the layer, C
T_{og}	=	initial temperature of the grain in aeration column, C
T_w	=	initial temperature of the grain in a layer, C
T_{wb}	=	wet-bulb temperature of the incoming air, C
V_{sa}	=	specific volume of the air, m ³ /kg dry air
w	=	specific humidity of air, kg water/kg dry air
w_g	=	specific humidity of the air that is in equilibrium with the grain at temperature T_w and moisture content m_i , kg water/kg dry air
w_e	=	specific humidity in equilibrium with the initial moisture content of the grain, kg water/kg dry air
w_i	=	specific humidity of air into the layer, kg water/kg dry air

w_o = specific humidity of air out of the layer,
kg water/kg dry air

ΔH = spatial increment, cm

Δt = time increment, h

CHAPTER I

INTRODUCTION

As recently as 5 to 7 years ago, it was practical to move large amounts of damp grain from Canadian prairie farms to central storage terminals. There it could be dried to prevent the initiation of spoilage due to fungi and bacteria. In the past, particularly when small grain export sales combined with increased production created larger than usual stocks of grain, the storage facilities on farms and in commercial elevators were often severely strained. Consequently, farmers were forced to store grain in make-shift granaries or in open piles on the ground for periods longer than 1 year (Sinha et al.; 1972). Generally, grain stored in make-shift granaries or in open piles for more than 1 year is susceptible to fungi, mite and insect infestations. Each additional year of storage intensifies the activity of grain pests and increases the rate of grain spoilage. In a particular year when the entire crop is harvested damp due to unfavourable weather conditions and the damp grain is stored for such a prolonged period, the rate of spoilage of stored grain further accelerates, mainly through damp grain heating ('hot spots') caused by microorganisms (Sinha and Wallace; 1965) and by infestation of larger numbers and more kinds of arthropod pests.

The drying of grain can be done in several ways. One of the most common methods is heated air drying. Heated air drying is a convective process and the rate of drying is a function of the temperature and relative humidity of the drying air, mass flow rate of the air, equilibrium moisture content which the product would acquire at the temperature and relative humidity of the incoming air, and the moisture content of the product. Heated air drying does the job faster than unheated air drying and it is not dependent on weather conditions, but may be more costly and may remove more moisture than necessary. Moreover, the grain is susceptible to cracking and thermal damage when exposed to high temperatures.

A reasonable amount of drying can be accomplished in most years in Western Canada with a low-cost unheated air drying system (Moysey and Wilde; 1965). Even if the relative humidity of the air were too high to allow drying of the grain to occur, it should be possible during the winter months to lower the temperature of the grain sufficiently to prevent spoilage. It could then be stored until more favourable weather conditions in spring would make it possible to dry the grain. If the grain is used for feed it is even desirable to have it at a high moisture content.

Since the potential for moisture removal by aeration with ambient air has been demonstrated (Moysey and Wilde; 1965), a mathematical model describing the movement of

moisture and heat in a mass of grain is desirable. Such a model can be used in establishing the limits of aeration drying systems as well as evaluating variables, such as airflow and grain depth, leading to system optimization.

The objective of this study was to develop digital computer models for simulating heat and mass transfer during aeration of wheat and rapeseed.

CHAPTER II

REVIEW OF LITERATURE

2.1 Tests on Field Systems

Research related to low temperature drying of cereal grains and oilseeds has been of three types: tests on field systems, analyses of weather data and development of simulation models. Tests on field systems carried out by Alderks (1948), Foster (1953, Saul and Lind (1958), and Shove and Andrew (1969) lead to the following conclusions:

- 1) The drying fan should be operated continuously. This is true for all the climatic regions where ambient air has a drying potential during an average year.
- 2) The time required for drying is, in general, inversely proportional to the rate of airflow.
- 3) The lowest airflow that should be provided is largely a function of the amount of product deterioration that is acceptable.
- 4) The rate of deterioration is largely a function of moisture content and temperature of the product.

The above type of research work, however, does not adequately evaluate the effects of year-to-year weather variations. Also, a limited number of combinations of initial moisture content and airflow rate were involved.

2.2 Weather Data Analyses

A number of researchers have analyzed weather data during post-harvest season to determine the potential for low-temperature drying of agricultural products. Schaper et al. (1961) used weather data to determine the average sensible heat available for 9-day drying periods during the haying season in Indiana. Schmidt and Waite (1962) summarized wet-bulb depression data for 82 U.S. Weather Bureau Stations throughout the United States for use in estimating drying equipment requirements. Brooker and McQuigg (1963) used 25 years of hourly weather observations at Columbia, Missouri, in studying effectiveness of both unheated and heated air drying systems. Zachariah and Lipper (1966) concluded that drying with unheated air is possible in the Topeka area during average years. Moysey and Wilde (1965), and Moysey (1969) examined weather data for Saskatoon and Prince Albert, respectively. They found that unheated air has a drying potential during average years for these locations.

While studies of weather data (Moysey and Wilde, 1965; Moysey, 1969; Schaper et al., 1961; Schmidt and Waite, 1962; Zachariah and Lipper, 1966; Brooker and McQuigg, 1963) provide

information concerning the expected drying potential of unheated air, they do not define the performance of unheated air drying systems in a particular year. The time required for drying, the expected final moisture content and temperature remain undefined.

2.3 Simulation Models of Drying With Ambient Air

One of the difficulties of past researchers, as pointed out by Zachariah and Lipper (1966), was that continuously changing drying conditions make it impossible to calculate the "exact time to dry" for a particular drying season. As a result agricultural engineers have recently attempted to simulate heat and mass transfer in deep beds of biological materials during drying with ambient air.

One of the first simulation models of grain drying with low flow rates of unheated air that has naturally fluctuating temperatures and relative humidities was developed by Bloome and Shove (1970). Input air conditions for their model may be variable, and initial moisture content and temperature gradients are permitted. The model is designed to accept hourly weather observations. Bloome and Shove (1970) simulated natural air drying of corn over periods as long as 65 days.

Alam and Shove (1971) modified the model of Bloome and Shove (1970) and applied it to soybeans. The model presented by Bloome and Shove requires the assumption that complete moisture equilibrium is reached between the air passing through

a layer of grain and the grain in that layer. Alam and Shove (1971) reported that better prediction results were obtained by assuming that in the first layer 98% of the complete moisture equilibrium takes place where as in the following layers it varies linearly from 98% to 100%.

Alam and Shove (1971) reported that in the early periods of drying the simulated moisture gradients did not agree with the measured gradients, as closely as they did in the later periods of drying. They suggested that several factors were responsible for this disagreement, such as errors in sampling of the drying column, variation in the recorded weather conditions, and microbial heating of the soybeans above 17.6% (as reported by Ramstad and Geddes; 1942). This heating would increase the drying capacity of the air thereby resulting in more drying in the middle layers. They also suggested that the difference in experimental and simulated values could be attributed to the assumption that all the processes are reversible. One other factor which they did not include in their discussion is the cooling of the air to near its wet-bulb temperature during passage through the wet soybeans during the initial hours of the drying process.

Thompson (1970a) modified the model of Bloome and Shove (1970). The modified model can predict grain temperature, moisture content, and dry matter decomposition resulting from, (1) aeration of grain with ambient air, (2) heat transfer through bin walls, and (3) respiration within the grain.

sutherland et al. (1971) developed a model to simulate equilibrium heat and moisture transfer during aeration of grain, but this model is not designed to accept hourly weather observations.

During the last 5 years a number of simulation models have been presented in the area of heated air drying. The models developed by Bakker-Arkema et al. (1966, 1967, 1968, 1969, 1970) are based on the laws of simultaneous heat and mass transfer and result in systems of differential equations. These equations are then solved analytically or (in most cases) numerically. Thompson et al. (1967, 1968, 1969, 1970b) proposed an alternative approach to the modeling of heated air drying. Their models are based on algebraic heat and mass transfer balances.

The above review of literature on the simulation of grain drying shows that there are only three models (Bloome and Shove, 1970; Alam and Shove, 1971; and Thompson, 1970) which are capable of simulating heat and mass transfer during aeration with ambient air. The models of Alam and Shove (1971) and Thompson (1970) are modified from the corn drying model of Bloome and Shove (1970) and use the same basic computational approach. Thompson's model also simulates the respiration within the grain and heat transfer through the bin walls along with drying of the grain through continuous aeration. Moreover, this model uses a trial-and-error procedure to estimate a more accurate value of the absolute

humidity of the air after the air has passed through a layer of grain. The estimation is carried out until the difference in the values of equilibrium relative humidity of the grain and the relative humidity of air after the air has passed through a layer of grain approaches zero. The computer time for such a sophisticated model may be considerably more than the computer time (102 seconds for 65 days of simulation on the IBM 360/75/50 for the PL1 programme) required by Bloome and Shove's model.

The above review of literature also indicates that most of the work done on drying of grain with ambient air has been limited to corn and soybeans. Little consideration has been given to the unheated drying of wheat and rapeseed which are two of the major crops on the Canadian Prairies. The performance of drying these crops with ambient air has not been defined for the climate of the Canadian Prairies.

CHAPTER III

MATHEMATICAL MODELING

3.1 The Computational Approach

During aeration with air at ambient temperatures and with low airflow rates a number of temperature gradients can exist in the grain mass at any one time, some increasing and some decreasing in temperature in the direction of airflow. In addition, the vapour pressure of the air in the grain column may be above or below the vapour pressure of the grain in individual layers. Therefore, four distinct processes are possible; (1) heating of the grain accompanied by drying, (2) heating of the grain accompanied by wetting, (3) cooling of the grain accompanied by wetting, and (4) cooling of the grain accompanied by drying.

The development of a simulation model of grain aeration with ambient air would require a different approach than that used to predict the performance of heated air systems. In an empirical drying model (Thompson et al.; 1967, 1968, 1969, 1970), the drying rate of the grain is controlled by a drying constant which has been experimentally determined. A small change in the moisture content of the grain results in large changes in temperature and specific humidity of the air in the grain column. In such a drying model, then, the changes in grain conditions are controlled by empirical drying constants

and changes in air conditions are calculated as incidental. These new air conditions are used to determine the drying constant appropriate to the next grain layer. Therefore, the accuracy of an empirical drying model is greatly dependent upon a precise determination of the drying constant. These difficulties are magnified when dealing with low temperature drying where mass transfer is slow and the drying period is long. Moreover, to apply the same type of analysis to the aeration of grain with ambient air, the drying and wetting constants for each of the four processes would have to be experimentally determined for the ranges of temperature and relative humidity of the ambient air.

Following a detailed consideration of the available simulation models of drying with ambient air (Sec. 2.3), I chose the model of Bloome and Shove (1970) for the basis of a mathematical simulation of heat and mass transfer during aeration of wheat and rapeseed bulks. However, I have attempted to take into account the wet-bulb depression of the entering air in the early hours of aeration.

3.2 Assumptions

The following assumptions are made in the model:

- 1) Individual layers of grain are isothermal and the temperature gradient within the grain kernel is negligible.

- 2) Conductive heat transfer within the grain mass is negligible.
- 3) There are no temperature and moisture gradients perpendicular to the direction of the airflow.
- 4) During early hours of aeration, relative humidity of the ambient air is lower than the equilibrium relative humidity of the grain.
- 5) During early hours of aeration, as air passes through wet grain, the dry-bulb temperature of the air drops to a temperature at which (having cooled at constant wet-bulb) the relative humidity of the air is in equilibrium with the moisture content of the grain.
- 6) In each time increment the final grain temperature in each layer is equal to the temperature of the air exiting that layer.
- 7) The final grain temperature and the exiting air temperature always fall at or between the extremes of initial temperature of the grain layer and the temperature of the air entering the grain layer.
- 8) In drying, all heat available from either the air or the grain is used in evaporation. In wetting, all heat needed to heat the air or the grain is obtained by condensation.

- 9) All processes are reversible without hysteresis.
- 10) Heat of respiration and spoilage is neglected.

The accuracy of the simulation model depends upon the validity of the assumptions made in the model. Bloome and Shove (1970) pointed out that assumption (9) may cause some error in prediction of heat and mass transfer when the drying front has passed through the column. Alam and Shove (1971) also considered assumption (9) to be responsible for the disagreement between their experimental and simulated results.

3.3 Formulas Used

3.3.1 Psychrometric Relationships

Brooker (1966) gives the following equations to determine the saturation vapour pressure, P_s :

$$P_s = \text{Exp} [58.8857 - 12301.688 / (491.69 + 1.8 T_{db}) - 5.16923 \text{ Ln } (491.69 + 1.8 T_{db})] \quad \dots\dots\dots (3.1)$$

if T_{db} is greater than or equal to 0 C, otherwise

$$P_s = \text{Exp} [27.6452 - 11286.6489 / (491.69 + 1.8 T_{db}) - 0.46057 \text{ Ln } (491.69 + 1.8 T_{db})] \quad \dots\dots\dots (3.2)$$

Where:

T_{db} = dry bulb temperature of the air, C

P_s = saturation vapour pressure at T_{db} , g/cm²

Ln = natural logarithm

since:

$$RH = P_v / P_s \quad \dots\dots\dots (3.3)$$

Where:

RH = relative humidity, decimal fraction

P_v = partial vapour pressure, g/cm²

then:

$$P_v = (RH) P_s$$

and the specific humidity of air, w, is given by:

$$w = 0.6219 P_v / (P_{atm} - P_v) \quad \dots\dots\dots (3.4)$$

Where:

w = specific humidity of air, g water/g air

P_{atm} = atmospheric pressure, g/cm²

The specific volume of air (Bloome; 1969) is given by:

$$V_{sa} = 0.007573 (491.69 + 1.8 T_{db}) (1 + 1.6055w) \dots (3.5)$$

Where:

V_{sa} = specific volume of the air, m³/kg dry air

The mass flow rate of the air, m_a , may now be calculated as:

$$m_a = Q_a / V_{sa} \quad \dots\dots\dots (3.6)$$

Where:

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

Q_a = flow rate of the air, m³/h

The specific heat of the air (Brooker; 1966) is given by:

$$C_{pa} = 0.2405 + 0.448w \quad \dots\dots\dots (3.7)$$

Where:

C_{pa} = specific heat of moist air, cal/g C

3.3.2 Basic Properties of Wheat

Othmer and Huang (1940), using the Clausius-Clapeyron equation, derived the following formula for the relative humidity, RH_e , of the air that is in equilibrium with wheat:

$$RH_e = \text{Exp} [(L/L_s) \text{Ln} (2.04816 P_s) + C] / 2.04816 P_s \dots (3.8)$$

Where:

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

P_s = saturation vapour pressure at the grain temperature, g/cm²

L/L_s = the ratio of the latent heat of vaporization of water in grain to that of free water

C = constant

By using the data obtained for Australian wheat by Gay (1946), the value of L/L_s was given by Gallaher (1951) as follows:

$$L/L_s = 1 + 23 \text{Exp} (0.40 m) \dots\dots\dots (3.9)$$

Where:

m = moisture content of grain, % dry basis

Sutherland et al. (1971) calculated the values of C over the temperature range 10 to 37.8 C, using the data published by Gay. They gave the following equation for C :

$$C = - 3.34 \times 10^4 m^{-4.0} \dots\dots\dots (3.10)$$

Brooker (1966) gives the latent heat of vaporization of free water as:

$$L_s = 597.768 - 0.56983 (T) \quad \dots\dots\dots (3.11)$$

Where:

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

T = temperature of water, C

The values of equilibrium relative humidity calculated using Equations 3.8, 3.9, and 3.10 were compared with the experimental data given by Pixton (1968) for Manitoba wheat at 25 C (Figure 3.1). At this temperature, the predicted values of relative humidity were within ± 3 percentage units of the measured values. The equation predicted grain moisture contents within ± 0.50 percentage units of moisture content.

Viravanichai (1971) determined the specific heat of hard red spring wheat for the temperature range - 33.5 C to 21.8 C. He obtained the following relationships:

$$\begin{aligned} C_{pw} &= 0.250 + 0.00743 m, \text{ for } - 33.5 \text{ to } - 21.4 \text{ C} \\ C_{pw} &= 0.279 + 0.00580 m, \text{ for } - 21.4 \text{ to } - 10.8 \text{ C} \\ C_{pw} &= 0.297 + 0.00708 m, \text{ for } - 10.8 \text{ to } 0.6 \text{ C} \\ C_{pw} &= 0.273 + 0.00933 m, \text{ for } 8.9 \text{ to } 21.8 \text{ C} \end{aligned} \quad \dots\dots\dots (3.12)$$

Where:

C_{pw} = specific heat of wheat, cal/g C
 m = moisture content % dry basis

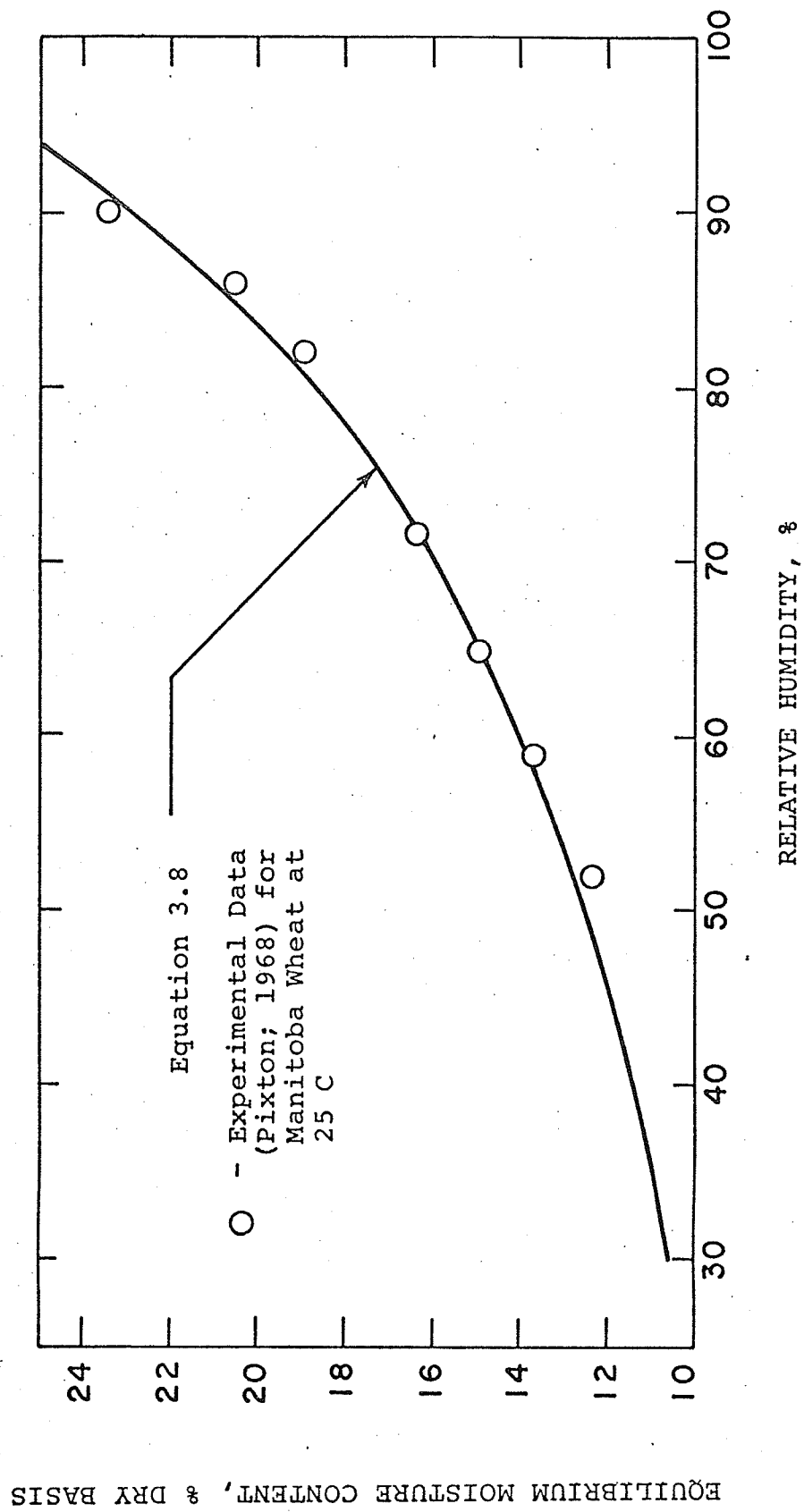


FIGURE 3.1 COMPARISON OF EXPERIMENTAL VALUES OF EQUILIBRIUM MOISTURE CONTENT OF MANITOBA WHEAT WITH THE THEORETICAL CURVE (EQUATION 3.8)

EQUILIBRIUM MOISTURE CONTENT, % DRY BASIS

3.3.3 Basic Properties of Rapeseed

Strohman and Yoerger (1967) developed the following equation for equilibrium relative humidity utilizing the linear form of the Othmer plots (Othmer and Huang; 1940):

$$RH_e = \text{Exp} (ae^{bm} \ln P_s + ce^{dm}) \quad \dots\dots\dots (3.13)$$

Where:

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

m = moisture content of the grain, % dry basis

a, b, c, d = constants

Using the data of Pichler (1956) for rapeseed, the values of constants, a, b, c and d were determined (Appendix - A) as follows:

$$a = 0.27725$$

$$b = - 0.10873$$

$$c = - 2.10496$$

$$d = - 0.11805$$

The relative humidity values calculated from Equation 3.13 using the above values of constants a, b, c , and d were compared with the experimental values of Pichler (1956). The predicted values of relative humidity were within 4 percentage units of the measured values. The equation predicted rapeseed moisture contents within ± 1 percentage units of measured moisture content values.

