A COMPARISON OF SIMULATION TECHNIQUES FOR WHEAT AERATION

By

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A COMPARISON OF SIMULATION TECHNIQUES
FOR WHEAT AERATION

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PREFACE

The major purpose of this study was to evaluate the performance of currently used simulation techniques in the prediction of heat and mass transfer in aerated beds of wheat. This investigation was intended to determine the most accurate methods for simulation to enhance research and design efforts in grain aeration systems.

The author wishes to express sincere appreciation to Dr. Marvin L. Stone for his invaluable technical expertise, encouragement, and criticism as major advisor. Thanks is also extended to Dr. Peter D. Bloome, Dr. Gerald H. Brusewitz, and Dr. Glenn A. Kranzler, members of the advisory committee, for guidance and critical review. Appreciation is given to Norvil Cole and other members of the Agricultural Engineering Laboratory staff for aid in construction of experimental equipment, to Gail Dowell for graphic work, to Jack Fryrear for photography and to Julio Narvaez for diligent and careful aid in collection of data.

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Deep gratitude is expressed to my parents for life-long

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LIST OF SYMBOLS

A	Constant in ERH equation, $^oC^{-1}$
C	Specific heat, kJ/kg-^oK
C'	Constant in ERH equation, ^oC
C_v	Specific heat of water vapor, kJ/kg-^oK
C_w	Specific heat of liquid water, kJ/kg-^oK
D	Depth term in logarithmic model, dimensionless
dt	Simulation time interval, hr
EMC	Equilibrium moisture content, % d.b.
ERH	Equilibrium relative humidity, dec.
G	Grain temperature, ^oC
H	Enthalpy of air, kJ/kg
K	Moisture transfer coefficient in thin-layer equation, hr^{-1}
K_d	Moisture desorption coefficient, hr^{-1}
K_w	Moisture adsorption coefficient, hr^{-1}
K'	Moisture transfer coefficient in logarithmic model, hr^{-1}
L	Latent heat of vaporization of water in grain, kJ/kg-^oK
L'	Latent heat of vaporization of water, kJ/kg-^oK
M	Grain moisture content, % d.b.
M_w	Grain moisture content, % w.b.
N	Constant in ERH equation, dimensionless
R	Grain to air ratio, kg grain/kg air

RH	Air relative humidity, dec.
T	Temperature, °C
T_K	Temperature, °K
Y	Time term in logarithmic model, dimensionless
t	time, hrs
W	absolute humidity of air, kg water/kg dry air

as subscript:

o	Initial
a	Air
e	Equilibrium
f	Final
g	Grain
i	Infeasible

CHAPTER I

INTRODUCTION

Wheat Aeration and Storage

Wheat has long been the most widely planted crop in Oklahoma. In 1976-1981, an average of 6.1 million acres of wheat was harvested annually in Oklahoma. With a 29.8 bushel per acre average yield and a price of $4.00 per bushel, this amounts to over 720 million dollars of revenue for the state's grain producers. By the year 2000, it is projected that these numbers will increase to 7.7 million acres of annually harvested wheat with an average yield of 46.8 bushels per acre. These increases would raise producers' revenue to 1,386 million dollars were wheat prices to remain as they are at present (Oklahoma Agriculture 2000, 1982). The prediction of almost doubled wheat revenue by the year 2000 is based on a yield increase trend observed in recent years. Yield increases have been attributed to adoption of improved varieties, to fertilization, and to improved management practices including pest and quality control.

One way in which management practices have been affected is in the rapidly expanding practice of on-farm storage. As much as 20% of Oklahoma's winter wheat is stored non-commercially (Oklahoma Agriculture 2000, 1982). Those producers new to on-farm storage are faced with a number of quality control problems long combatted by commercial grain managers. Serious losses are caused by insects, rodents, sprouting of grain, and mold infestation (Bloome and Brusewitz, 1974).

Molds may infest grain both in the field and after storage. Rate of growth of molds is dependent on grain temperature and moisture content. Mold growth rates at given storage conditions can be used to predict allowable storage time as shown by Table I. This table was developed for shelled corn, but the general inferences available from it are applicable to all grains. The effect of both grain temperature and moisture content are marked on safe storage time. Grain at either high moisture content or high temperature is subject to mold infestation and quality reduction.