By using the experimental data obtained for rapeseed by Small (1972), the following regression equations were derived for specific heat:

$$C_{pr} = 0.3115 + 0.01342 m, \text{ for } -18.2 \text{ to } -8.5 \text{ C}$$

$$C_{pr} = 0.2733 + 0.01358 m, \text{ for } -8.5 \text{ to } 1.8 \text{ C}$$

$$C_{pr} = 0.2957 + 0.00914 m, \text{ for } 1.8 \text{ to } 10.2 \text{ C}$$

$$C_{pr} = 0.3328 + 0.00494 m, \text{ for } 10.2 \text{ to } 20.6 \text{ C}$$

Where:

C_{pr} = specific heat of rapeseed, cal/g C

m = moisture content of rapeseed, % dry basis

3.4 Formulation of the Model

3.4.1 Temperature Changes During Early Hours of Aeration

At the start of aeration, as air moves upward through the wet grain, it gives up heat to evaporate moisture from the grain. The temperature drops to an equilibrium value below which it will not fall. This limiting temperature (T_g) is that at which (having cooled at constant wet-bulb) the relative humidity of the air is in equilibrium with the moisture content of the grain. On the psychrometric chart (Figure 3.2 or 3.3) T_g can be located by first finding the point representing the initial conditions of the air, that is the initial dry-bulb temperature T_{db} , and the relative humidity, RH. From this point the line of constant

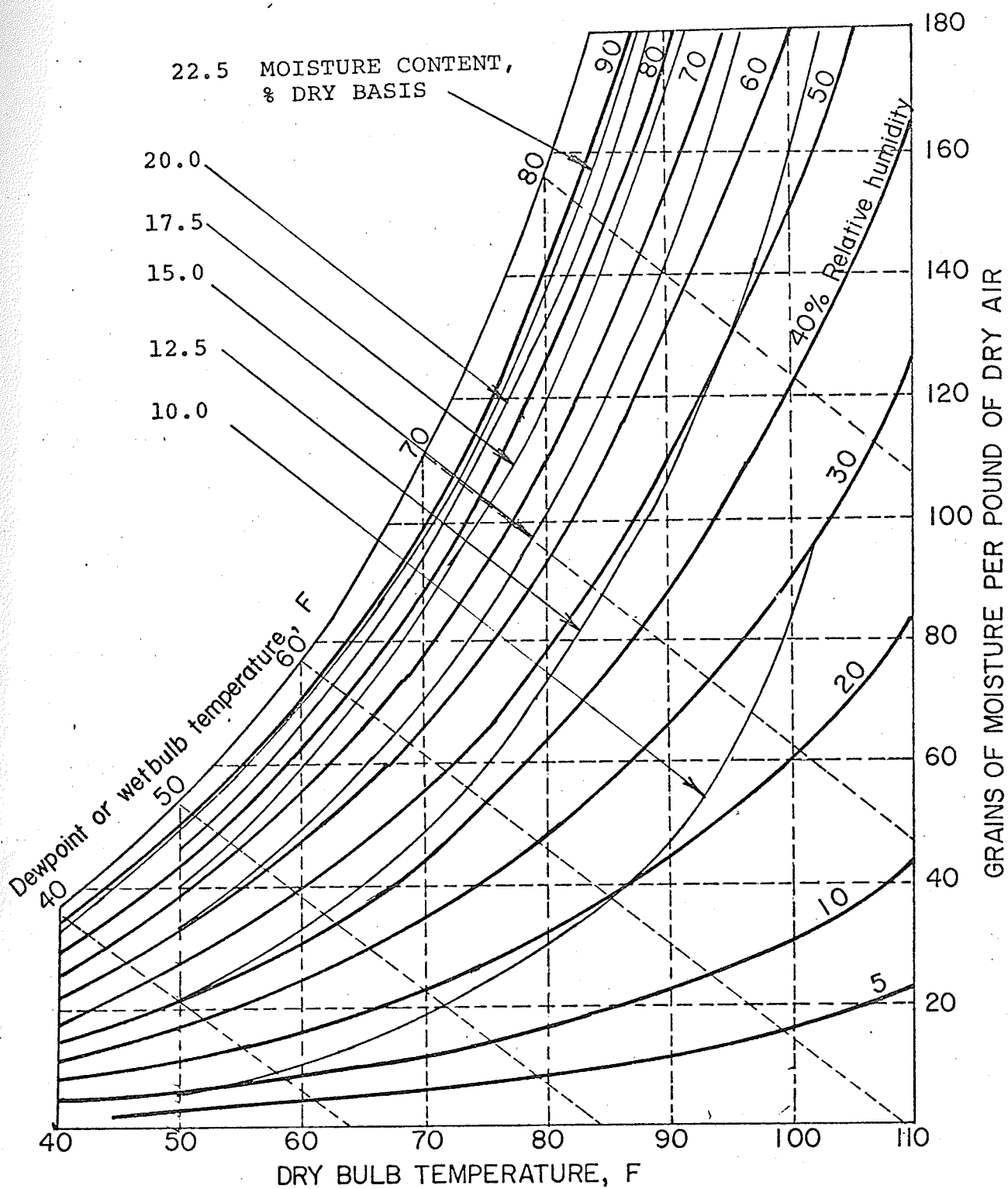


FIGURE 3.2 LINES OF CONSTANT EQUILIBRIUM MOISTURE CONTENT OF WHEAT (EQUATION 3.8) SHOWN SUPERIMPOSED ON A PSYCHROMETRIC CHART

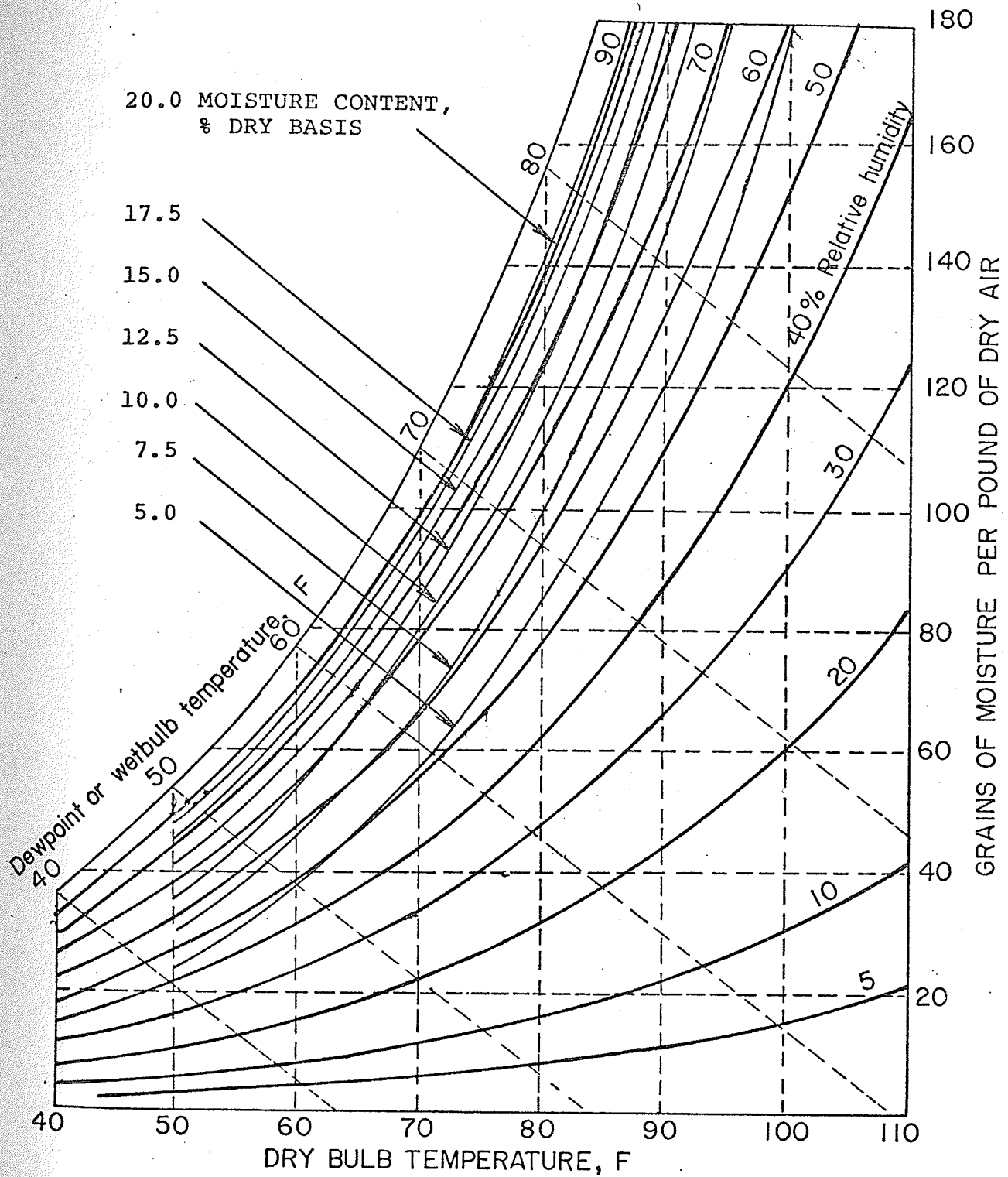


FIGURE 3.3 LINES OF CONSTANT EQUILIBRIUM MOISTURE CONTENT OF RAPESEED (EQUATION 3.13) SHOWN SUPERIMPOSED ON A PSYCHROMETRIC CHART

wet-bulb is followed to the initial moisture content of the grain (Figure 3.2 for wheat and Figure 3.3 for rapeseed). The dry-bulb temperature at this point is the value of T_g . If the moisture content of the grain is high enough so that its equilibrium relative humidity is 100% then the grain temperature will approach the wet-bulb temperature of the incoming air. The temperature of grain at lower moisture contents will be greater than the wet-bulb temperature.

The rate at which the initial temperature of the grain approaches T_g depends on characteristics of the grain, initial temperature and moisture content of the grain, temperature and humidity of the incoming air, and the rate of flow of the circulating air. After the early hours of aeration the temperature of the air and the grain in the grain column is (1) independent of the initial grain temperature; (2) independent of the dry-bulb temperature of the incoming air; (3) dependent on the moisture content of the grain. That is, moisture equilibrium is the overriding control as compared to temperature equilibrium.

The temperature, T_g , of the air and grain in the column is taken as the initial grain temperature for the simulation

of the aeration process. It is important to note here that no separate simulation is carried out for early hours of aeration and subsequent hours of aeration. This is because, with the extent of our present knowledge it is difficult to simulate the rate at which the initial temperature of the grain approaches T_g . The duration of this initial period of aeration is believed to be small (Sec. 5.1) compared with the duration of the subsequent hours of aeration.

3.4.2 Heat and Mass Balance Equations

In the simulation of the aeration process, the grain column is assumed to consist of a finite number of thin layers of grain of equal thickness, ΔH , called the spatial increment. These layers are positioned normal to the direction of airflow (Figure 3.4). The simulation model, as described in the following paragraphs is then used to predict average changes in the exhaust air and the grain during the specified time increment for each thin layer of grain. The exhaust air from one layer in the column of grain is then used as the input air to the next layer. This process is repeated for the entire depth of the simulated grain column. The following heat and mass balance equations may be written for the process taking place

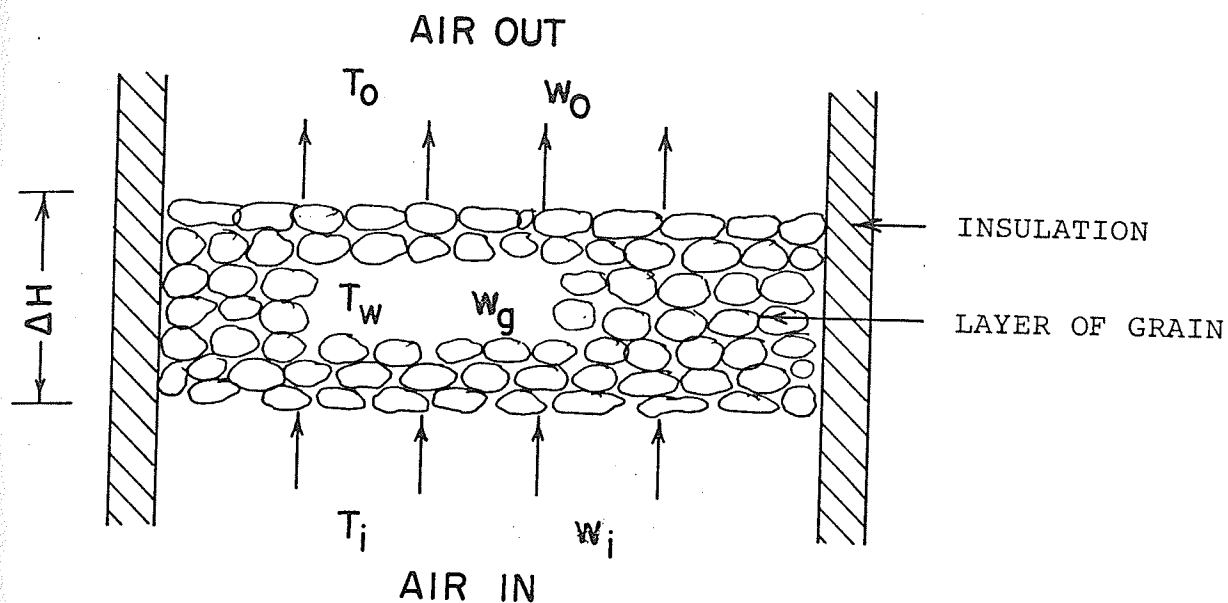


FIGURE 3.4 AN INCREMENTAL LAYER OF GRAIN

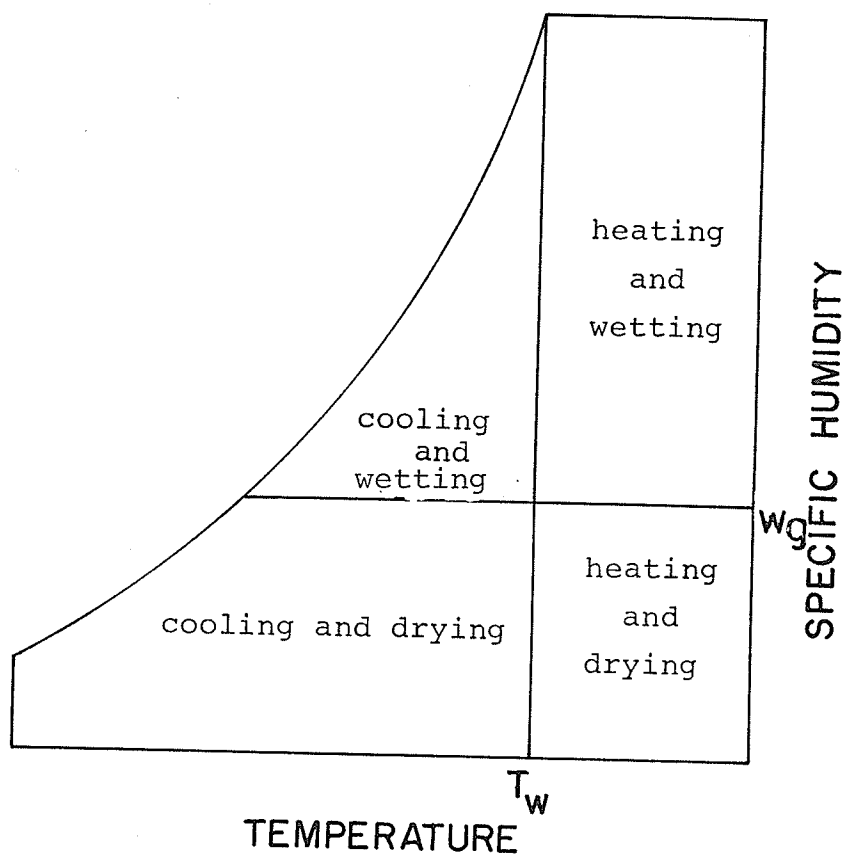


FIGURE 3.5 LOCATION OF INITIAL AIR CONDITIONS FOR EACH PROCESS ON A PSYCHROMETRIC CHART

in each layer of grain:

Heat Balance

<u>1st term</u>	<u>2nd term</u>	<u>3rd term</u>	
Sensible heat gained	+ Heat gained by	+ Latent heat = 0	
by the air	the grain	gained by	
		the air	

$$m_a \Delta t C_{pa} (T_o - T_i) + m_g C_{pg} (T_o - T_w) + (W_o - W_i) m_a \Delta t L = 0$$

..... (3.15)

Mass Balance

Moisture gained	+ Moisture gained	= 0
by the air	by the grain	

$$(m_o - m_i) m_d + 100 (w_o - w_i) m_a \Delta t = 0 \quad \text{..... (3.16)}$$

Where:

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

Δt = time increment, h

C_{pa} = specific heat of the moist air, kcal/kg C

T_o = air temperature out of the layer, C

T_i = air temperature into the layer, C

m_g = mass of the grain in the layer, recalculated as
moisture content changes, kg

C_{pg} = specific heat of the grain, kcal/kg C

T_w = initial temperature of the grain, C

w_o = specific humidity of air out of the layer, kg water/
kg dry air

w_i = specific humidity of air into the layer, kg water/
kg dry air

L = heat of vaporization of water in grain, kcal/kg
water

m_i = initial moisture content of the grain, % dry basis

m_o = moisture content of the grain subsequent to
simulation for the time increment, Δt , % dry basis

m_d = mass of solids in a layer of grain, kg

The vapour pressure, P_g , of the moisture in the grain can be found at temperature T_w and moisture content m_i using Equations 3.1 or 3.2, 3.8, and 3.3. Let P_{vi} be the partial vapour pressure of the incoming air. There are four possible transport phenomena that may take place depending upon the temperature and vapour pressure differentials.

The four possibilities are as follows:

- (1) Heating and Drying: If $T_i > T_w$ and $P_{vi} < P_g$
- (2) Cooling and Wetting: If $T_i < T_w$ and $P_{vi} > P_g$
- (3) Cooling and Drying: If $T_i < T_w$ and $P_{vi} < P_g$
- (4) Heating and Wetting: If $T_i > T_w$ and $P_{vi} > P_g$

Figure 3.5 indicates the regions in which the initial

air condition (temperature and specific humidity) will be found for each of the four processes, given the initial grain temperature and w_g , the equilibrium specific humidity calculated by substituting the value of P_g in Equation 3.4.

In the processes of heating accompanied by drying and of cooling accompanied by wetting the final air and grain temperatures will tend toward the initial grain temperature. Therefore the initial grain temperature is used in calculating the equilibrium vapour pressure of these two processes. In the processes of heating accompanied by wetting and cooling accompanied by drying the final air and grain temperatures will tend toward the initial air temperature. Therefore, the entering air temperature is used in calculating the equilibrium vapour pressure of these two processes. Equation 3.4 is then used to calculate the specific humidity, w_e , in equilibrium with the initial moisture content of the grain.

It is assumed that all temperature changes are small. Therefore the equilibrium specific humidity may be considered constant for these temperature changes. Based on the earlier assumptions (Sec. 3.2), the four processes involved can be described as follows using the psychrometric chart.

3.4.3 Heating and Drying

During heating and drying the air passing through the grain will pick up moisture and its specific humidity will

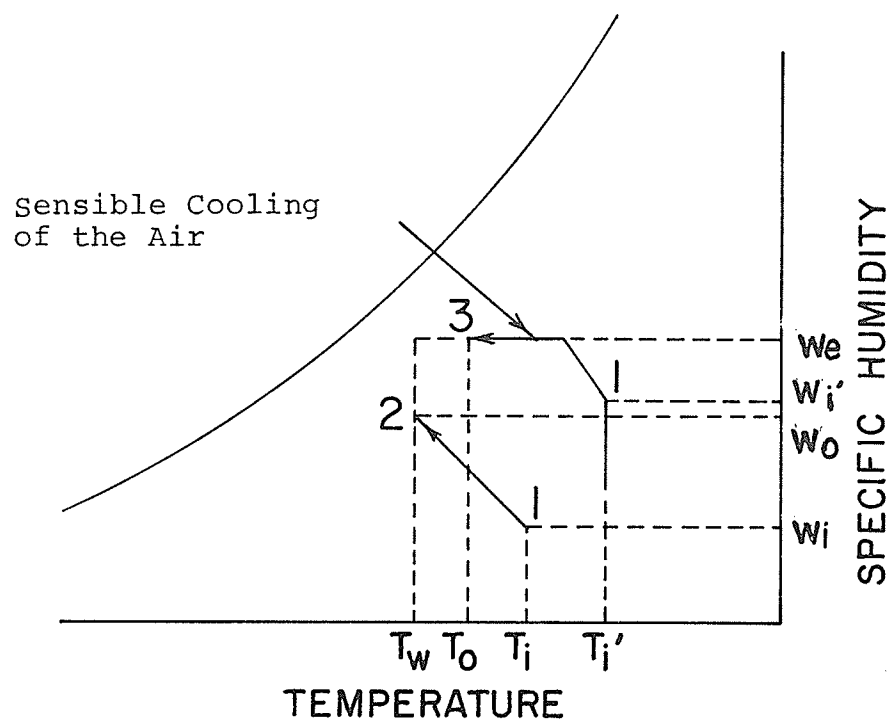


FIGURE 3.6 HEATING AND DRYING OF THE GRAIN

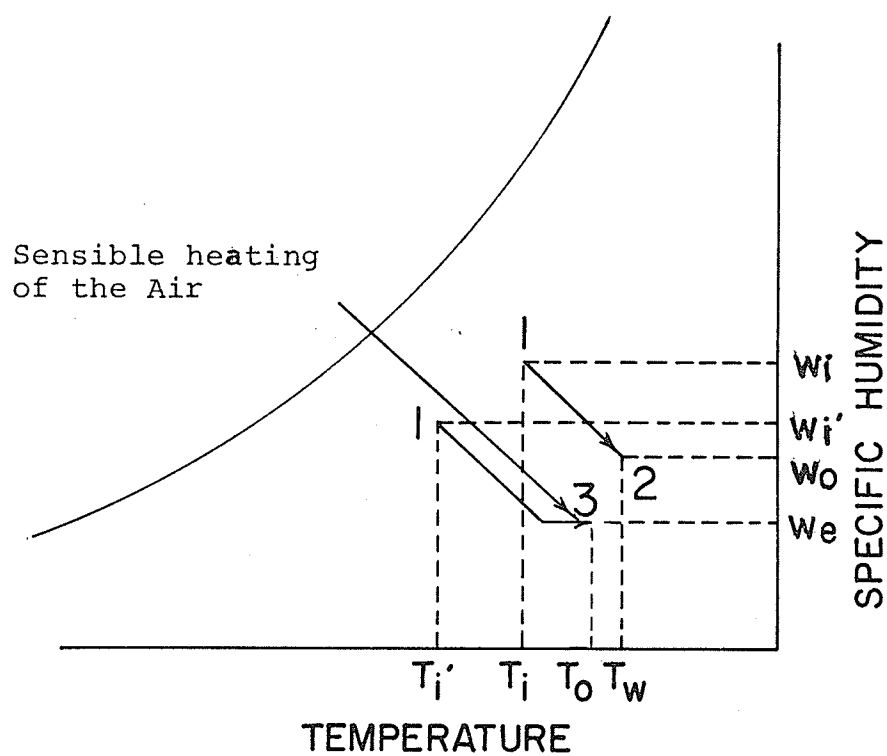


FIGURE 3.7 COOLING AND WETTING OF THE GRAIN

approach the specific humidity, w_e , in equilibrium with the initial moisture content of the grain. (Figure 3.6). Air is the source of heat for evaporation. If the initial air conditions are such that the equilibrium specific humidity of the air is not attained, before the air temperature has decreased to the initial grain temperature (process 1-2) the final grain and air temperatures equal the initial grain temperature; w_o falls between w_e and w_i and the final state point 2 is reached. The grain is dried but not heated. If the initial air conditions are such that the heat required for the air to reach the equilibrium specific humidity is less than the amount of heat that is released as the air temperature decreases to the initial grain temperature (process 1-3), the final grain and air temperatures will be somewhere between the initial grain and initial air temperature; w_o equals w_e and final state point 3 is reached. The air undergoes a humidification process and then sensible cooling while the grain is dried and heated. The lines drawn on Figure 3.6 to 3.9, especially the lines from (1) to (3) may not represent the actual line that the air will follow to get from (1) to (3).

3.4.4 Cooling and Wetting

Figure 3.7 represents the case of cooling and wetting. Air passing through the grain will lose some of its moisture

to the grain. The heat of adsorption will cause a rise in the temperature of the air. If the amount of sensible heat required to bring the air to the initial grain temperature is less than the amount of latent heat that would be given up by dehumidifying the air to w_e (process 1-2), the final air and grain temperatures equal the initial grain temperature, w_o falls between w_e and w_i and final state point 2 is reached. The grain is wetted but not cooled. If, however, the amount of sensible heat required to raise the temperature of the air to the initial grain temperature is more than the amount of latent heat given up by dehumidifying the air to w_e (process 1-3), then the final air and grain temperatures lie somewhere between the initial air and initial grain temperatures, $w_o = w_e$ and final state point 3 is reached. The air undergoes dehumidification and then sensible cooling while the grain undergoes wetting and cooling.

3.4.5 Cooling and Drying

The process of cooling and drying (Figure 3.8) may be considered as a heat balance between the sensible heat gained by lowering the grain temperature and the latent heat absorbed by water evaporating from the grain. If the initial air conditions are such that the amount of heat given up by the grain in lowering its temperature is less than the amount of latent heat required to increase the humidity ratio of the

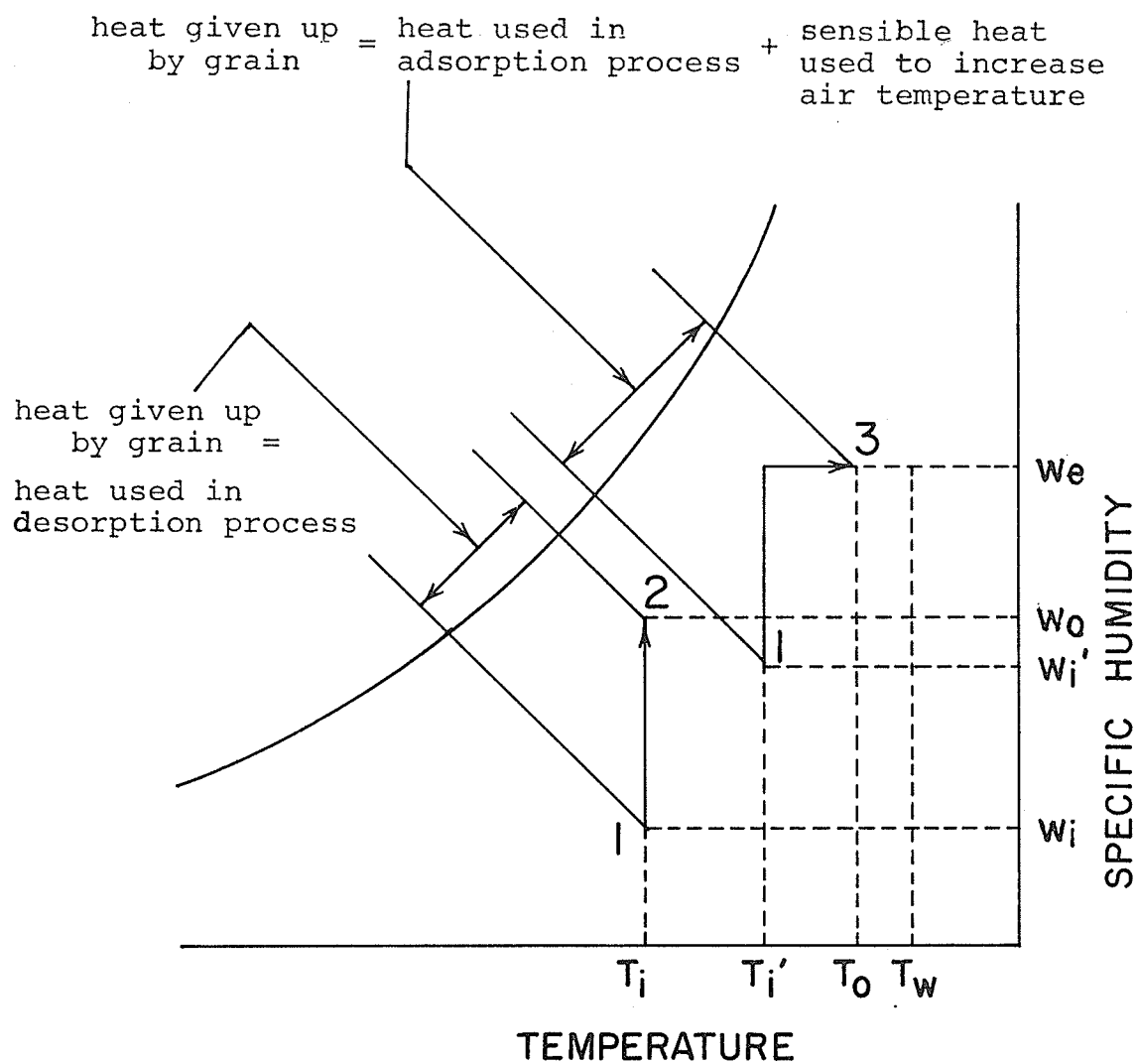


FIGURE 3.8 COOLING AND DRYING OF THE GRAIN

air to w_e (Process 1-2), then the final air and grain temperatures equal the initial air temperature, w_o falls between w_e and w_i and final state point 2 is reached. If the initial air conditions are such that the amount of heat available in cooling the grain to the initial air temperature is more than the amount of heat required to increase the humidity ratio of the air to w_e (Process 1-3), the final air and grain temperature will be between the initial air and grain temperatures, $w_o = w_e$ and final state point 3 is reached.

3.4.6 Heating and Wetting

The process of heating and wetting may be considered as a heat balance between the latent heat that is given up by moisture in the air as it is adsorbed by the grain, and the heat that is absorbed by the grain as its temperature increases. If the amount of heat needed to warm the grain to the initial air temperature is less than the amount of latent heat given up by the air as its specific humidity is decreased from w_i to w_e (Process 1-2, Figure 3.9) then the final air and grain temperatures will equal the initial air temperature, w_o falls between w_i and w_e and final state point 2 is reached. If the amount of heat needed to heat the grain to the initial air temperature is more than the amount of latent heat given up by the air in decreasing its humidity ratio to w_e , (Process 1-3), then the air and grain reach an equilibrium temperature somewhere between the two initial temperatures, $w_o = w_e$, and final state point 3 is reached.

3.5 The Logic Sequence

As mentioned earlier, T_g is taken as the initial temperature of the grain in the column for the simulation of drying with ambient air. The temperature, T_g can be found by following the process as described in the beginning of Section 3.4.1.

Since T_i , the dry-bulb temperature and w_i , the specific humidity of the air entering the layer are known, the following calculations can be made:

P_{si} , the saturation vapour pressure of the incoming air may be calculated at T_i by Equation 3.1 or Equation 3.2. Equation 3.4 may be written in the form

$$P_{vi} = (w_i) P_{atm} / (0.6219 + w_i) \quad \dots\dots\dots (3.17)$$

Where P_{vi} = partial vapour pressure of the incoming air, g/cm^2

Similarly P_g , the vapour pressure of the moisture in grain can be found at temperature T_w and moisture content m_i using Equations 3.1 or 3.2, 3.8, and 3.4. Comparing P_{vi} with P_g of the layer and comparing T_i with the temperature of the grain will indicate the process that will occur in the layer.

Choosing either T_i or the grain temperature depending on the process and using Equation 3.8 will provide RH_e . Equation 3.4 provides w_e , the specific humidity in equilibrium with the moisture content of the layer.

A copy of the digital computer programme written in

Fortran is presented in Appendix-B. A flow chart and variable list are also provided.

CHAPTER IV

METHODS AND MATERIALS

4.1 Experimental Equipment

4.1.1. The Vertical Aeration Column

Experimental equipment was constructed in the laboratory for aeration of wheat and rapeseed (Figure 4.1). The description of the equipment which follows is divided into three sections: the vertical aeration column to hold the grain, the environmental chamber to condition the air, and the air distribution system for drawing conditioned air through the grain columns.

Figure 4.2 is a schematic diagram of one of the four columns to hold the grain for aeration. Each column consisted of an air plenum, two concentric cylinders, and a false floor.

The air plenum was made by gluing and nailing 2-cm thick pieces of plywood sheet. The plenum was insulated with 5-cm thick styrofoam to minimize the heat transfer to and from the surroundings.

Two concentric cylinders were used to hold the grain. The inner cylinder was an acrylonitrile-butadiene-styrene (ABS) plastic pipe with 10.16-cm inside diameter and 0.32-cm wall thickness. Because of the low thermal conductivity

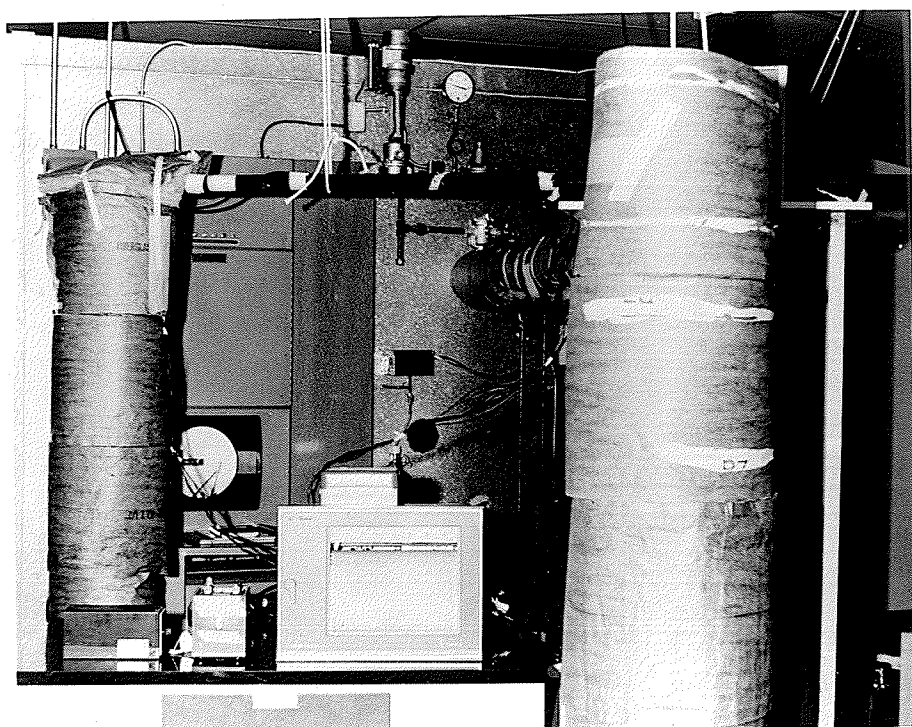


FIGURE 4.1 EXPERIMENTAL EQUIPMENT

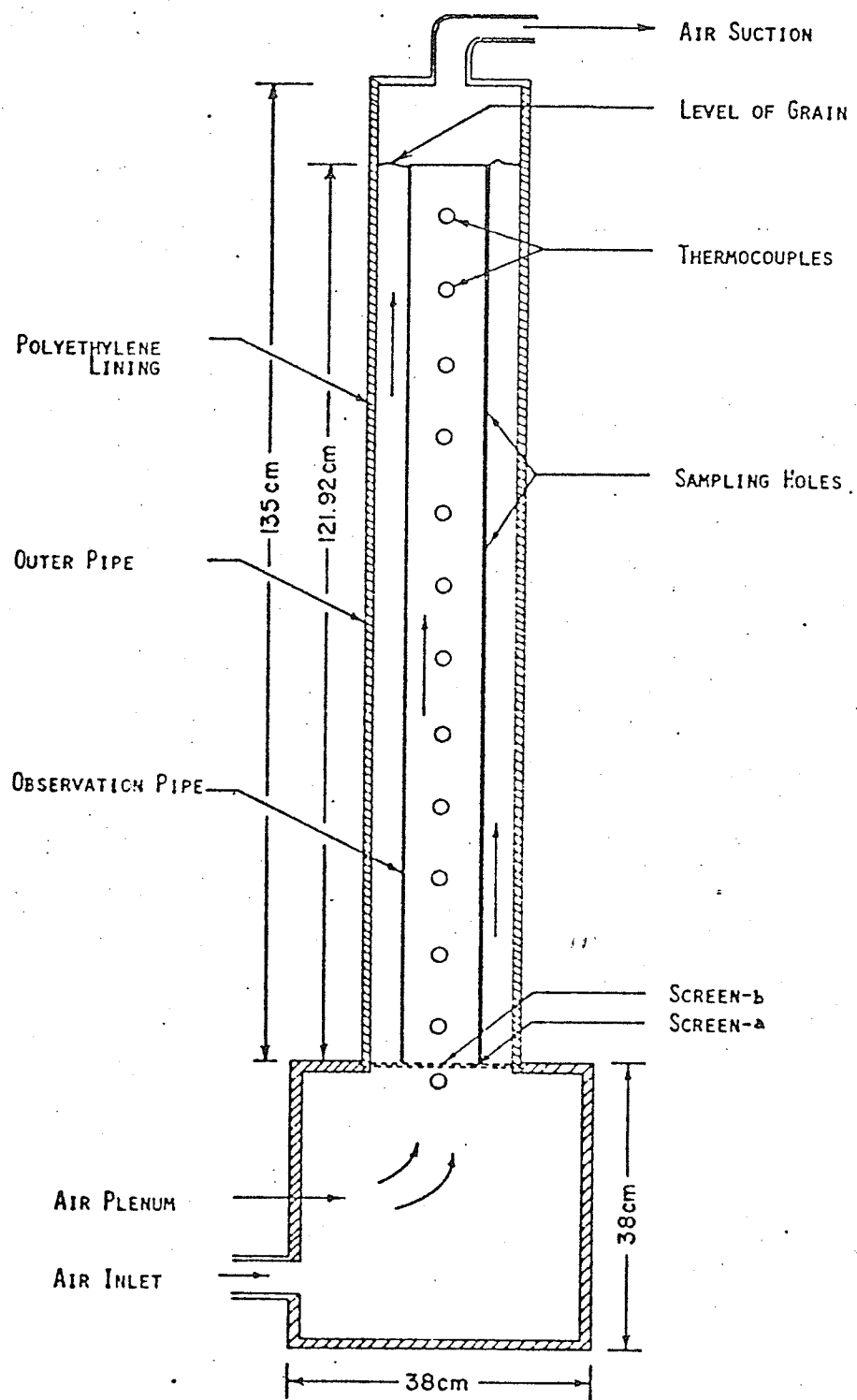


FIGURE 4.2 VERTICAL AERATION COLUMN

(0.00041 cal/cm sec C) of ABS plastic, it was assumed that the conductive heat transfer along the pipe wall, in the direction of airflow was negligible. The other criteria for selection of ABS plastic pipe were its low cost, light weight, sufficient strength to hold the grain, and ease of installation. This inner pipe was called the observation pipe.

The height of the observation pipe (grain column) was 121.92 cm. This height was selected to give a clear picture of moisture and temperature gradients in the grain column, when aerated with low rates of airflow (Sutherland et al., 1971; Bloome and Shove, 1970). Twelve holes with 1.27 cm diameter were made at a centre to centre distance of 10.16 cm along the length of the observation pipe. The holes were used to take the grain samples for moisture determination and to mount the thermocouples at the centre of the observation pipe.

The outer cylinder was an asbestos and portland cement sewer pipe with 20 cm inside diameter and 1.6-cm thick wall. Plastic pipes and paper containers were also considered but these were not locally available. The sewer pipe was cheaper and heavy enough (27 kg for 136 cm length of the pipe) to stand in place without any extra support, while holding the grain. However, the pipe was difficult to cut to size.

The inside wall of the outer cylinder was lined with 0.0254-cm thick polyethylene to prevent moisture transfer between the grain and the cylinder wall. The purpose of grain surrounding the observation pipe was to provide a guard ring similar to that used in measuring thermal conductivity (Lentz; 1961). Low thermal conductivity values of the guard ring and wall of the outer pipe (0.00036 cal/cm sec C) and 6.25-cm thick layer of fiberglass insulation reduced lateral heat loss by conduction and convection from the wall of the observation pipe.

The false floor consisted of two screens as shown in Figure 4.3. Screen-a was 0.0625-cm thick perforated metal with 33% opening area. Screen-b was woven aluminium wire mesh with 75 holes/cm². The opening area for Screen-b was 60% and the diameter of the wire was 0.0254 cm. Screen-b was permanently fixed at the bottom of the observation pipe and was also placed in the annular space between the two concentric cylinders on Screen-a. This arrangement of screens ensured a uniform pressure drop over the entire area of the false floor.

4.1.2 The Environmental Chamber

The laboratory was equipped with an environmental chamber.*

* CreLab Variable Temperature and Humidity Environmental Cabinet. Model WHL3-610M, Serial No. 3868.

Temperature range: -26.1 to 35 C (- 15 F to 95 F),
Differential $\pm$ 0.2778 C ($\pm$ 0.5 F)

Humidity range: 30% to 95%, Differential $\pm$ 5%

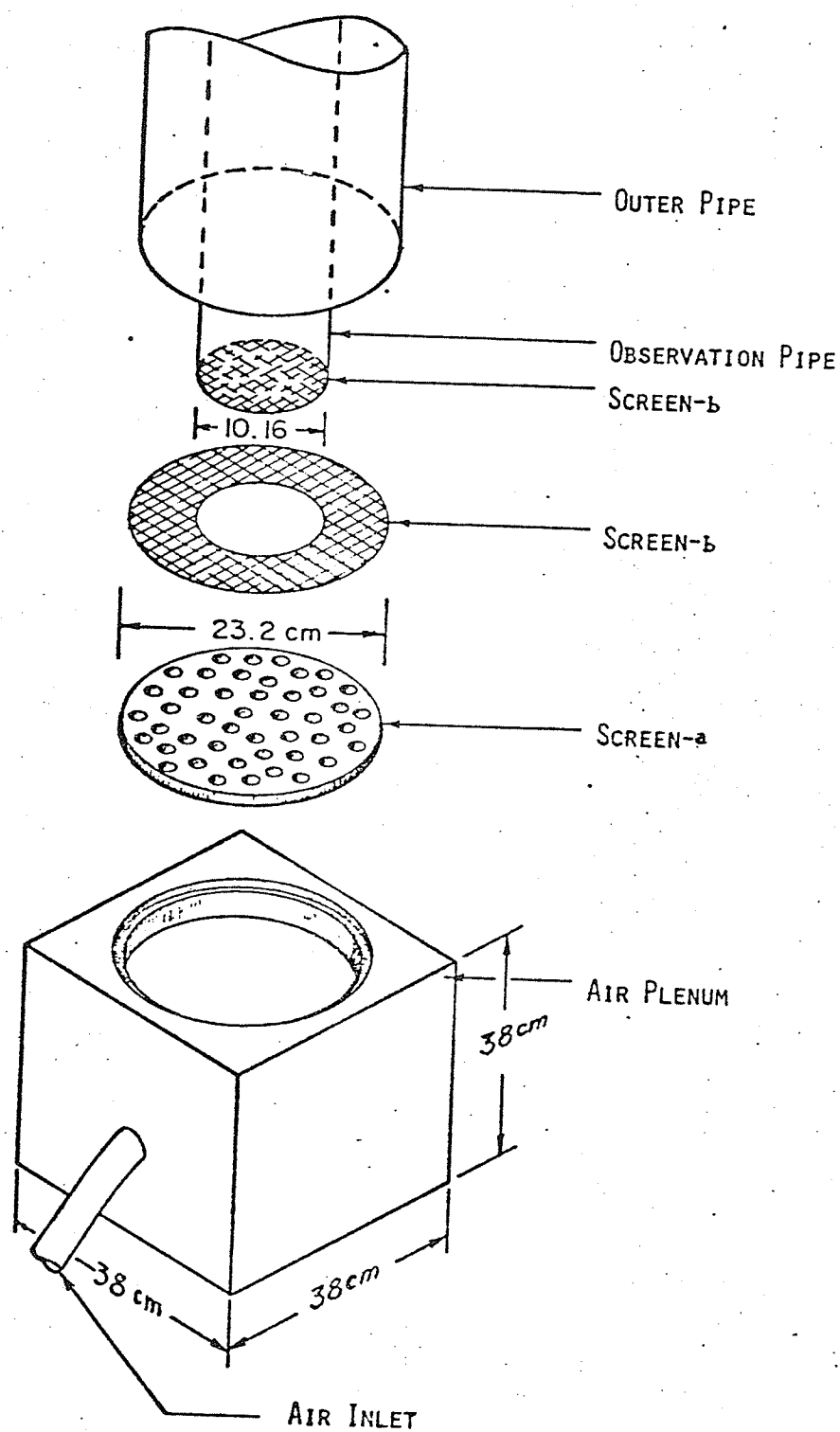


FIGURE 4.3 DETAILS OF THE FALSE FLOOR

Heating and cooling cycles of the temperature control unit of the chamber caused rapid temperature fluctuations inside the chamber. To reduce these fluctuations, a wooden cabinet (Figure 4.4) was installed inside the environmental chamber. The size of the cabinet was 70 cm X 60 cm X 70 cm. At a height of 5 cm from the bottom of the cabinet, 4 holes of 2.54-cm diameter were drilled on each side of the cabinet. The conditioned air from the chamber entered the wooden cabinet through these holes. A 10.16-cm diameter exit hole was made at the centre of the top of the cabinet. From the exit hole the air was taken out through a 10.16-cm diameter sheet metal pipe to the grain column. The cabinet reduced the temperature fluctuation at the exit to less than 0.556 C (1 F) from a previous fluctuation of 2.77 C to 3.88 C (5 F to 7 F).

4.1.3 The Air Distribution System

A centrifugal blower, coupled to a 373 W electric motor was used to draw the conditioned air from the environmental chamber through the grain columns. The rated capacity of the blower was $2.83 \text{ m}^3/\text{min}$ of air at 25.4 cm of water pressure. The blower unit was installed above the ceiling of the laboratory. This location of the unit offered the following advantages: (1) required smaller length of the connecting pipe and less number of bends, (2) created less noise, and (3) did not require any extra space in the laboratory.

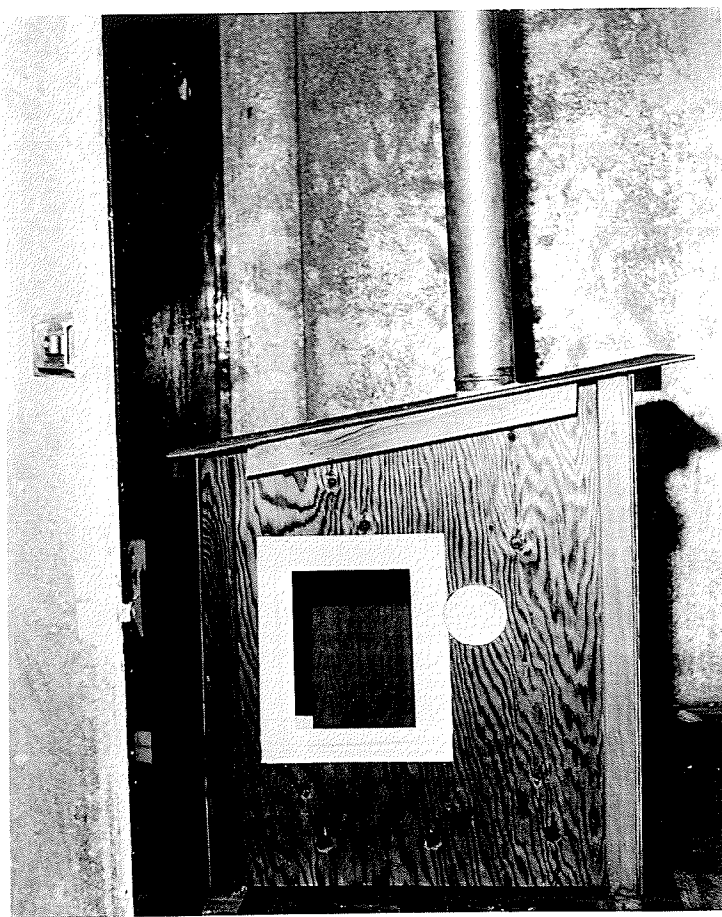


FIGURE 4.4 WOODEN CABINET

A 10.16-cm diameter sheet metal pipe was used to carry the air from the wooden cabinet (Figure 4.4) to the distribution manifold. The pipe outside the chamber was wrapped with 6.25-cm thick fiberglass insulation. The distribution manifold (Figure 4.5) was made by gluing and nailing 2-cm thick pieces of plywood sheet. The dimensions of the manifold were 38 cm X 38 cm X 38 cm. To minimize the heat transfer to or from the surroundings the manifold was insulated with 5-cm thick styrofoam.

An ABS plastic pipe of 3.8 cm diameter was used to carry the air to the grain column from the distribution manifold. All the connecting pipes and flowmeters were wrapped with 6.25-cm thick fiberglass insulation.

The air coming out of the grain columns was carried to the collection manifold (Figure 4.6) by 3.8-cm ABS plastic pipes. The collection manifold was similar to the distribution manifold in construction. The collection manifold was connected to the blower by using a 10.16-cm sheet metal pipe.

To make sure that the system was airtight the following cements and glues were used:

- (1) ABS solvent cement was used for all ABS plastic connections.
- (2) At the joints of plywood and sheet metal, and ABS plastic and plywood a blend of epoxy resin and hardener was used.



FIGURE 4.5 FLOWMETER INSTALLED BETWEEN DISTRIBUTION MANIFOLD AND AERATION COLUMN

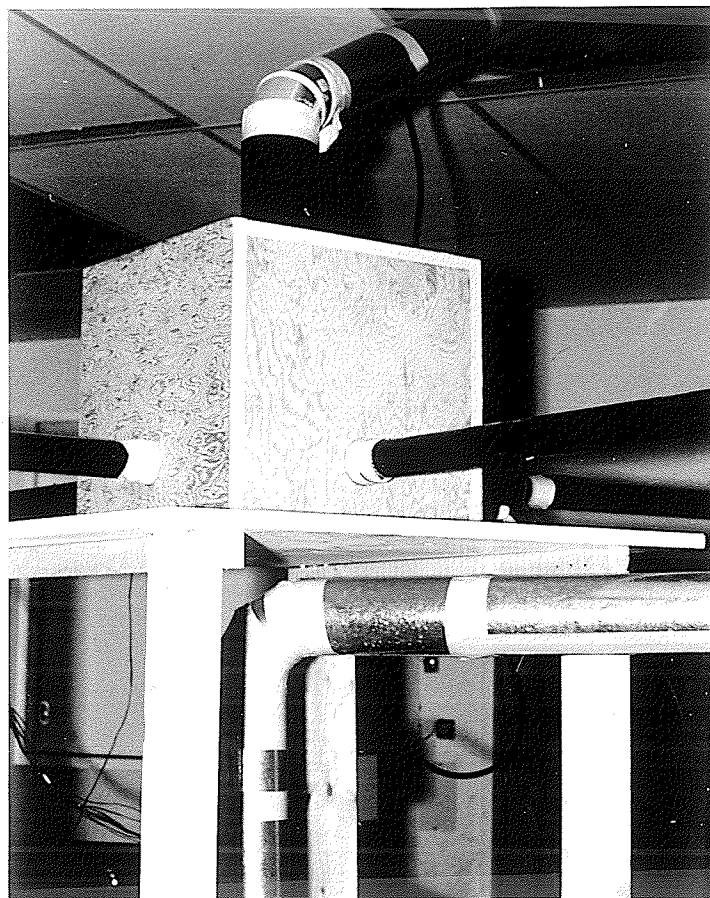


FIGURE 4.6 COLLECTION MANIFOLD

- (3) To join the outer cylinder temporarily with the plywood plenum handi-calk was used. Handi-calk was a blend of tough, elastic, non-staining, water repellent oils, pigments and asbestos fibre.

4.2 Selection and Preparation of Test Materials

The experimental wheat was a hard red spring variety, Neepawa, and was certified No. 1 seed wheat. The initial moisture content of the wheat was 14%. The rapeseed was Zephyr variety and certified No. 1 seed with an initial moisture content of 11%.

Moisture contents above the initial moisture content were obtained by adding calculated amounts of distilled water. These high moisture content grain samples were put in plastic containers (garbage cans). The containers were stored in the environmental chamber at 5 C and at a relative humidity which was in equilibrium with the moisture content of the grain sample. To assure the uniform distribution of moisture the samples were stored for 10 - 12 days and mixed twice a day. Mixing was accomplished by stirring the grain with hands and also by dumping it from one container to another.

The samples were stored at a low temperature (5 C) to prevent the growth of microorganisms in the grain. After equilization of moisture throughout the samples of grain, the temperature inside the chamber was changed to the desired

initial temperature in a particular test. The grain was kept at this temperature for about 24 h and was mixed several times to obtain a uniform temperature throughout the sample.

4.3 Measurement of Variables

4.3.1 Moisture Content

For the initial moisture content determination 8 samples of grain per column were taken while filling the grain into the observation pipe. At the end of each test the observation pipe was removed and 12 samples of grain, one from each observation hole in the inner pipe were taken by a 1.27-cm. diameter probe.

Moisture contents of the grain samples were determined by an oven drying method (American Society of Agricultural Engineers; 1972). Samples of about 25 g to 30 g were weighed to 0.0001 g and dried in a ventilated oven at 130 C for 19 hours and then reweighed. Moisture contents were calculated from the difference between initial and final weights and expressed in percentage of final weight, i.e., % dry basis (m), i.e.:

$$m = \frac{\text{initial weight} - \text{final weight}}{\text{final weight}} \times 100\% \quad \dots (4.1)$$

4.3.2 Relative Humidity

The relative humidity of air inside the chamber was

measured by using a wet and dry bulb psychrometer. Figure 4.7 shows how the relative humidity was measured near the exit hole of the wooden cabinet where the temperature fluctuation was negligible. The psychrometer used for the measurement was made with thermometers having 0.556 C (1 F) graduations. According to a technical report (Hygro-dynamics, Inc., Washington, D.C.; ?), at dry-bulb temperature of 21.11 C (70 F) and wet-bulb temperature of 14.44 C (58 F), the magnitude of error in relative humidity could be as much as 11 percentage units of relative humidity, if the psychrometer used had thermometers having 0.556 C (1 F) graduations. To make sure that improper psychrometric techniques did not give errors in relative humidity measurement, the following precautions were taken at the time of the observations:

- (1) The mechanical conditions of psychrometer were noted to make sure that it was whirling freely on the pivot.
- (2) A clean wick was used and its contamination from oil, dust or chemicals was avoided.
- (3) The wick was wetted thoroughly with distilled water and slipped over the bulb approximately as far on the stem as the length of the bulb, just below the lowest graduation of the thermometer. The wick was then firmly tied with a stout string

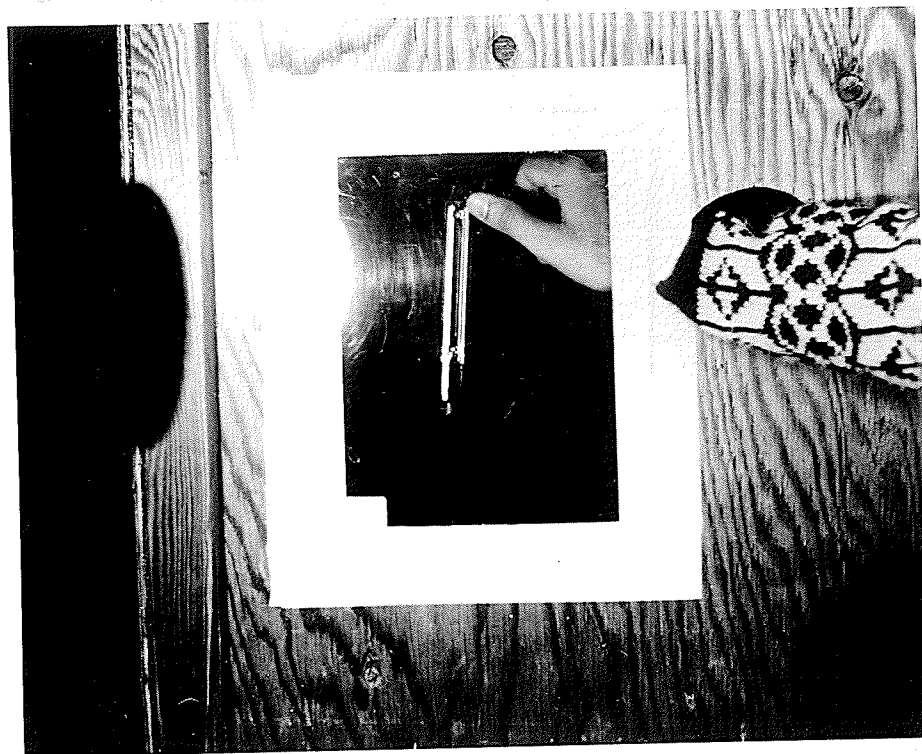


FIGURE 4.7 MEASUREMENT OF RELATIVE HUMIDITY

near the end of the wick covering the stem of the thermometer. The wick was also tied in the middle and at the top of the bulb.

- (4) To take the readings the wick on the thermometer was dipped in distilled water and whirled for 30 s. The reading was then taken quickly on the wet bulb. This process was repeated until the lowest reading was obtained.

4.3.3. Airflow

Brooks glass tube flowmeters (Model 1110) were installed in the flow lines between the distribution manifold and the vertical aeration columns (Figure 4.5). To achieve the desired airflow rates of 2.44 and 4.36 m/min,* glass tubes No. R-8M-25-2 were used with two standard floats, 8-RV-3 and 8-RS-8. The glass tubes had a scale 250 mm. long. The accuracy of the flowmeters as given by the manufacturer was $\pm 2\%$ of full scale.

4.3.4 Bulk Density

The bulk density of the grain was determined by weighing the amount of grain required to fill the observation pipe and

* The airflow rate is expressed in m/min, which is derived from m^3/min of air per m^2 of the false floor (i.e., m^3/min $\text{m}^2 = \text{m}/\text{min}$).



FIGURE 4.8 INSTALLATION OF THERMOCOUPLES
IN THE OBSERVATION PIPE

dividing by its volume. A consistent filling procedure was used to avoid variation in compaction. The density was separately measured for each test.

4.3.5 Temperature

Temperature was measured at the centre of the observation pipe with thermocouples installed in each sampling hole as shown in Figure 4.8. The thermocouples were made from copper-constantan wires of 0.058 cm. diameter. The size of the soldered joint was kept as small as possible to reduce the effect of extended surface on the heat transfer from the joint. The temperature readings were obtained by connecting these thermocouples to a multi-point recording potentiometer.* One thermocouple was also installed at a point in the air plenum below each column, where the air was entering the grain column. These thermocouples were connected through a switchbox to a potentiometer having 0.28 C (0.5 F) graduations. The accuracy of the thermocouples connected to the recorder and the potentiometer was checked by taking the temperature readings of a known reference junction maintained at 0 C. The difference in temperature readings obtained by the thermocouples were within ± 0.25 C of the reference temperature.

* Elektronik 16
Model No. 154-155-211-270
Temperature range: -40 C to 43.3 C (-40 F to 110 F)

4.4 Preliminary Test

A preliminary test was performed to check the validity of the assumption that in the test apparatus the temperature gradients perpendicular to the direction of air flow were negligible. Columns No. 2 and 4 (arbitrarily numbered) of the apparatus were loaded with wheat at 11.5 C and 17.5% moisture content. The other two columns (No. 1 and 3) were loaded with wheat at 35 C temperature and 12.23% moisture content. Air at 22.2 C dry-bulb temperature and 25% relative humidity was drawn through the columns at a flow rate of 4.36 m/min.

Thermocouples were installed 66 cm. above the bottom of the grain column (Figure 4.9). Temperatures around the periphery of the observation pipe, at any time during the aeration did not differ by more than ± 0.28 C (0.5 F). Table 4.1 shows, for example, the temperature readings after 24 h of aeration. On the basis of this comparison of the temperatures around the periphery of the observation pipe, it was assumed that the air flow was uniform throughout the cross-section of the column.

The temperature at the centre of the observation pipe, T_c (Figure 4.9), was within ± 0.28 C (0.5 F) of the temperatures outside the observation pipe. A small temperature gradient was existing in the direction perpendicular to the air flow (Table 4.1). This gradient was caused by a temperature difference (ΔT_r) of 10 C (23.7 C to 13.7 C) between the room

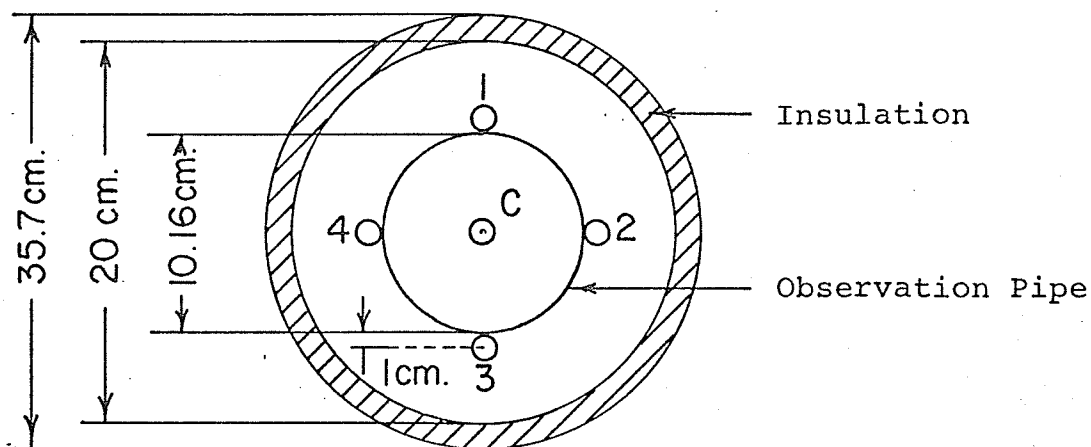


FIGURE 4.9 LOCATION OF THERMOCOUPLES 66 cm. ABOVE THE BASE OF THE COLUMN

TABLE 4.1 TEMPERATURES AT LOCATIONS SHOWN IN FIGURE 4.9 AFTER 24 h OF AERATION

Column No.	Temperature, C				
	Location - c	Location - 1	Location - 2	Location - 3	Location - 4
1	21.6	21.6	21.6	21.6	21.6
3	21.1	21.0	21.0	21.0	21.0
2	13.7	13.8	13.8	13.8	13.8
4	13.4	13.6	13.6	13.7	13.7

temperature and T_c , the temperature at the centre of the observation pipe. In the experimental tests to verify the model, however, the temperature difference (ΔT_r) was always less than 5 C. The temperature gradient in the direction perpendicular to airflow, therefore, was expected to be negligible for the tests. The preliminary test was not considered for verification of the model because the grain had reached equilibrium with the air when the aeration was stopped after 6 days.

4.5 Verification of the Aeration Model

To verify the accuracy of the model, experimental tests were carried out in the laboratory for wheat and rapeseed aeration. Selected conditions of air and grain (Table 4.2) were used for this purpose. The symbols used in Table 4.2 are defined as follows:

M_o = initial moisture content of the grain, % dry basis

T_{og} = initial temperature of the grain, C

T_g = temperature of air and grain at which the relative humidity of the air is equal to the equilibrium relative humidity of the grain assuming that air cools at a constant wet-bulb temperature, C

T_{db} = dry-bulb temperature of the air, C

RH_a = relative humidity of the incoming air, %

T_{wb} = wet-bulb temperature of the incoming air, C

Q_a = rate of airflow, m/min

Table 4.2 Test Conditions Used in the Verification of Aeration Model

Test No.	Test Material	M _o	T _{og}	T _g	T _{db}	RH _a	T _{wb}	Q _a
1	Wheat	24.20	28.3	21.9	25.0	72.0	21.1	2.44
2	Wheat	25.40	24.0	21.7	24.2	77.0	21.1	2.44
3(a)	Wheat	19.25	22.0	19.4	23.1	58.0	17.5	2.44
3(b)	Wheat	19.25	22.0	19.4	23.1	58.0	17.5	4.36
4	Rapeseed	17.07	23.6	19.73	25.0	55.0	18.6	2.44

Table 4.2 shows that only tough and damp grades (The Canadian Wheat Board; 1972-73) of wheat and rapeseed were used for the experimental tests. The initial temperature of the grain was kept near the room temperature in all the tests. The dry-bulb temperature and relative humidity of the air in the experimental tests were selected arbitrarily to be representative of atmospheric conditions for Winnipeg at the time of harvest. In each test the relative humidity of air, however, was less than the initial equilibrium relative humidity of the grain.

Rates of air flow were selected on the basis of the previous work on aeration by Sutherland et al. (1971), Bloome and Shove (1970), Alam and Shove (1971).

In all experimental tests two replications were carried out. In test No. 2, after 90 h of aeration one of the two grain

columns was unloaded to take the grain samples for moisture content determination. The remaining grain column was unloaded after 144 h of aeration. In test No. 3, the two aeration columns were loaded with the grain at same initial conditions. These columns were aerated with 2.44 m/min and 4.36 m/min of airflow rates separately.

CHAPTER V

RESULTS AND DISCUSSION

5.1 Temperature Changes During Early Hours of Aeration

A typical cooling behaviour of grain during early hours of aeration is shown in Figure 5.1 for Test No. 3. Similar changes in grain temperature were observed in all the experimental tests conducted in this study. The reason to select Test No. 3 for showing these temperature changes is that the test also indicates the effect of air flow rate on the initial cooling of grain.

The grain kernels are cooled by evaporation of moisture from their surface. The evaporation occurs if the air passing over the kernels has a relative humidity below the equilibrium relative humidity of the grain. A cooling front is established in the grain column. The cooling front spreads out while passing through the grain column, thereby producing leading and trailing edges (Figure 5.1). Sutherland et al. (1971) found that the leading edge travels at a speed 1.96 times greater than the speed of the trailing edge. At higher flow rates the cooling front moves faster through the column of grain because the rates of heat and mass transfer are greater (Figure 5.1).

The measured temperature of the grain after initial hours of aeration was slightly lower than the value of T_g which is 19.4 C for the conditions of Test No. 3.

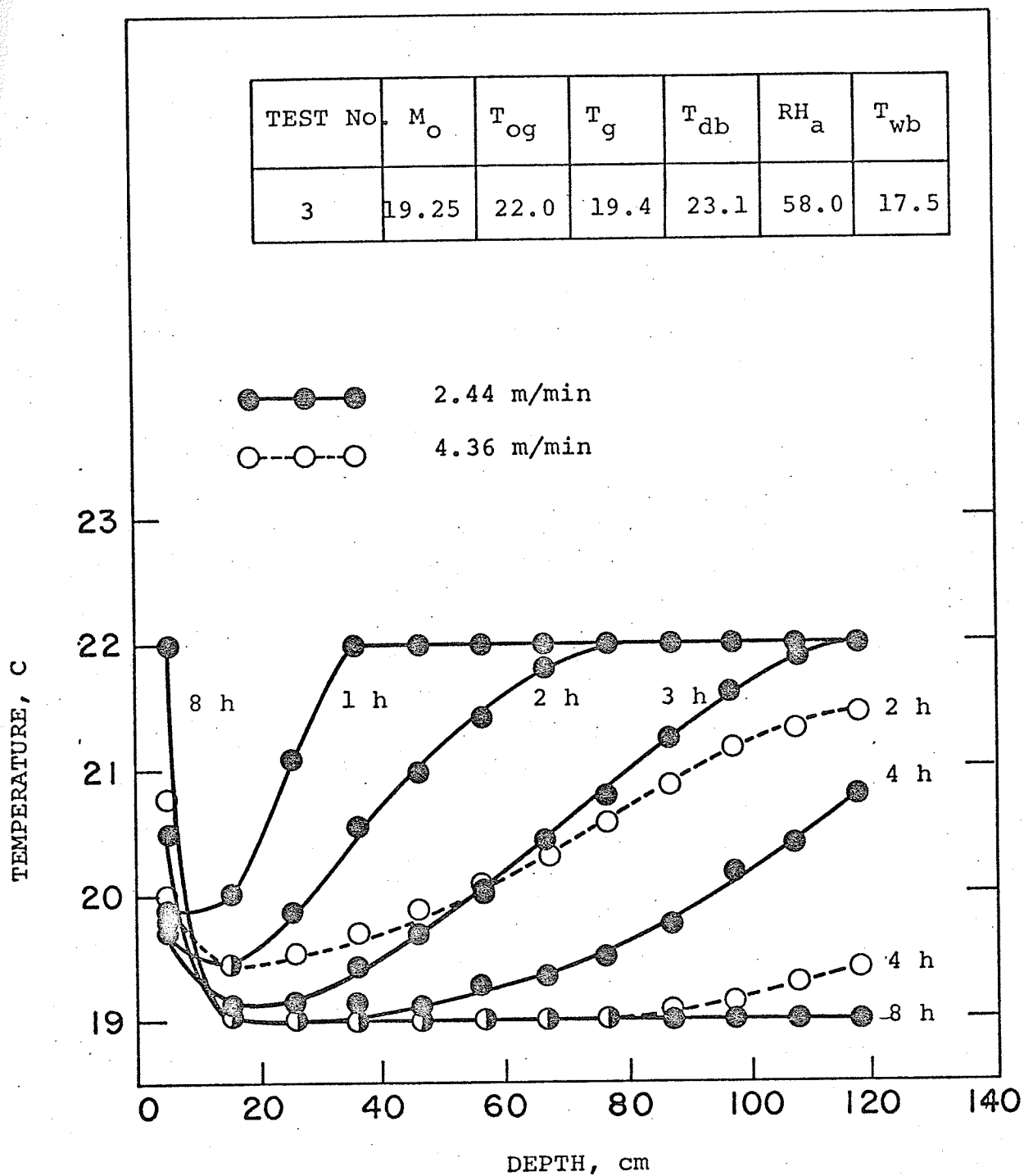


FIGURE 5.1 TEMPERATURE CHANGES DURING EARLY HOURS OF AERATION

The grain reached a temperature of 19.0 C. However, this value of temperature was well above the wet-bulb temperature of the incoming air which was 17.0 C. This deviation of T_g from the observed value is due to the possible errors in the measurement of relative humidity of the air and the possible errors in predicting the equilibrium relative humidity of the grain using the mathematical model of the sorption process (Equation 3.8).

5.2 Moisture and Temperature Gradients

The models of wheat and rapeseed aeration gave moisture and temperature gradients in the grain column similar to those experimentally observed (Figures 5.2 to 5.14). The air flowing into the grain column causes the formation of three zones (A, B, and C), separated by the temperature and moisture fronts which move through the grain column in the direction of airflow.

In zone A, the grain has reached equilibrium with the incoming air and no further change takes place. The temperatures of the grain and the incoming air are equal and the grain moisture content has reached the value which is in equilibrium with the relative humidity of the air.

Zone B, bounded by the temperature and moisture fronts, is of greatest importance and is the zone where the drying of the grain is taking place and the temperature of the grain is tending towards the dry-bulb temperature of the air. Zone

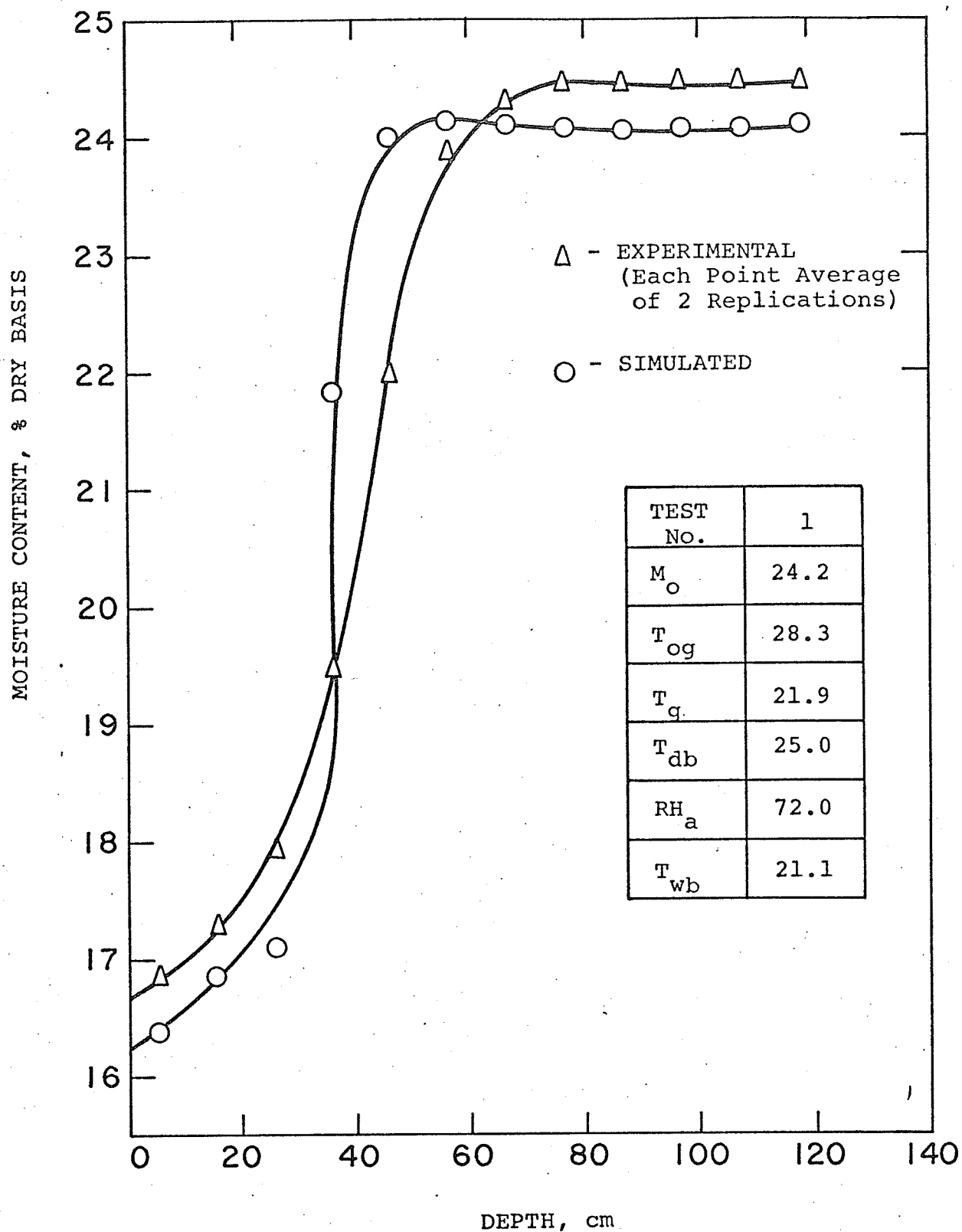


FIGURE 5.2 EXPERIMENTAL AND SIMULATED MOISTURE GRADIENTS IN A COLUMN OF WHEAT AFTER 80 h OF AERATION AT 2.44 m/min OF AIR

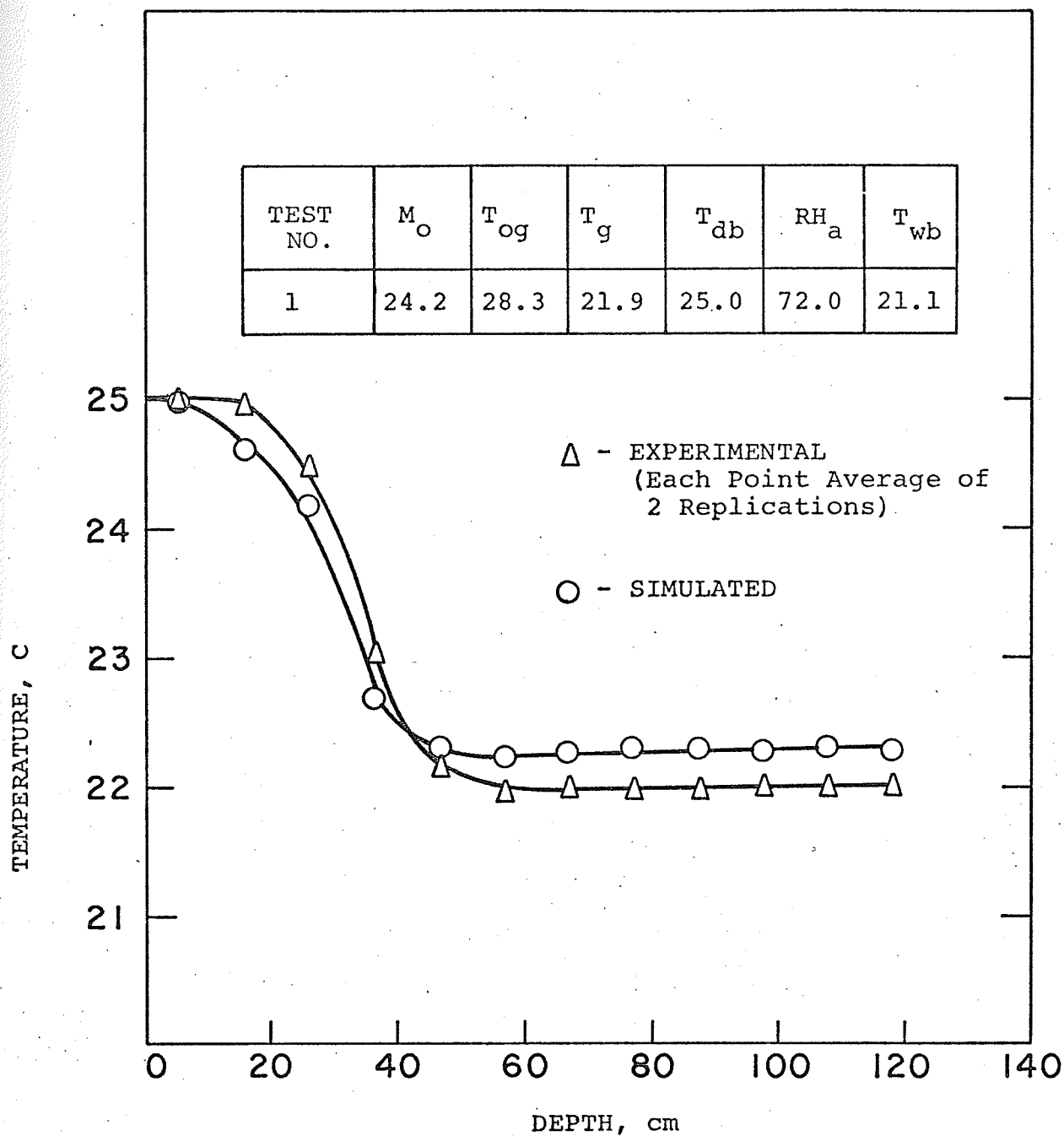


FIGURE 5.3 EXPERIMENTAL AND SIMULATED TEMPERATURE GRADIENTS IN A COLUMN OF WHEAT AFTER 80 h OF AERATION AT 2.44 m/min OF AIR

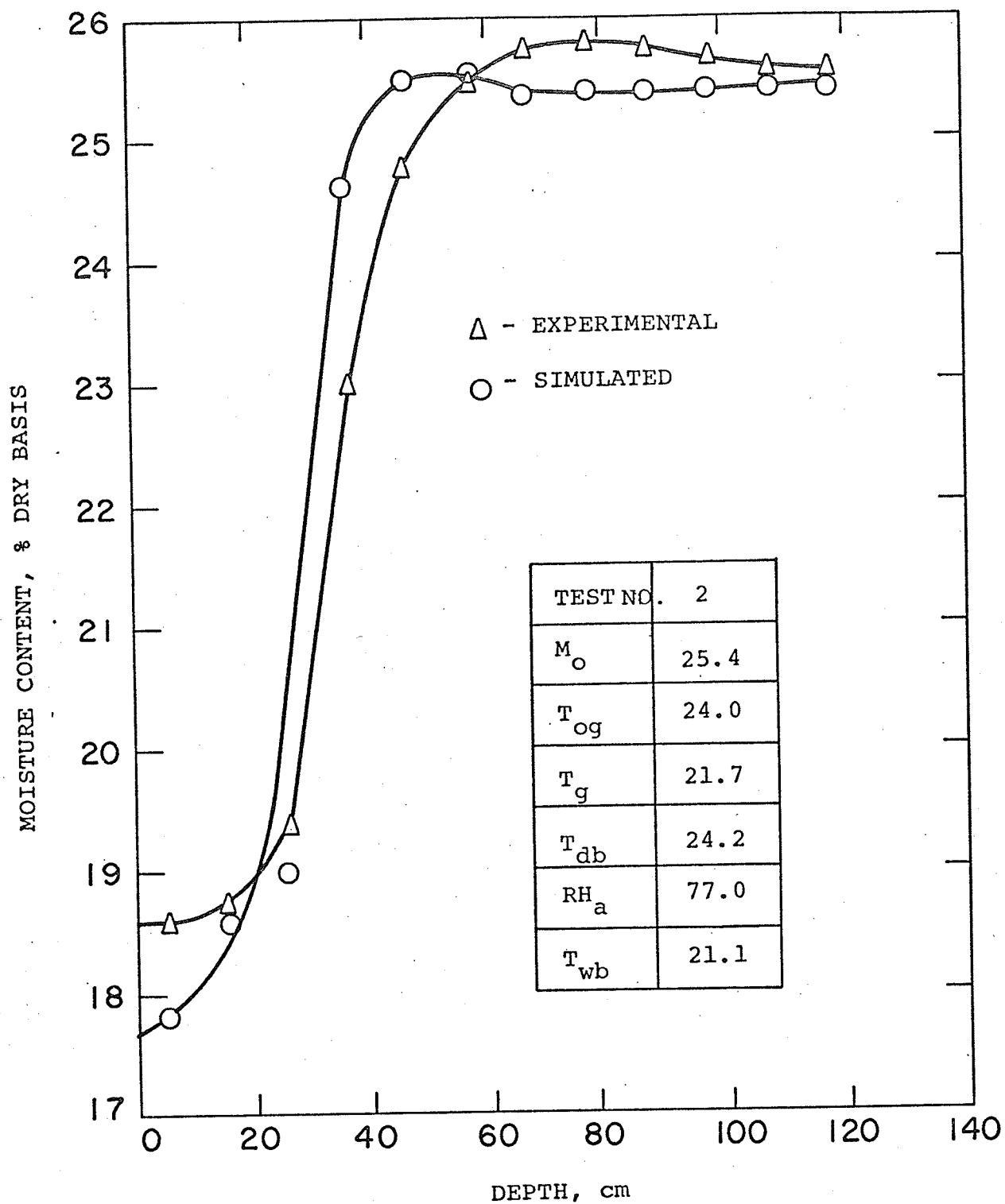


FIGURE 5.4 EXPERIMENTAL AND SIMULATED MOISTURE CONTENT IN A COLUMN OF WHEAT AFTER 90 h OF AERATION AT 2.44 m/min OF AIR

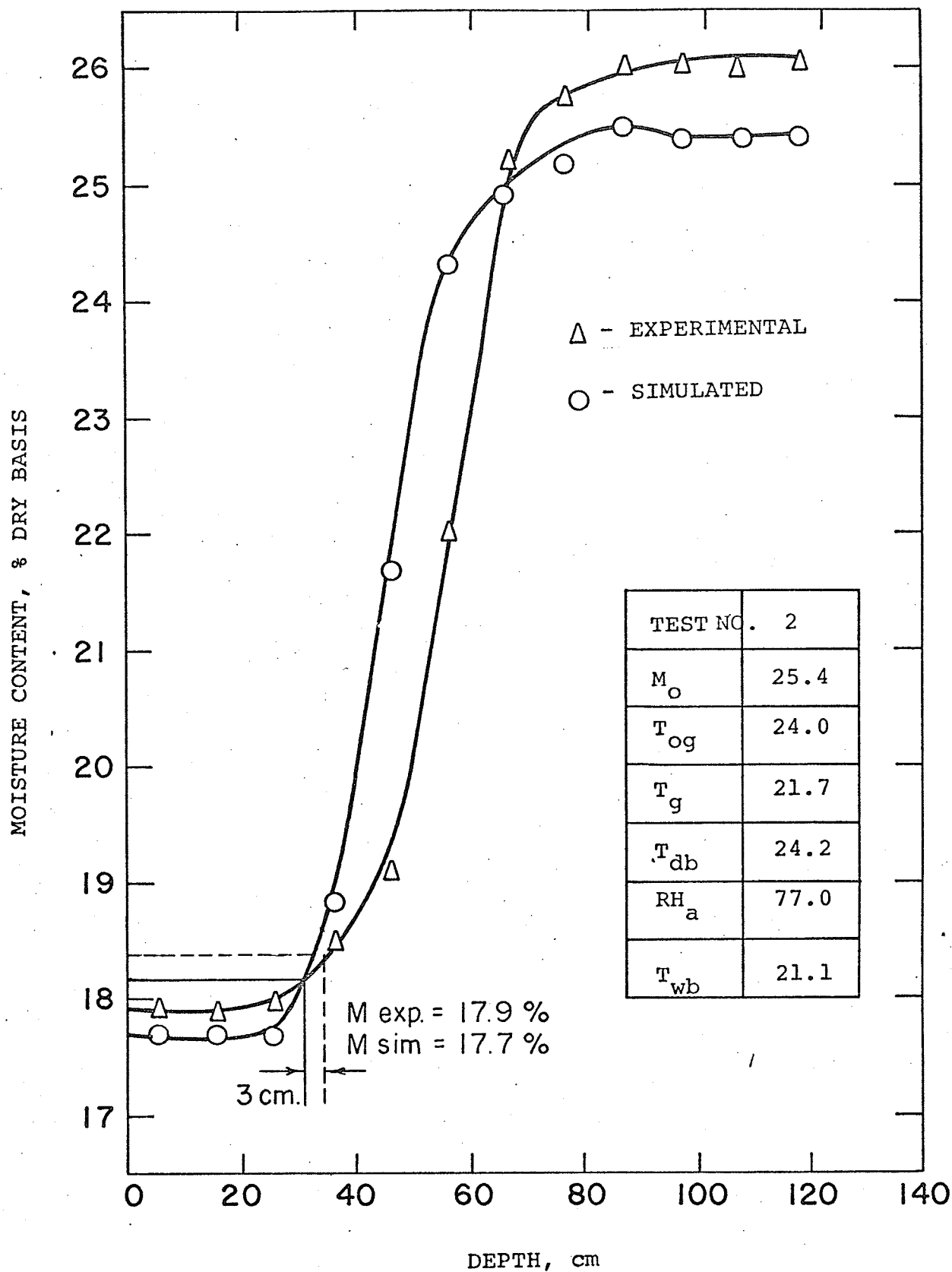


FIGURE 5.5 EXPERIMENTAL AND SIMULATED MOISTURE CONTENT IN A COLUMN OF WHEAT AFTER 144 h OF AERATION AT 2.44 m/min OF AIR

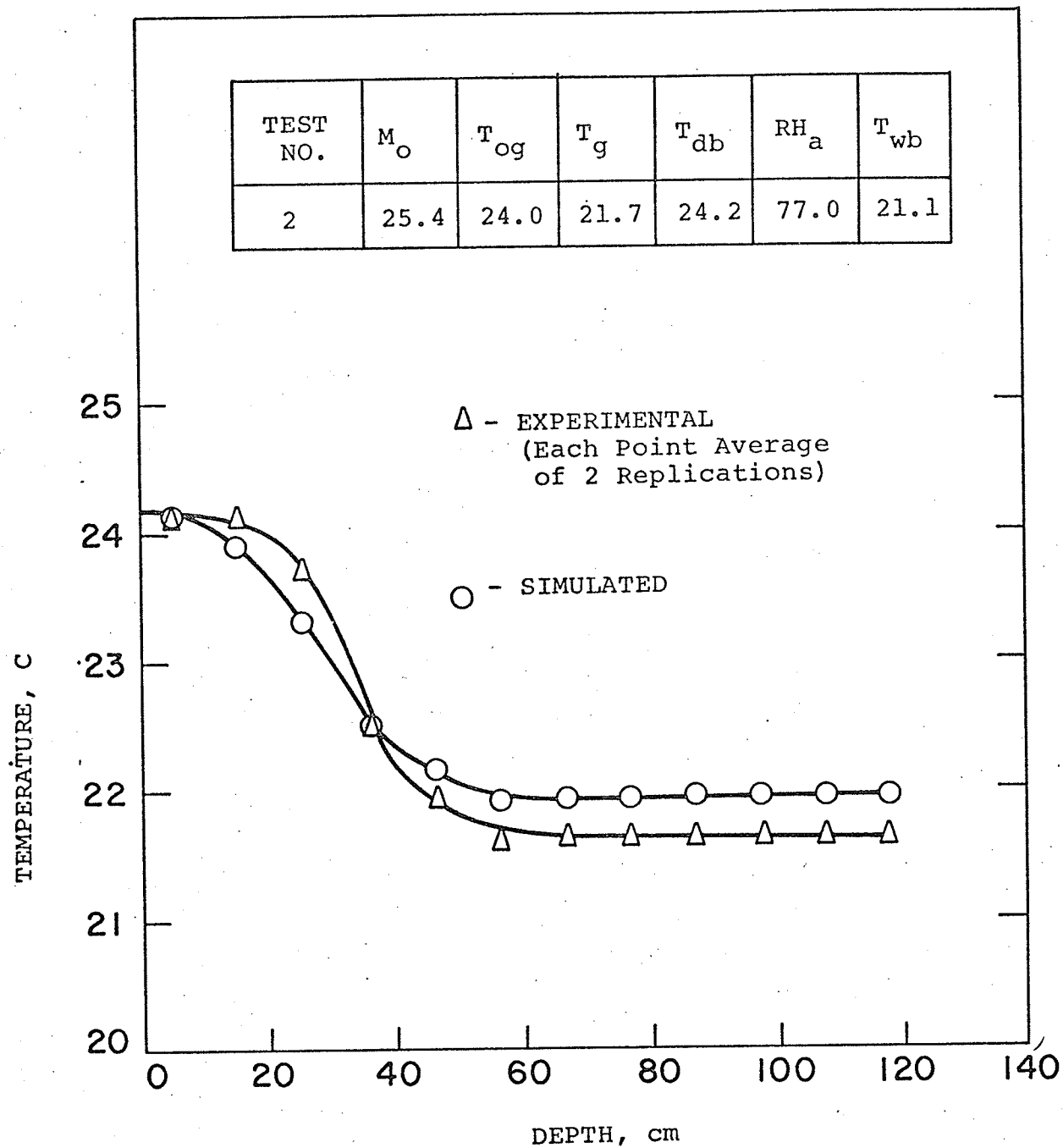


FIGURE 5.6 EXPERIMENTAL AND SIMULATED TEMPERATURE GRADIENTS IN A COLUMN OF WHEAT AFTER 90 h OF AERATION AT 2.44 m/min OF AIR

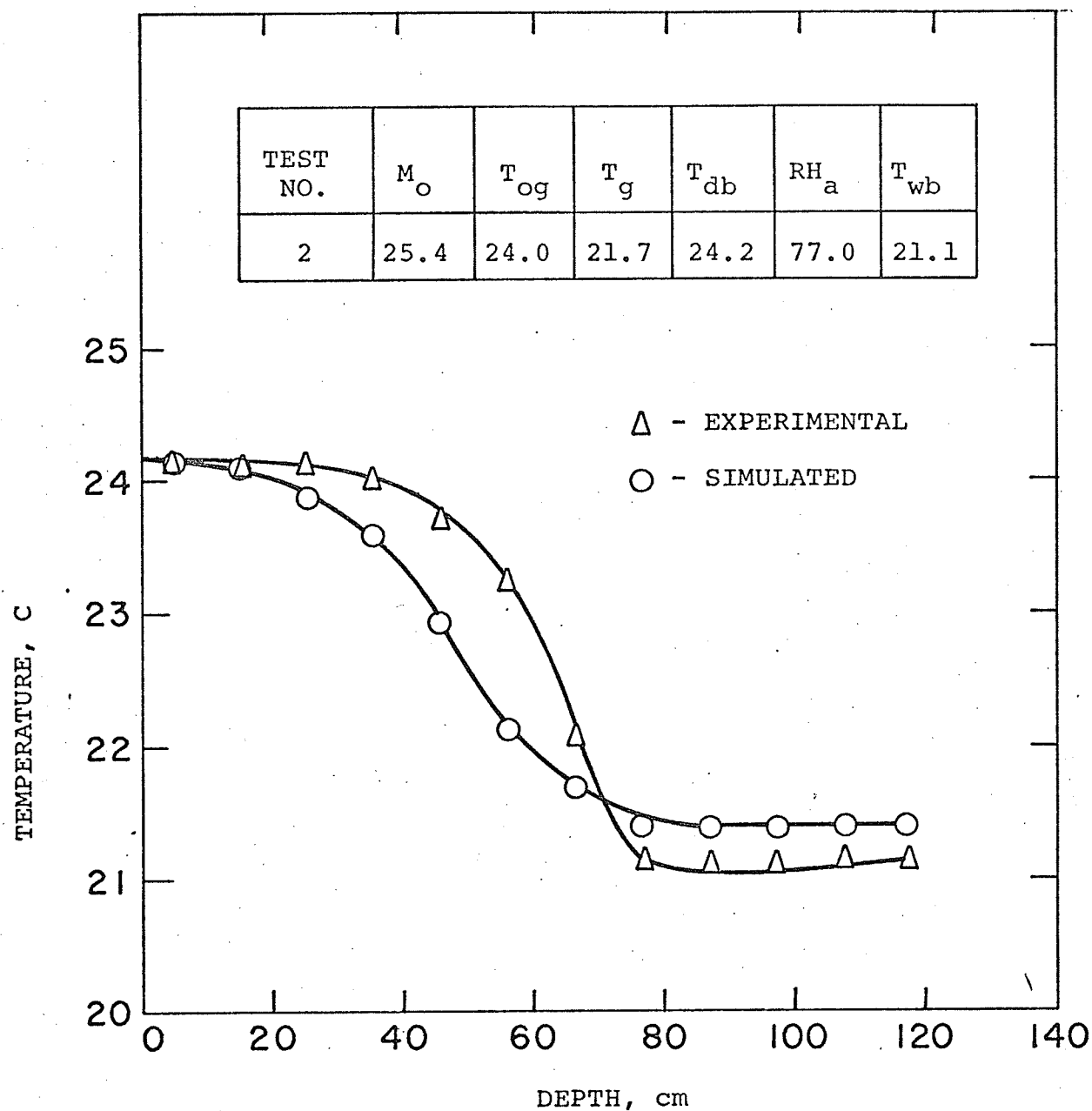


FIGURE 5.7 EXPERIMENTAL AND SIMULATED TEMPERATURE GRADIENTS IN A COLUMN OF WHEAT AFTER 144 h OF AERATION AT 2.44 m/min OF AIR

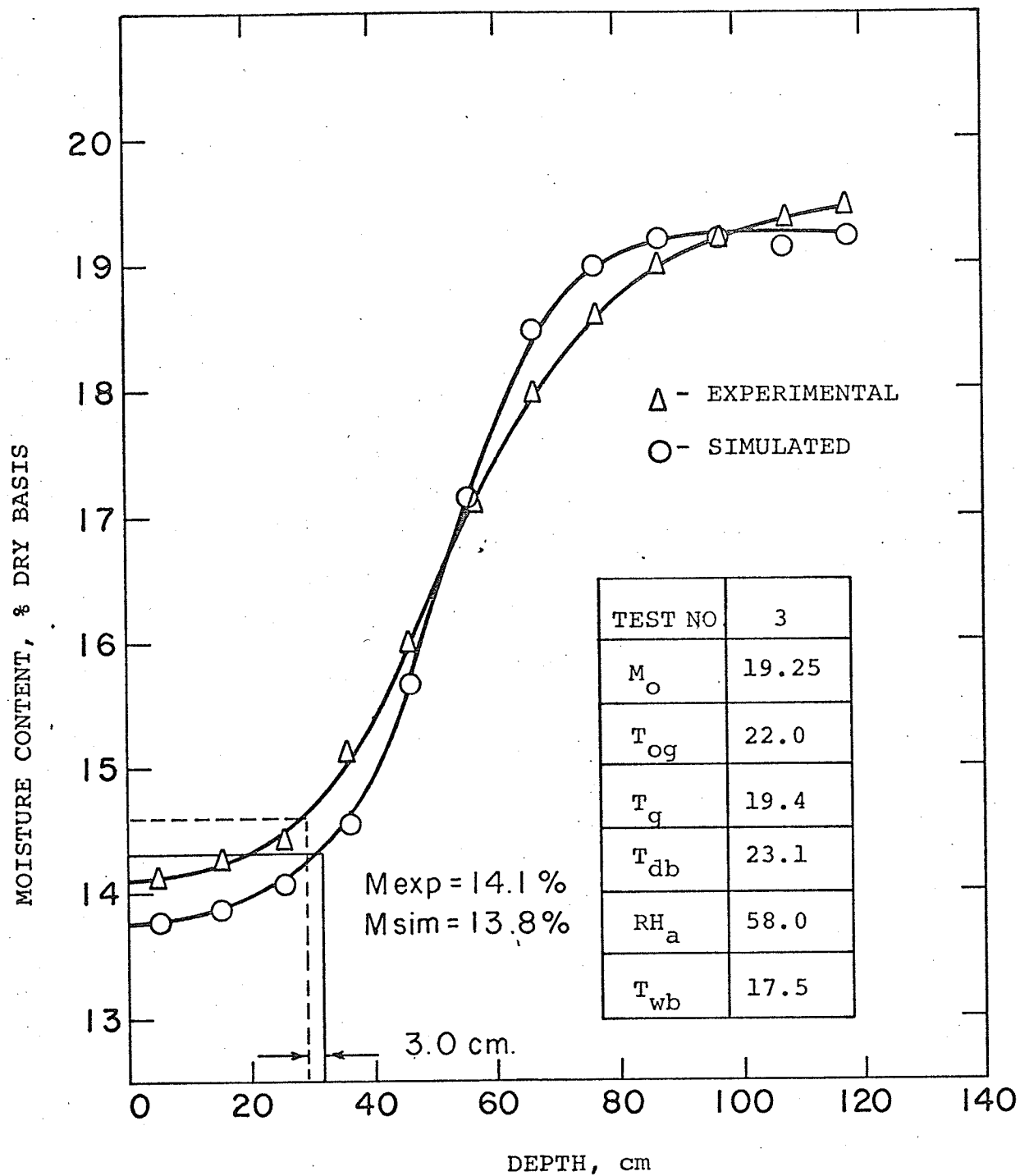


FIGURE 5.8 EXPERIMENTAL AND SIMULATED MOISTURE GRADIENTS IN A COLUMN OF WHEAT AFTER 75 h OF AERATION AT 2.44 m/min OF AIR

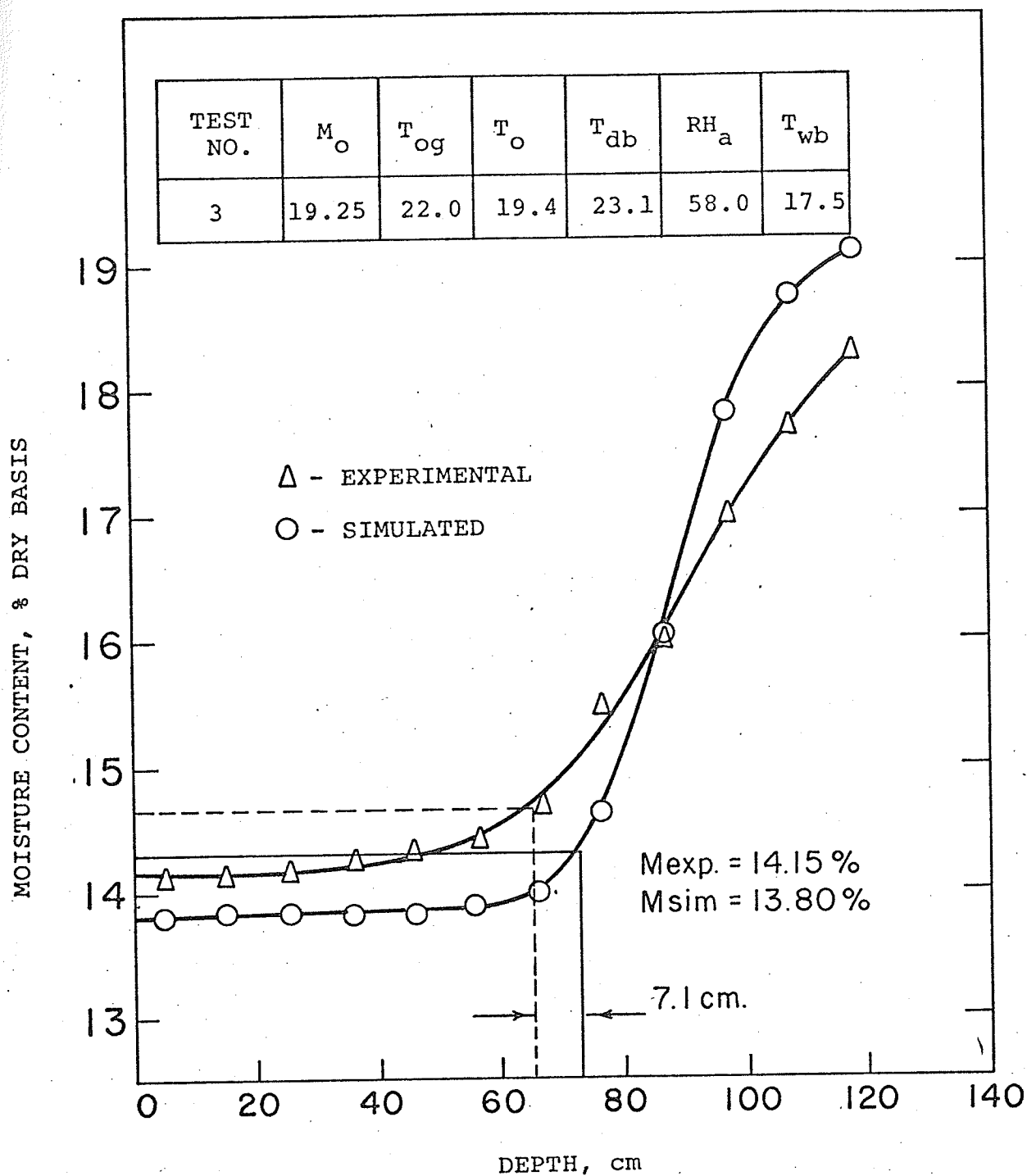


FIGURE 5.9 EXPERIMENTAL AND SIMULATED MOISTURE GRADIENTS IN A COLUMN OF WHEAT AFTER 75 h OF AERATION AT 4.36 m/min OF AIR

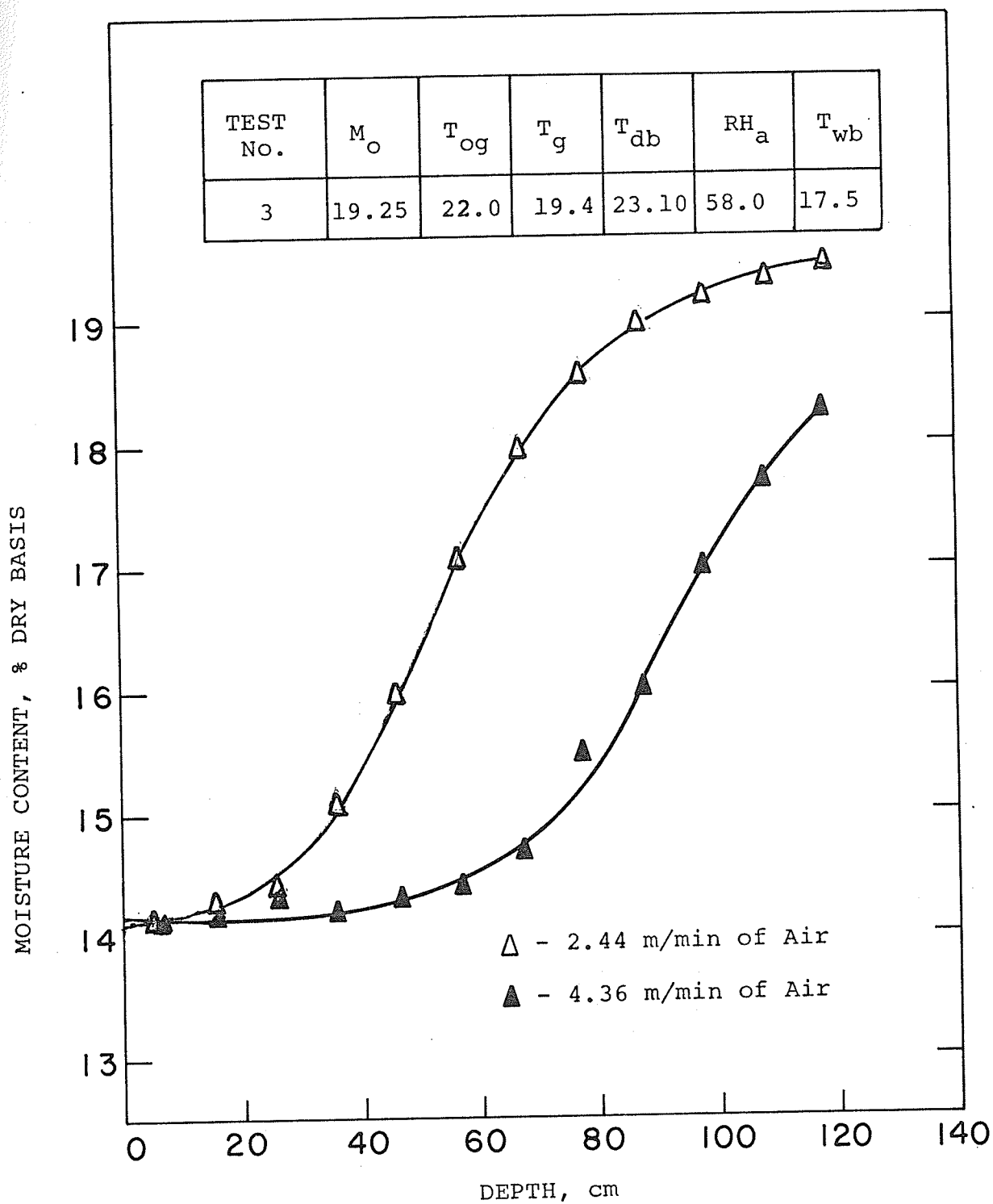


FIGURE 5.10 COMPARISON OF EXPERIMENTAL MOISTURE GRADIENTS AT DIFFERENT AIRFLOW RATES AFTER 75 h OF AERATION

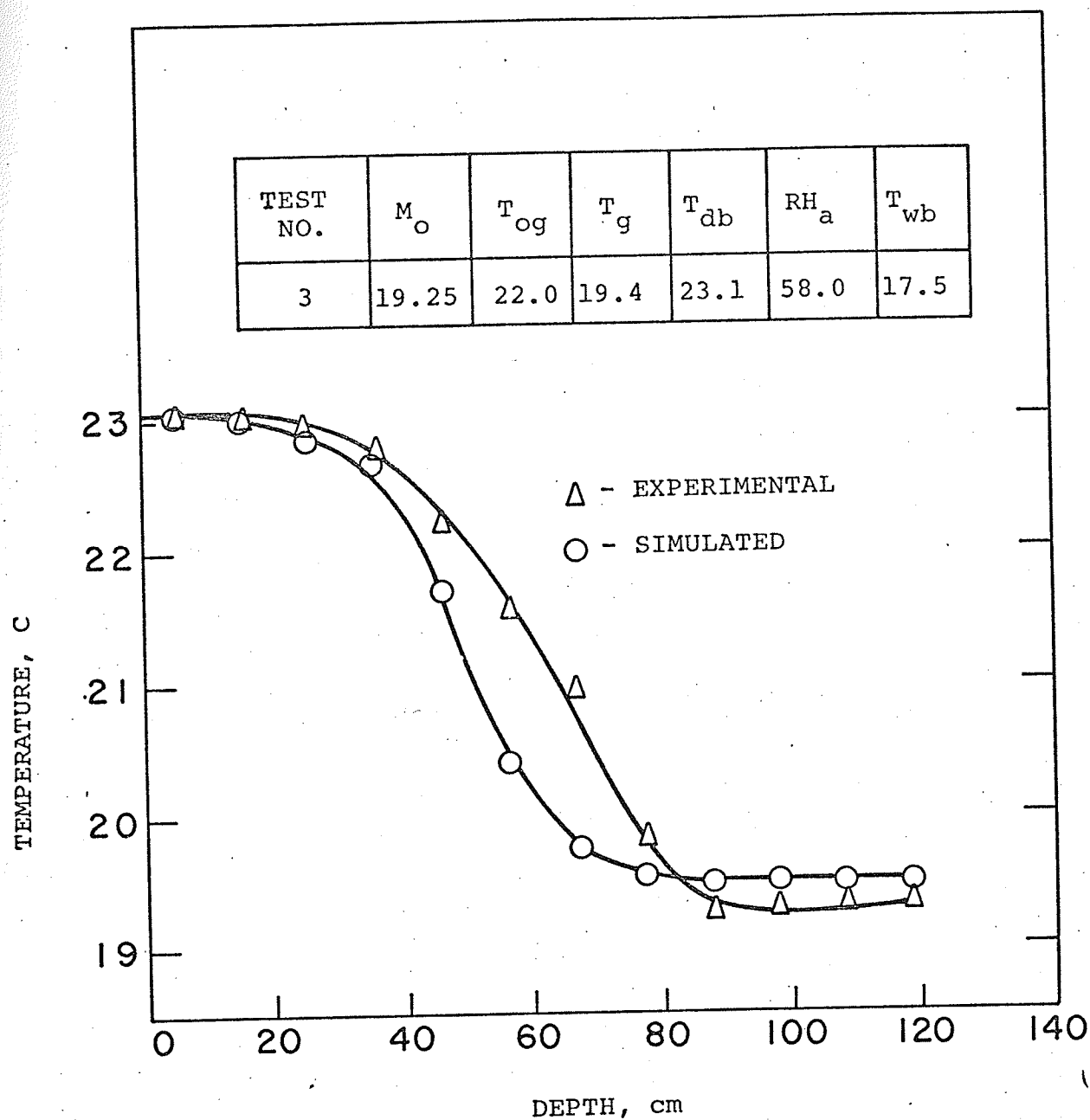


FIGURE 5.11 . EXPERIMENTAL AND SIMULATED TEMPERATURE GRADIENTS IN A COLUMN OF WHEAT AFTER 75 h OF AERATION AT 2.44 m/min OF AIR

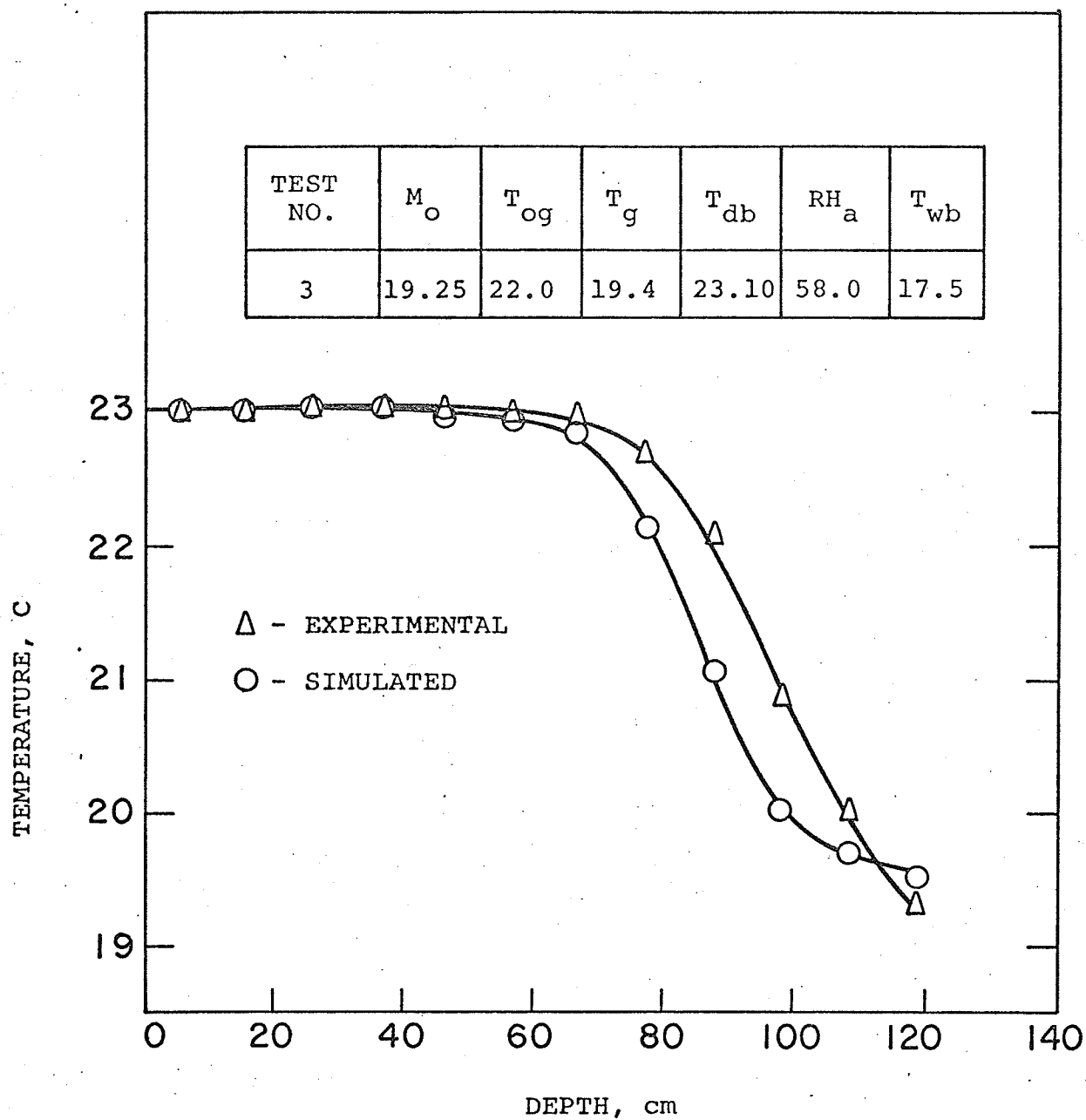


FIGURE 5.12 EXPERIMENTAL AND SIMULATED TEMPERATURE GRADIENTS IN A COLUMN OF WHEAT AFTER 75 h OF AERATION AT 4.36 m/min OF AIR

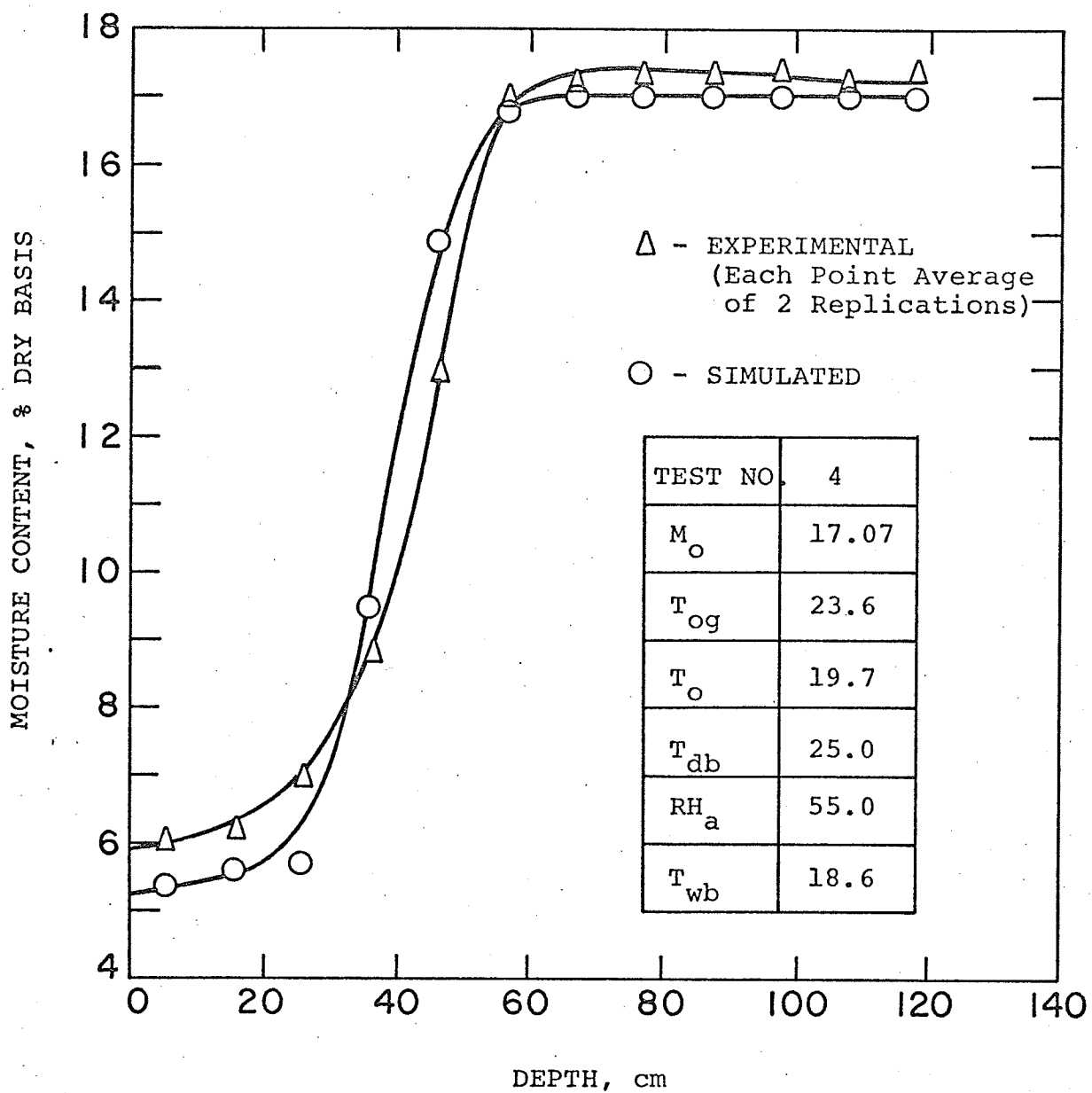


FIGURE 5.13 EXPERIMENTAL AND SIMULATED MOISTURE GRADIENTS IN A COLUMN OF RAPESEED AFTER 75 h OF AERATION AT 2.44 m/min OF AIR

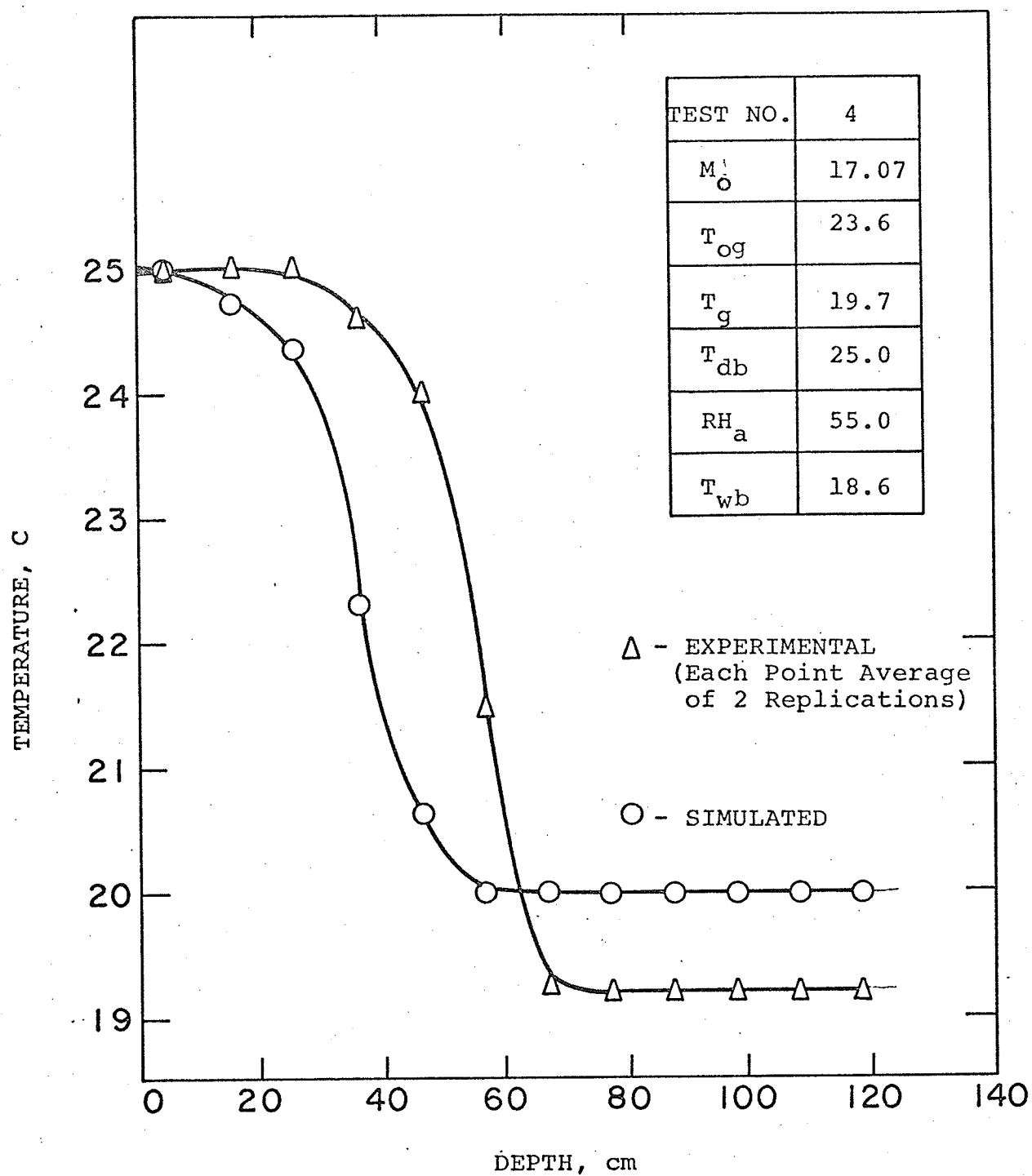


FIGURE 5.14 EXPERIMENTAL AND SIMULATED TEMPERATURE GRADIENTS IN A COLUMN OF RAPESEED AFTER 75 h OF AERATION AT 2.44 m/min OF AIR

B begins at the beginning of the moisture front.

In zone C, the grain temperature has not changed from T_g (the temperature reached by the grain during early hours of aeration). The moisture content of the grain has not changed from the initial value or it may have increased due to adsorption of moisture from the air. As the air passes through the grain it picks up moisture from the lower layers. The relative humidity of this air may exceed the equilibrium relative humidity of the grain in upper layers and cause wetting of the grain. The temperature of the air and grain in zone C could be expected to be more than T_g due to wetting of grain. But the air coming from the lower layers which is at T_g takes this heat of wetting out of the grain in upper layers and keeps the grain at temperature T_g .

The predicted moisture content values for all the tests are somewhat lower than the measured values of moisture content in zones A and C. The predicted moisture contents for individual layers range up to a maximum of 0.9% less than the measured values. The predicted values of moisture content are higher than the measured values in zone B only. The over-prediction in moisture content is on the safe side, therefore, the magnitudes of this type of deviation are not important in grain storage.

The lower values of moisture content in zones A and C are probably due to the following reasons: (1) the mathematical models of the sorption process (Equation 3.8 for wheat and

Equation 3.13 for rapeseed) do not predict the equilibrium moisture contents of the grain accurately, (2) there is an error in the measurement of the relative humidity of the incoming air.

The observed moisture front tends to be somewhat wider than the predicted moisture front. This is possibly due to the reason that complete moisture equilibrium is not reached between the air passing through a layer of grain and the grain in that layer during the time increment Δt .

The shapes of the simulated and experimental temperature gradients are similar, though the actual temperature in zone B (except near the end) is higher than the predicted temperature. The deviation of the temperature in zone B is due to the fact that the response of agricultural grains to temperature change is considerably faster than to moisture changes (Hamdy and Barre; 1969). In all the experimental tests, the temperatures in the upper layers of the column (zone C) are slightly lower than T_g . An explanation for such discrepancy was given in Section 5.1.

Figures 5.8 to 5.12 show that the higher airflow rate of 4.36 m/min causes rapid heat and mass transfer. Although, there is not much evidence, it seems that as the airflow rate increases the deviation between experimental and simulated moisture gradients increases. The probable reason is that at higher airflow rates moisture equilibrium is not reached between the air passing through a layer of grain and the grain in that layer.

The experimental and simulated moisture gradients (Figure 5.13) show that as compared with wheat a better agreement is achieved in experimental and simulated results during aeration of rapeseed. This is due probably to the effect of larger surface area per unit volume of rapeseed bulk which results in an increase in the mass transfer. The assumption that complete equilibrium is reached between the air passing through a layer of grain and the grain in that layer holds better for rapeseed than wheat.

The experimental data indicate that the simulation programmes for wheat and rapeseed aeration do not seem to predict the wetting of the upper layers of the grain column. This discrepancy may be due to possible errors in relative humidity measurements and possible errors in predicting the equilibrium relative humidity of the grain using the mathematical models of the sorption process (Equation 3.8 and 3.13).

5.3 Location of Drying Front

Analyses of the locations of the drying fronts are shown in Figures 5.5, 5.8, and 5.9. M_{exp} and M_{sim} represent the experimental and simulated equilibrium moisture contents respectively. The experimental and predicted drying fronts are considered then to be located at the heights above the base of the drying column where moisture content of the grain has reached within 0.5% of the M_{exp} and M_{sim} , respectively. The model is capable of predicting the location of the drying

front within ± 3.0 cm of the observed drying front for the airflow rate of 2.44 m/min, and with ± 7.1 cm for the airflow rate of 4.36 m.min.

CHAPTER VI

CONCLUSIONS AND LIMITATIONS OF THE SIMULATION MODELS

The general conclusions of this study on the simulation of heat and mass transfer during aeration of wheat and rapeseed bulks are:

1. When the air passing through the grain has a relative humidity lower than the equilibrium relative humidity of the grain, the grain is cooled by the evaporation of moisture from its surface during early hours of aeration.
2. During the first few hours of aeration the temperatures of the air and the grain are dependent on the wet-bulb temperature of the air and initial moisture content of the grain. That is the moisture equilibrium is the overriding control as compared with temperature equilibrium, during the early hours of aeration.
3. The initial grain temperature has only a minor effect on heat and mass transfer during aeration of grain using ambient air.

Simulation models for wheat and rapeseed have been developed which can predict changes in grain temperature and moisture content resulting from aeration using ambient air. The models

have been verified for the following ranges of variables:

- (i) dry-bulb temperature of the incoming air:
 - wheat - 23.1 C to 25.0 C
 - rapeseed - 25.0 C
- (ii) relative humidity of the incoming air:
 - wheat - 58% to 77%
 - rapeseed - 55%
- (iii) initial moisture content of the grain:
 - wheat - 19.25% to 25.4%
 - rapeseed - 17.07%
- (iv) initial temperature of the grain:
 - wheat - 22.0 C to 28.3 C
 - rapeseed - 23.6 C
- (v) rate of airflow:
 - wheat - 2.44 m/min to 4.36 m/min
 - rapeseed - 2.44 m/min

Bloome and Shove (1970) and Alam and Shove (1971) simulated corn and soybean drying, respectively, using ambient air in central Illinois. These models for corn and soybean simulated the drying with ambient air, and since the wheat and rapeseed models, given here, simulated aeration at the selected conditions, it is expected that the models would simulate

the drying under ambient conditions for a wide range of variables. This range of variables is, however, dependent upon the range for which the equations of the properties of a particular grain are available.

For wheat the mathematical model of the sorption process (Equation 3.8) holds only for a temperature range of 10 C to 37.5 C. This equation of the sorption process seems to hold good for a relative humidity range of 30% to 90% and an equilibrium moisture content range of 10% to 25% (Figure 3.1). The mathematical model of the sorption process for rapeseed (Equation 3.13) is given for a temperature range of 20 C to 80 C. This equation of the sorption process of rapeseed seems to hold good for a relative humidity range of 50% to 90% and an equilibrium moisture content range of 5% to 20% (Figure A.5).

Following the above consideration the models of wheat and rapeseed presented here may simulate the drying with ambient air for the following approximate ranges of air and grain conditions:

(i) dry-bulb temperature of the incoming air:

wheat - 10.0 C to 37.5 C

rapeseed - 20.0 C to 37.5 C

(ii) relative humidity of the incoming air:

wheat - 30% to 90%

rapeseed - 50% to 90%

(iii) initial moisture content of the grain:

wheat - 10% to 25%

rapeseed - 5% to 20%

(iv) initial temperature of the grain:

wheat - 10.0 C to 37.5 C

rapeseed - 25.0 C to 37.5 C

The aeration model for wheat does not seem to simulate satisfactorily at the higher airflow rate of 4.36 m/min as compared with 2.44 m/min. An exact limit of the airflow rate cannot be set at this time but it is expected that the models of drying with ambient air would simulate the process satisfactorily at airflow rates equal to or less than 2.44 m/min of air.

CHAPTER VII

SUGGESTIONS FOR FURTHER STUDY

1. Weather data should be analyzed using hourly weather observations available at various weather stations in the Canadian Prairies to predict the performance of aeration systems using ambient air.
2. An investigation should be done to find out the range of moisture content of grain at the time of harvest.
3. Better mathematical models of the sorption process should be developed. These models should be able to cover the wide range of ambient air temperatures found in the Canadian Prairies.
4. A more precise determination of the specific heat of rapeseed should be done at low temperatures.
5. The effect of moisture content and temperature on density of the grain should be studied thoroughly. This will enable to calculate the density for each layer of grain in each time increment.
6. The verification of the models should be done at low temperatures.
7. Economics of the aeration system using ambient air should be studied and compared with conventional drying systems.

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APPENDICES

APPENDIX A

DERIVATION OF EQUILIBRIUM MOISTURE

CONTENT EQUATION FOR RAPESEED

Figure A.1 shows the equilibrium moisture content data (Pichler; 1956). Figure A.2 is obtained from Figure A.1 by picking off a series of points at constant moisture content. The X axis is the saturation vapour pressure (P_s) corresponding to each test temperature and can be found from steam tables. The Y axis is $P (=P_s \times RH_e/100)$, where RH_e (Equilibrium relative humidity) equals $(P/P_s) \times 100$ by definition. The linearity of this plot reduces the problem by one dimension and leaves only functions of the equilibrium moisture content, m , to be found. The family of lines in Figure A.2 can be represented in the following form:

$$\ln P = f_1(m) \ln P_s + f_2(m) \quad \dots\dots (A.1)$$

Gallaher (1951) following the work of Othmer and Huang (1940) worked with the data in the form of Figure A.2 to find an expression for the latent heat of vaporization of water in the grain. He proposed that $f_1(m)$ (the slope of the lines in Figure A.2) had the form:

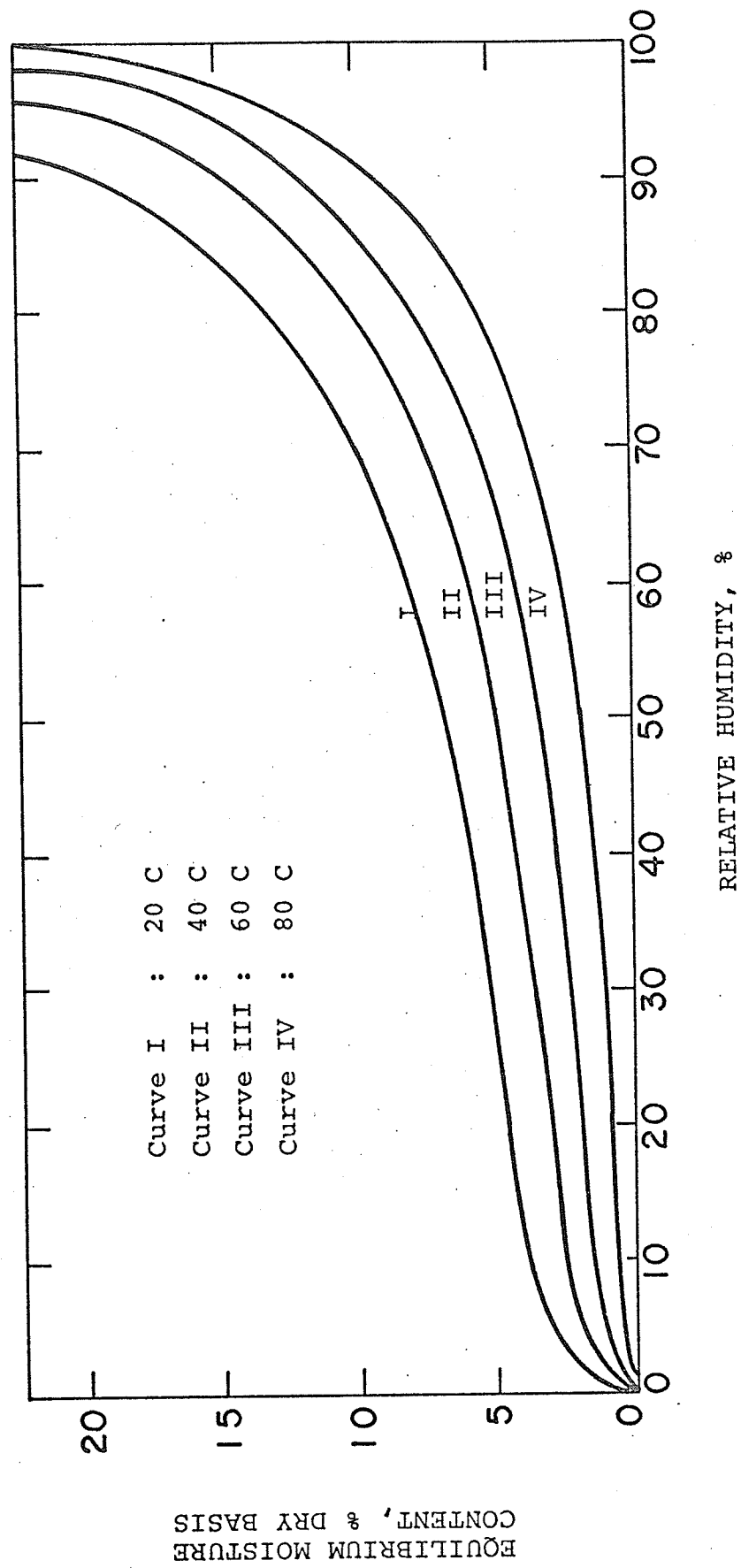


FIGURE A.1 SORPTION ISOTHERMS FOR RAPESEED (PICHLER; 1956)

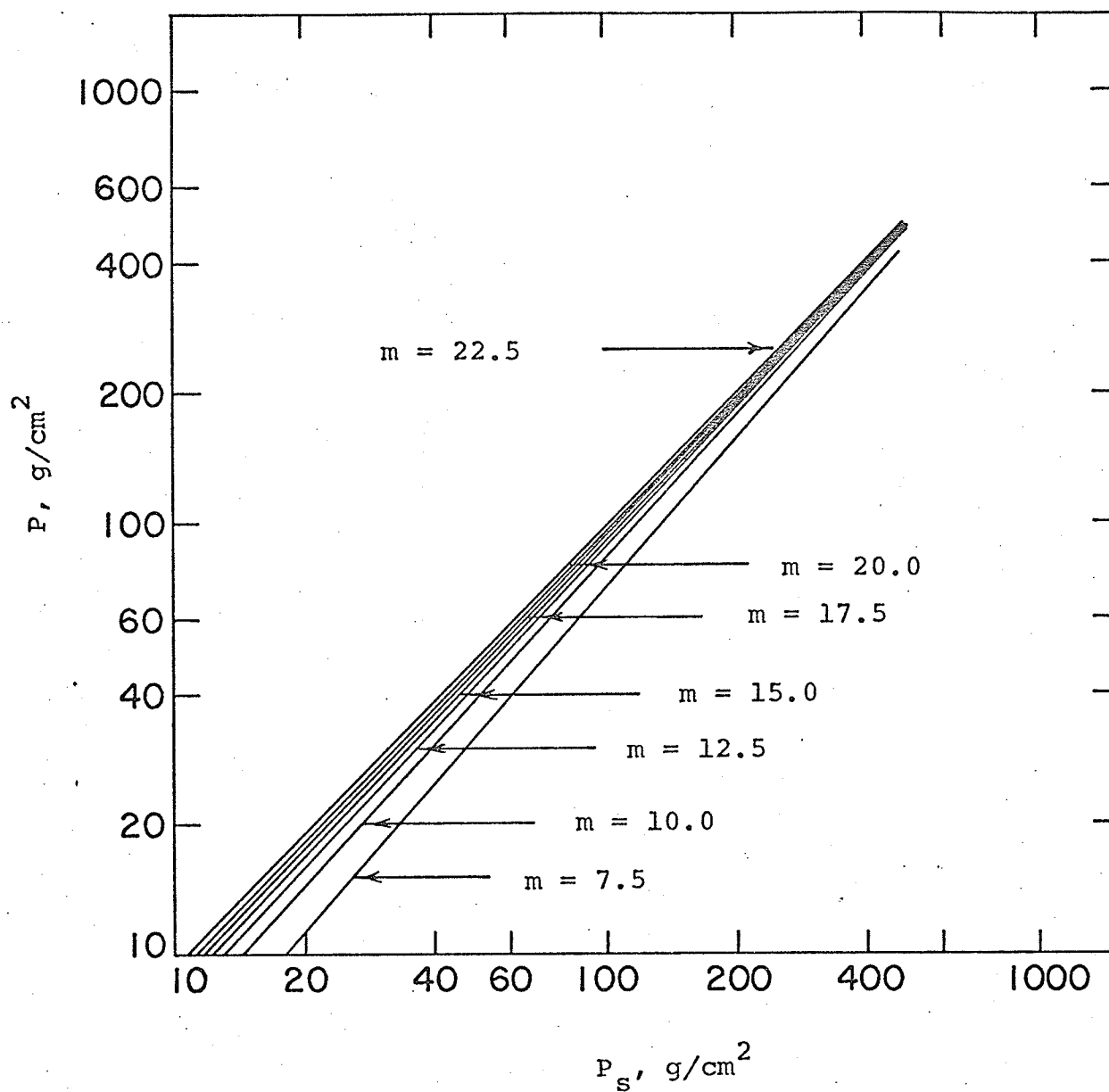


FIGURE A.2 PLOT OF EQUILIBRIUM MOISTURE CONTENT DATA

$$f_1(m) = 1 + ae^{bm} \quad \dots\dots\dots (A.2)$$

where a and b are constants.

By linear regression analysis on each of the lines in Figure A.2 using $\ln P$ and $\ln P_s$ as variables and assuming all the error was in $\ln P$, the slope of each line was found. The results are plotted in Figure A.3. A regression analysis was then done on the slopes using $\ln [f_1(m) - 1]$ and m (moisture content, % dry basis) as variables and assuming all the error was in $\ln [f_1(m) - 1]$. The values of a and b (the unknown constants) were found from this analysis. Values for the intercepts of the line in Figure A.2 were calculated by using the slopes for each moisture content calculated from $f_1(m)$ and the mean values of $\ln P$ and $\ln P_s$ for each line as calculated in the first regression analysis. The values for $f_2(m)$ (intercepts) were then found from the following relationship:

$$f_2(m) = [\ln P]_{\text{mean}} - f_1[m] [\ln P_s]_{\text{mean}} \quad \dots\dots (A.3)$$

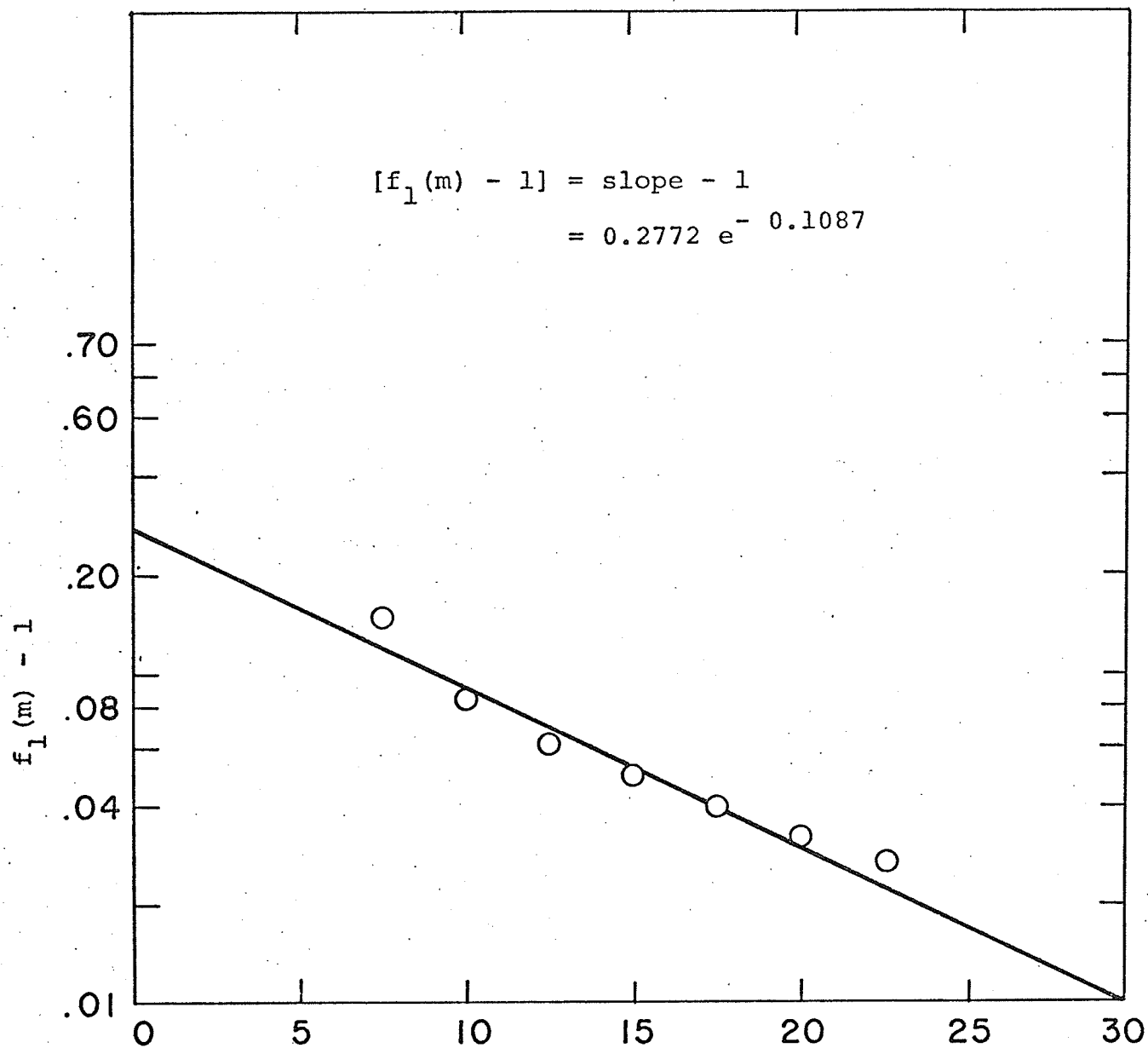
The values of $f_2(m)$ were obtained for 7 moistures and the results are shown in Figure A.4.

The form of $f_2(m)$ was given by

$$f_2(m) = ce^{dm} \quad \dots\dots (A.4)$$

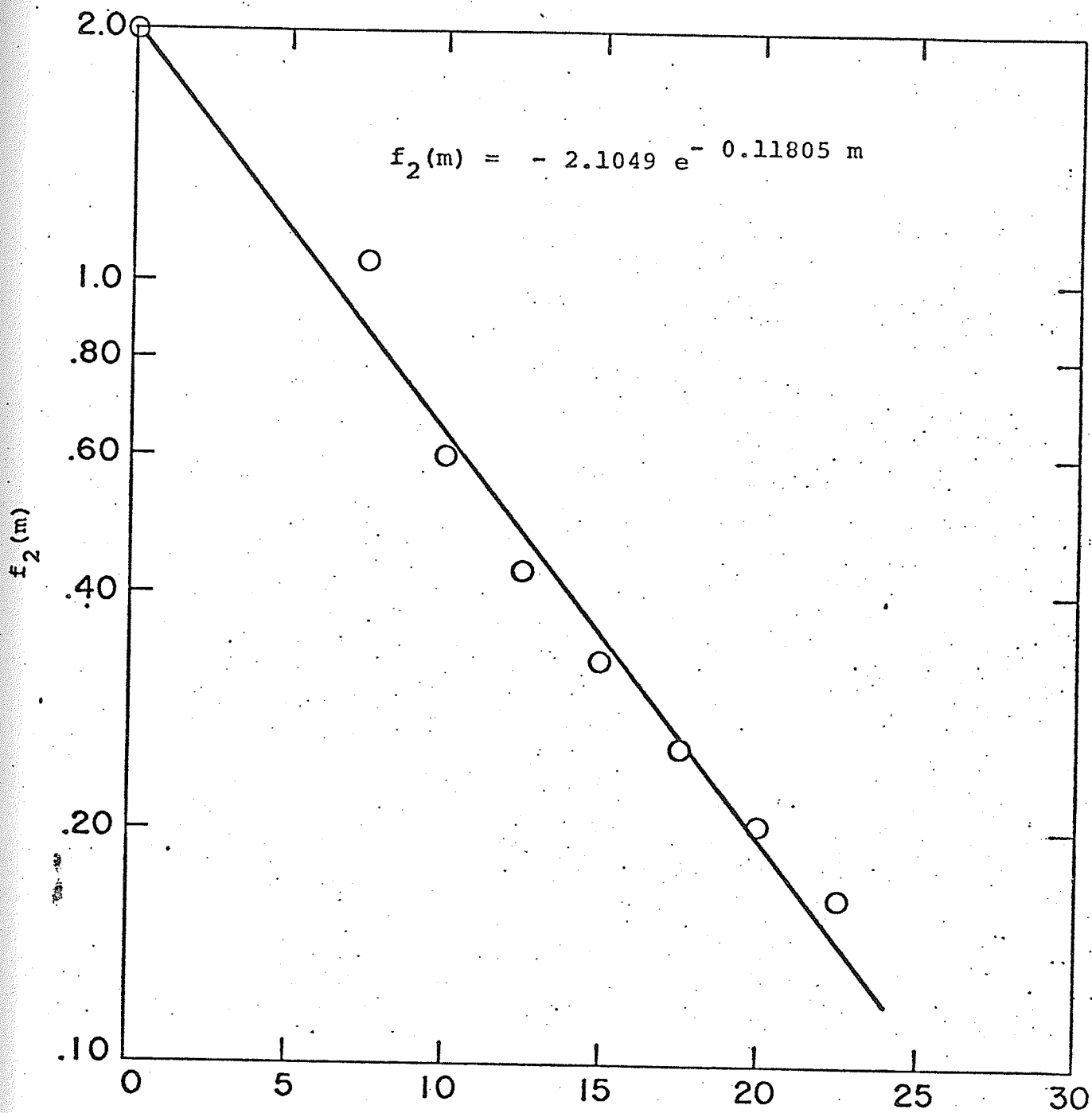
Where c and d are constants.

A regression analysis was performed on the points in Figure A.4 using $\ln [f_2(m)]$ and m as variables and assuming



m - EQUILIBRIUM MOISTURE CONTENT, % DRY BASIS

FIGURE A.3 GRAPH OF POINTS TO FIND $f_1(m)$



m - EQUILIBRIUM MOISTURE CONTENT, % DRY BASIS

FIGURE A.4 GRAPH OF POINTS TO FIND $f_2(m)$

all the error was in $\text{Ln}[f_2(m)]$. Thus the values of c and d were found.

The final equation was:

$$\text{Ln}P = (1 + ae^{bm}) \text{Ln}P_s + ce^{dm} \quad \dots\dots\dots (A.5)$$

which can be written in the form:

$$\text{Ln}(P/P_s) = ae^{bm} \text{Ln}P_s + ce^{dm} \quad \dots\dots\dots (A.6)$$

$$\text{Or } P/P_s = \text{Exp} (ae^{bm} \text{Ln}P_s + ce^{dm}) \quad \dots\dots\dots (A.7)$$

$$\text{Or } RH_e = \text{Exp} (ae^{bm} \text{Ln}P_s + ce^{dm}) \quad \dots\dots\dots (A.8)$$

The values calculated from the analysis are

$$a = 0.27725$$

$$b = - 0.10873$$

$$c = - 2.10496$$

$$d = - 0.11805$$

Figure A.5 shows how well the equation fits the data.

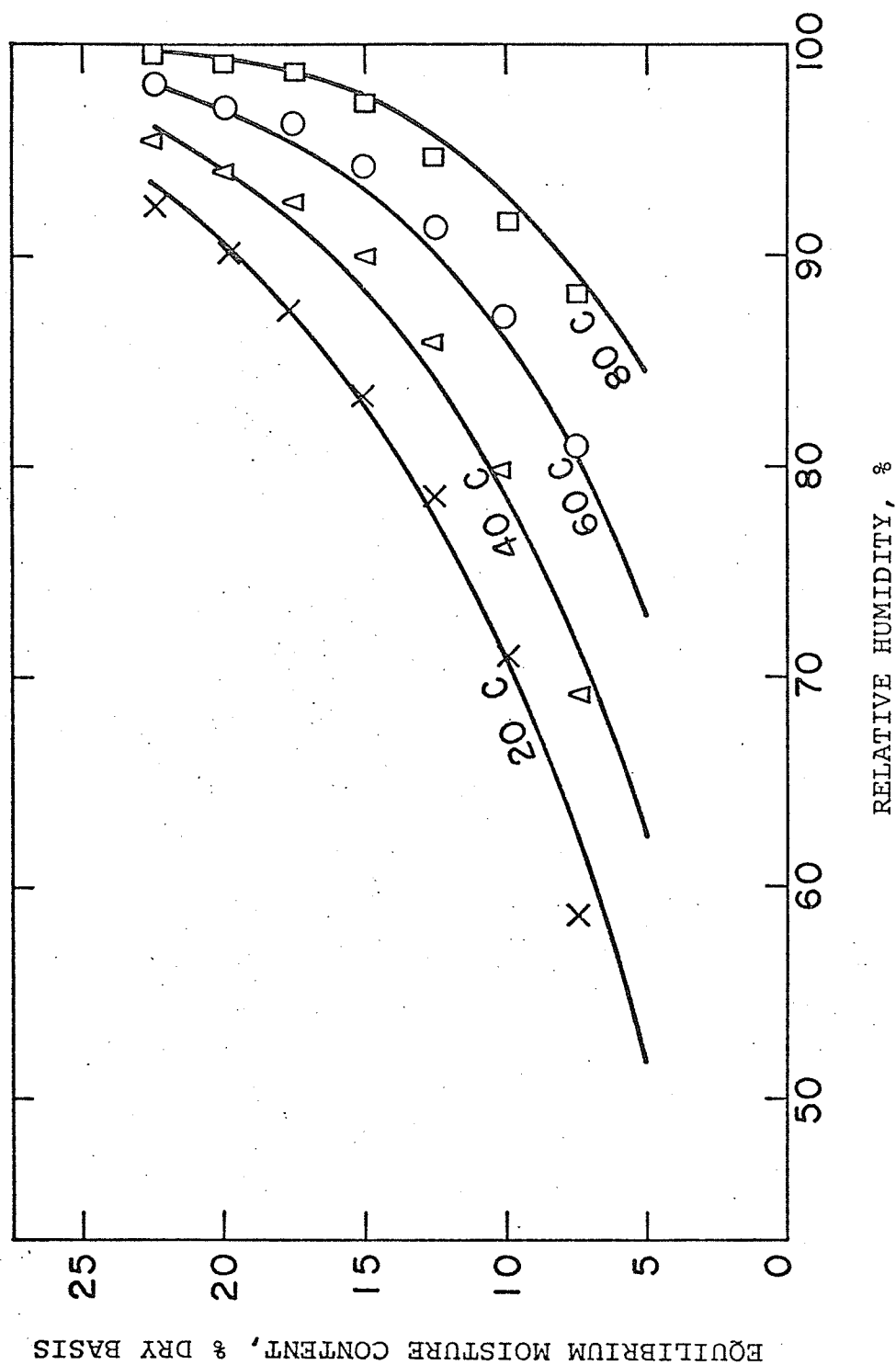


FIGURE A.5 PLOT OF FINAL EQUATION AND PICHLER (1965) DATA FOR RAPESEED

APPENDIX B

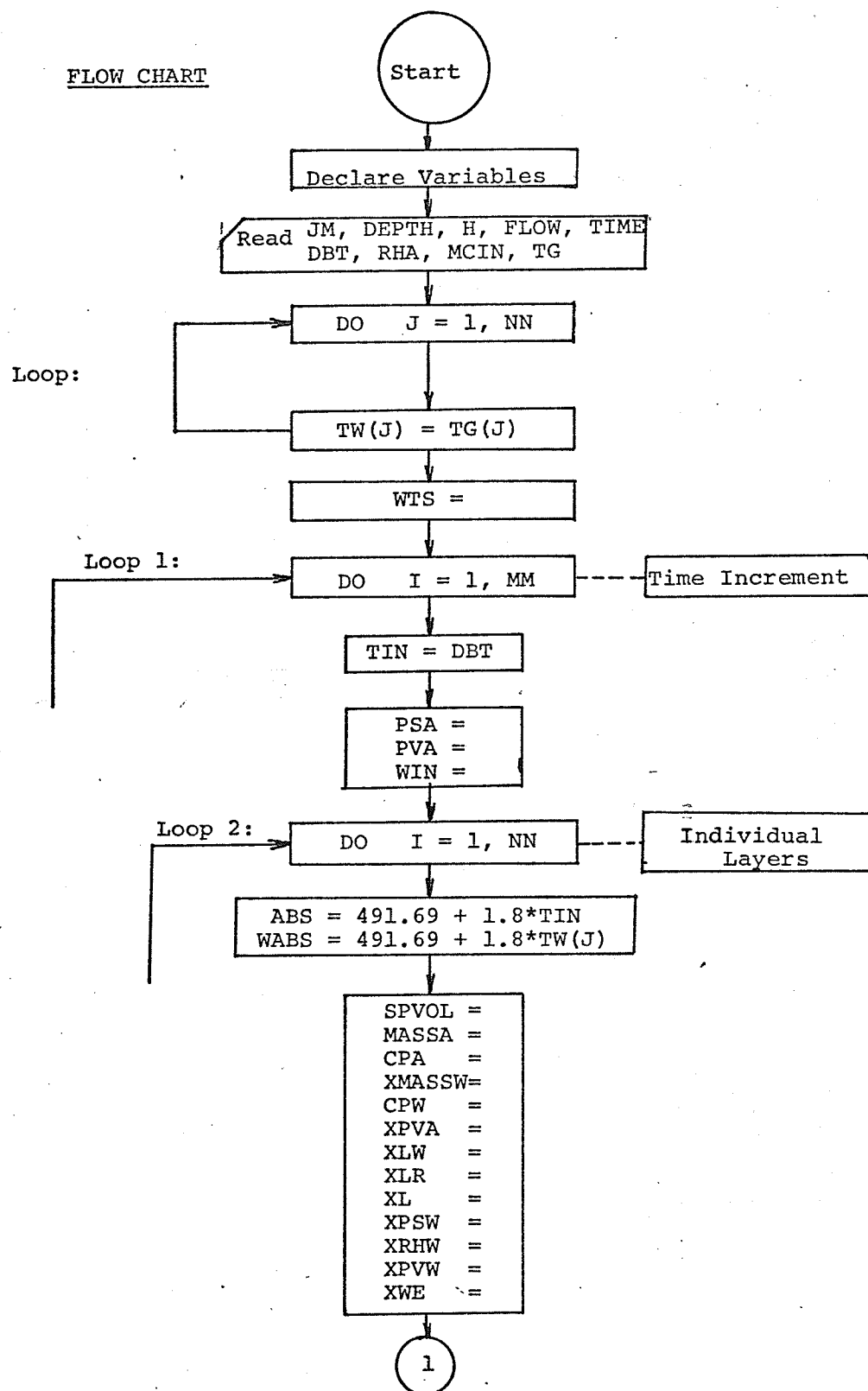
THE MODELS

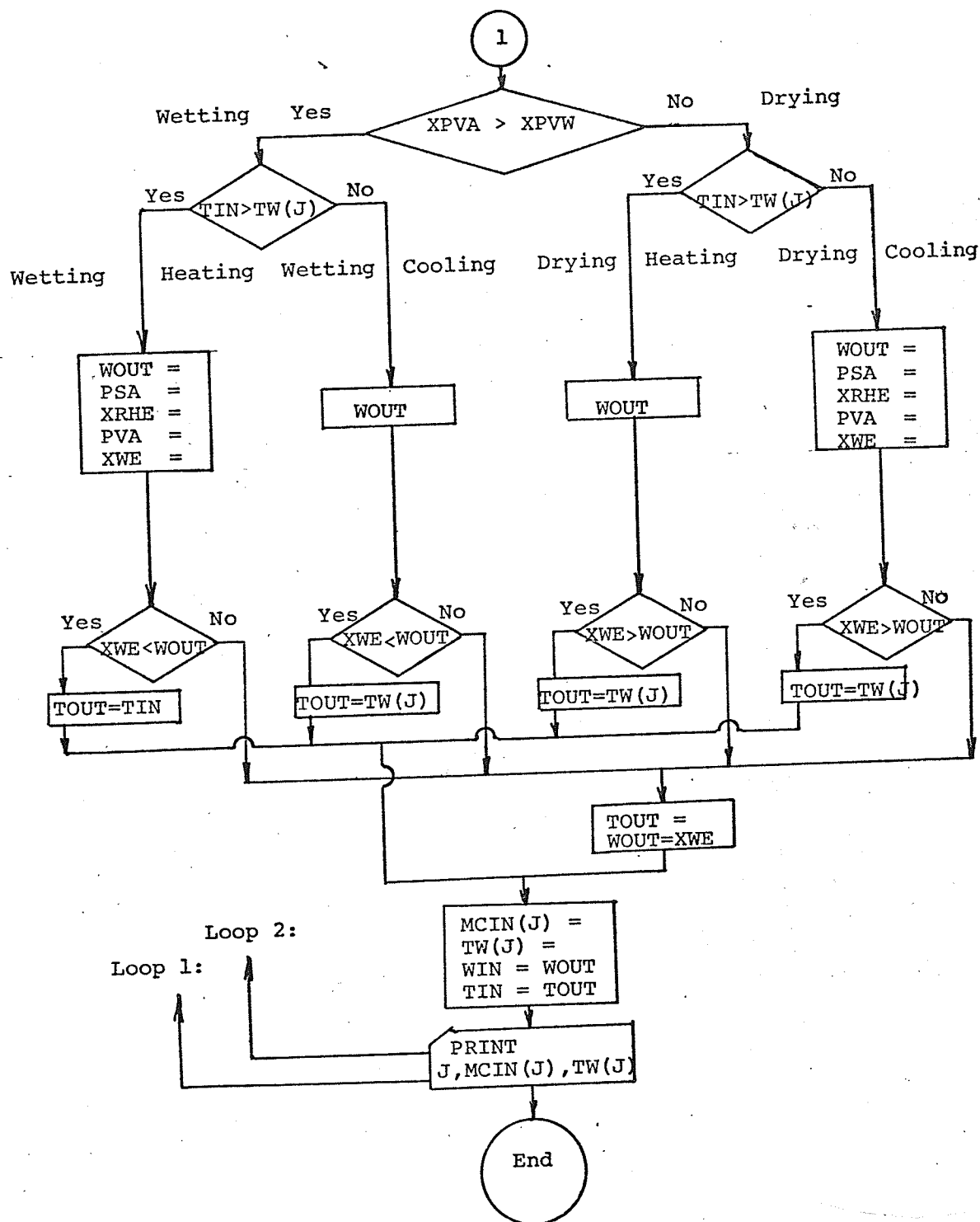
Variable List

CPA	=	specific heat of the moist air, cal/g C
CPW	=	specific heat of the grain, cal/g C
DBT	=	dry-bulb temperature of the incoming air, C
DEPTH	=	total depth of the grain column, cm
FLOW	=	air flow rate, m/min
H	=	spatial increment, cm
JM	=	time of aeration, h
MCIN	=	moisture content of the grain, % dry basis
MASSA	=	mass flow rate of the air, kg/m ² min
MM	=	number of time increments
NN	=	number of spatial increments in the column of grain
PSA	=	saturation vapour pressure, g/cm ²
PVA	=	vapour pressure, g/cm ²
RHA	=	relative humidity of the incoming air, decimal fraction
SPVOL	=	specific volume of air entering any simulation layer of the grain, m ³ /kg
TIME	=	time increment, min
TIN	=	dry-bulb temperature of the air entering a layer of grain, C

TOUT	=	dry-bulb temperature of the air leaving a layer of grain, C
TG	=	temperature of air and grain at which the relative humidity of the air is equal to the equilibrium relative humidity of the grain assuming the air cools at a constant wet-bulb temperature, C
TW	=	temperature of the grain in a layer, C
WIN	=	specific humidity of the air entering a layer of grain, kg water/kg dry air
WOUT	=	specific humidity of the air leaving a layer of grain, kg water/kg dry air
WTS	=	weight of solids in a layer of grain, kg/m^2
XL	=	latent heat of vaporization of water in wheat, kcal/kg water
XLR	=	ratio of latent heat of water in grain to latent heat of free water, dimensionless
XLW	=	latent heat of vaporization of free water, kcal/kg water
XMASSW	=	mass of grain in a layer, kg/m^2
XRHE	=	equilibrium relative humidity of the grain, decimal fraction
XPSW	=	saturation vapour pressure at the grain temperature, g/cm^2
XPVA	=	vapour pressure of the air entering a layer of grain, g/cm^2
XPVW	=	vapour pressure of the grain, g/cm^2
XWE	=	equilibrium specific humidity, kg water/kg dry air

FLOW CHART





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      C    UNIVERSITY OF MANITOBA
      C    SIMULATION MODEL OF WHEAT AERATION USING AMBIENT AIR
      C    DEVELOPED BY SATISH C. SHARMA
0001      REAL MCIN(50), TG(50), MASSA, TW(50)
0002      READ40, JM
0003      40    FORMAT(4I4)
0004      READ42, DEPTH, H, FLOW, TIME
0005      42    FORMAT(1CF8.3)
0006      NN=DEPTH/H
      C    NN=NO OF LAYERS
0007      MM=JM*60/TIME
0008      READ42, DBT, RHA
0009      READ42, (MCIN(J), J=1, NN)
0010      READ42, (TG(J), J=1, NN)
0011      DO 110 J=1, NN
0012      110   TW(J)=TG(J)
0013      WTS=62.739
0014      DO 43 I=1, MM
0015      T=TIME*I/60.0
0016      IF(I.LT. JM) GO TO 68
0017      PRINT64, T
0018      PRINT65
0019      68    TIN=CBT
0020      ABS=491.69+1.8*DBT
0021      IF(TIN.LT.0) GO TO 45
0022      TXA=58.8857-12301.688/ABS-5.16923*ALOG(ABS)
0023      GO TO 46
0024      45    TXA=27.6452-11286.6489/ABS-0.46057*ALOG(ABS)
0025      46    PSA=EXP(TXA)
0026      PVA=PSA*RHA
0027      WIN=0.6219*PVA/(1033.23-PVA)
0028      DO 41 J=1, NN
0029      ABS=491.69+1.8*TIN
0030      SPVOL=0.001573*ABS*(1.0+1.6055*WIN)
0031      MASSA=FLOW/SPVOL
0032      WABS=1.8*TW(J)+491.69
0033      CPA=0.2405+0.448*WIN
0034      XMASSW=WTS+WTS*(MCIN(J)/100.0)
0035      IF(TW(J).LE.-21.4) GO TO 47
0036      IF(TW(J).GE.-21.4.AND.TW(J).LE.-10.8) GO TO 48
0037      IF(TW(J).GE.-10.8.AND.TW(J).LE.0.6) GO TO 49
0038      IF(TW(J).GE.0.6.AND.TW(J).LE.8.9) GO TO 50
0039      IF(TW(J).GE.8.9) GO TO 51
0040      47    CPW=0.250+0.743E-2*MCIN(J)
0041      GO TO 52
0042      48    CPW=0.279+0.580E-2*MCIN(J)
0043      GO TO 52
0044      49    CPW=0.297+0.708E-2*MCIN(J)
0045      GO TO 52
0046      50    CPW=0.245+0.1058E-2*MCIN(J)
0047      GO TO 52
0048      51    CPW=0.273+MCIN(J)/100.0
0049      52    XPVA=WIN*1033.23/(0.6219+WIN)
0050      XLW=597.768-0.56983*TIN
0051      XLR=1.0+23.*EXP(-0.40*MCIN(J))
0052      XL=XLW*XLR
0053      IF(TW(J).LT.0) GO TO 53
0054      TXW=58.8857-12301.688/WABS-5.16923*ALOG(WABS)

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0055      GO TO 54
0056      53 TXW=27.6452-11286.6489/WABS-C.46057*ALOG(WABS)
0057      54 XPSW=EXP(TXW)
0058      X=XLR*ALOG(2.04816*XPSW)
0059      Y=-0.334E5/(MCIN(J)**4)
0060      XRHW=EXP(X+Y)/(2.04816*XPSW)
0061      XPVW=XPSW*XRHW
0062      XWE=C.6219*XPVW/(1033.23-XPVW)
0063      IF(XPVA.GT.XPVW)GO TO 55
0064      IF(TIN.GT.TW(J))GO TO 56
      C      PROCESS OF DRYING AND COOLING
0065      WOUT=XMASSW*CPW*(TW(J)-TIN)
0066      WOUT=WOUT/(MASSA*TIME*XL)
0067      WOUT=WIN+WOUT
0068      IF(TIN.LT.0)GO TO 57
0069      TXA=58.8857-12301.688/ABS-5.16923*ALOG(ABS)
0070      GO TO 58
0071      57 TXA=27.6452-11286.6489/ABS-C.46057*ALOG(ABS)
0072      58 PSA=EXP(TXA)
0073      X=XLR*ALOG(2.04816*PSA)
0074      Y=-0.334E5/(MCIN(J)**4)
0075      XRIE=EXP(X+Y)/(2.04816*PSA)
0076      PVA=XRIE*PSA
0077      XWE=C.6219*PVA/(1033.23-PVA)
0078      IF(XWE.GE.WOUT)GO TO 59
0079      TOUT=TIN
0080      GO TO 60
0081      59 TOUT=MASSA*CPA*TIME*TIN
0082      TOUT=TOUT+XMASSW*CPW*TW(J)
0083      TOUT=TOUT+(WIN-XWE)*MASSA*TIME*XL
0084      TOUT=TOUT/(MASSA*CPA*TIME+XMASSW*CPW)
0085      WOUT=XWE
0086      GO TO 60
      C      PROCESS OF DRYING AND HEATING
0087      56 WOUT=MASSA*CPA*TIME*(TIN-TW(J))
0088      WOUT=WOUT/(MASSA*TIME*XL)
0089      WOUT=WIN+WOUT
0090      IF(XWE.LT.WOUT)GO TO 59
0091      TOUT=TW(J)
0092      GO TO 60
0093      55 IF(TIN.GE.TW(J))GO TO 61
      C      PROCESS OF WETTING AND COOLING
0094      WOUT=MASSA*CPA*TIME*(TW(J)-TIN)
0095      WOUT=WOUT/(MASSA*TIME*XL)
0096      WOUT=WIN-WOUT
0097      IF(XWE.GT.WOUT)GO TO 59
0098      TOUT=TW(J)
0099      GO TO 60
      C      PROCESS OF WETTING AND HEATING
0100      61 WOUT=XMASSW*CPW*(TIN-TW(J))
0101      WOUT=WOUT/(MASSA*TIME*XL)
0102      WOUT=WIN-WOUT
0103      IF(TIN.LT.0)GO TO 62
0104      TXA=58.8857-12301.688/ABS-5.16923*ALOG(ABS)
0105      GO TO 63
0106      62 TXA=27.6452-11286.6489/ABS-C.46057*ALOG(ABS)
0107      63 PSA=EXP(TXA)
0108      X=XLR*ALOG(2.04816*PSA)

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0109      Y=-0.334E5/(MCIN(J)**4)
0110      XRHE=EXP(X+Y)/(2.04816*PSA)
0111      PVA=XRHE*PSA
0112      XWE=C.6219*PVA/(1033.23-PVA)
0113      IF(XWE.GT.WOUT)GO TO 59
0114      TOUT=TIN
0115      60      MCIN(J)=MCIN(J)-100.0*(WOUT-WIN)*MASSA*TIME/WTS
0116      TW(J)=TOUT
0117      IF(I.LT.JM)GO TO 69
0118      66      PRINT67,J,TW(J),MCIN(J)
0119      69      TIN=TOUT
0120      WIN=WOUT
0121      41      CONTINUE
0122      64      FORMAT('C',20X,'TIME OF AERATION = ',F8.3,'HOURS',//)
0123      65      FORMAT('C','NO OF LAYER',7X,'WHEAT TEMP',10X,
1      'MOISTURE CONTENT',//)
0124      67      FORMAT('C',5X,I2,8X,F8.3,12X,F8.3)
0125      43      CCNTINUE
0126      STOP
0127      END
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      C  UNIVERSITY OF MANITOBA
      C  SIMULATION MODEL OF RAPID-ED AERATION USING AMBIENT AIR
      C  DEVELOPED BY SATISH C. SHARMA
0001  REAL MCIN(50), TW(50), MASSA, A(10), TG(50)
0002  READ40, JM
0003  40  FORMAT(4I4)
0004  READ49, (A(I), I=1, 4)
0005  49  FORMAT(10F9.5)
0006  READ42, DEPTH, H, FLOW, TIME
0007  42  FORMAT(10F8.3)
0008  NN=DEPTH/H
      C  NN=NO OF LAYERS
0009  MM=JM*60/TIME
0010  READ42, DBT, RHA
0011  READ42, (MCIN(J), J=1, NN)
0012  READ42, (TG(J), J=1, NN)
0013  DO 110 J=1, NN
0014  110  TW(J)=TG(J)
0015  WTS=57.10
0016  DO 43 I=1, MM
0017  T=TIME*I/60.0
0018  IF(I.LT.JM) GO TO 68
0019  PRINT64, T
0020  PRINT65
0021  68  TIN=DBT
0022  ABS=491.69+1.8*DBT
0023  IF(TIN.LT.0) GO TO 45
0024  TXA=58.8857-12301.688/ABS-5.16923*ALOG(ABS)
0025  GO TO 46
0026  45  TXA=27.6452-11286.6489/ABS-0.46057*ALOG(ABS)
0027  46  PSA=EXP(TXA)
0028  PVA=PSA*RHA
0029  WIN=0.6219*PVA/(1033.23-PVA)
0030  DO 41 J=1, NN
0031  ABS=491.69+1.8*TIN
0032  SPVOL=0.001573*ABS*(1.0+1.6055*WIN)
0033  MASSA=FLOW/SPVOL
0034  WABS=1.8*TW(J)+491.69
0035  CPA=0.2405+0.448*WIN
0036  XMASSW=WTS+WTS*(MCIN(J)/100.0)
0037  IF(TW(J).LE.-8.5) GO TO 47
0038  IF(TW(J).GE.-8.5.AND.TW(J).LE.1.8) GO TO 48
0039  IF(TW(J).GE.1.8.AND.TW(J).LE.10.2) GO TO 51
0040  IF(TW(J).GE.10.2) GO TO 50
0041  47  CPW=0.3115+0.01342*MCIN(J)
0042  GO TO 52
0043  48  CPW=0.2733+0.01358*MCIN(J)
0044  GO TO 52
0045  51  CPW=0.2957+0.00914*MCIN(J)
0046  GO TO 52
0047  50  CPW=0.3328+0.00494*MCIN(J)
0048  52  XPVA=WIN*1033.23/(0.6219+WIN)
0049  XLW=597.768-0.56983*TIN
0050  XLR=1.0+A(1)*EXP(A(2)*MCIN(J))
0051  XL=XLW*XLR
0052  IF(TW(J).LT.0) GO TO 53
0053  TXW=58.8857-12301.688/WABS-5.16923*ALOG(WABS)
0054  GO TO 54

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0055      53      TXW=27.6452-11286.6489/WABS-0.46057*ALOG(WABS)
0056      54      XPSW=EXP(TXW)
0057              X=A(1)*EXP(A(2)*MCIN(J))*ALOG(XPSW)
0058              Y=A(3)*EXP(A(4)*MCIN(J))
0059              XRHW=EXP(X+Y)
0060              XPVW=XPSW*XRHW
0061              XWE=C.6219*XPVW/(1033.23-XPVW)
0062              IF(XPVA.GT.XPVW)GO TO 55
0063              IF(TIN.GT.TW(J))GO TO 56
      C      PROCESS OF DRYING AND COOLING
0064              WOUT=XMASSW*CPW*(TW(J)-TIN)
0065              WOUT=WOUT/(MASSA*TIME*XL)
0066              WOUT=WIN+WOUT
0067              IF(TIN.LT.0)GO TO 57
0068              TXA=58.8857-12301.688/ABS-5.16923*ALOG(ABS)
0069              GO TO 58
0070      57      TXA=27.6452-11286.6489/ABS-C.46057*ALOG(ABS)
0071      58      PSA=EXP(TXA)
0072              X=A(1)*EXP(A(2)*MCIN(J))*ALOG(PSA)
0073              Y=A(3)*EXP(A(4)*MCIN(J))
0074              XRHE=EXP(X+Y)
0075              PVA=XRHE*PSA
0076              XWE=C.6219*PVA/(1033.23-PVA)
0077              IF(XWE.GE.WOUT)GO TO 59
0078              TOUT=TIN
0079              GO TO 60
0080      59      TOUT=MASSA*CPA*TIME*TIN
0081              TOUT=TOUT+XMASSW*CPW*TW(J)
0082              TOUT=TOUT+(WIN-XWE)*MASSA*TIME*XL
0083              TOUT=TOUT/(MASSA*CPA*TIME+XMASSW*CPW)
0084              WOUT=XWE
0085              GO TO 60
      C      PROCESS OF DRYING AND HEATING
0086      56      WOUT=MASSA*CPA*TIME*(TIN-TW(J))
0087              WOUT=WOUT/(MASSA*TIME*XL)
0088              WOUT=WIN+WOUT
0089              IF(XWE.LT.WOUT)GO TO 59
0090              TOUT=TW(J)
0091              GO TO 60
0092      55      IF(TIN.GE.TW(J))GO TO 61
      C      PROCESS OF WETTING AND COOLING
0093              WOUT=MASSA*CPA*TIME*(TW(J)-TIN)
0094              WOUT=WOUT/(MASSA*TIME*XL)
0095              WOUT=WIN-WOUT
0096              IF(XWE.GT.WOUT)GO TO 59
0097              TOUT=TW(J)
0098              GO TO 60
      C      PROCESS OF WETTING AND HEATING
0099      61      WOUT=XMASSW*CPW*(TIN-TW(J))
0100              WOUT=WOUT/(MASSA*TIME*XL)
0101              WOUT=WIN-WOUT
0102              IF(TIN.LT.0)GO TO 62
0103              TXA=58.8857-12301.688/ABS-5.16923*ALOG(ABS)
0104              GO TO 63
0105      62      TXA=27.6452-11286.6489/ABS-C.46057*ALOG(ABS)
0106      63      PSA=EXP(TXA)
0107              X=A(1)*EXP(A(2)*MCIN(J))*ALOG(PSA)
0108              Y=A(3)*EXP(A(4)*MCIN(J))

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0109      XRHE=EXP(X+Y)
0110      PVA=XRHE*PSA
0111      XWE=0.6219*PVA/(1033.23-PVA)
0112      IF(XWE.GT.WOUT)GO TO 59
0113      TOUT=TIN
0114      60      MCIN(J)=MCIN(J)-100.0*(WOUT-WIN)*MASSA*TIME/WTS
0115      TW(J)=TCUT
0116      IF(1.LT.JM)GO TO 69
0117      66      PRINT67,J,TW(J),MCIN(J)
0118      69      TIN=TCUT
0119      WIN=WOUT
0120      41      CONTINUE
0121      64      FORMAT('C',20X,'TIME OF AERATION = ',F8.3, 'HOURS',//)
0122      65      FORMAT('C','NU OF LAYER',7X,'WHEAT TEMP',10X,
1'MOISTURE CCNTENT',//)
0123      67      FORMAT('O',5X,I2,8X,F8.3,12X,F8.3)
0124      43      CONTINUE
0125      STOP
0126      END
```