On the average, Oklahoma wheat is fairly dry when harvested. The average moisture content for 1983 was 11.9% (Anderson, 1984), but in some cases moisture content may be as high as 14-15%, which is above the limit for growth of some storage fungi at higher temperatures (Bloome and Brusewitz, 1974). Freshly harvested wheat is often loaded into the bin at temperatures as high as 30 degrees Celsius. Regardless of moisture content, wheat at this temperature is in danger. The bin of wheat represents sufficient thermal mass to render conductive cooling a very slow process by low temperature winter air. Indeed, depending on conductive

TABLE I

ALLOWABLE STORAGE TIME FOR CORN

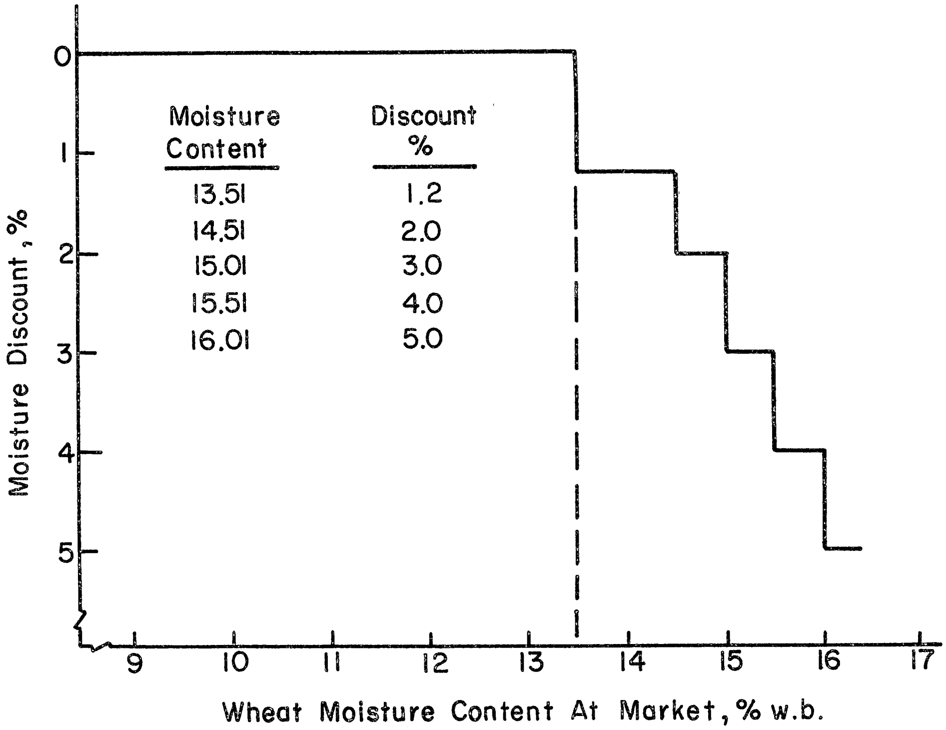
Grain temp, degrees C	Corn Moisture Content, %w.b.						
	18	20	22	24	26	28	30
	Days						
0	509	248	148	96	69	56	46
5	262	130	77	51	37	29	24
10	135	68	40	27	20	16	13
15	70	35	21	14	11	8	7
20	36	18	11	7	6	4	3
25	19	10	6	4	3	2	2
30	10	5	3	2	2	1	1

Adapted from: Midwest Plan Service (1980). Low Temperature and Solar Grain Drying Handbook (MWPS-22). Ames: Iowa State University, p 7.

cooling is a danger in itself due to the possibility of moisture migration (Shove, 1968). Grain near the surface and near the walls of a bin cools first, while grain near the center of the bin remains warm. This temperature difference establishes slowly moving air currents, with cool air near the walls moving downward, forcing warm air upward through the bin's center. This warm, moist air then comes into contact with cold grain near the surface, and condensation often occurs. Thus, although average bin moisture content is at a level suitable for safe storage, localized portions of grain may become wet and spoil (Bloome et al., 1974). Once biological activity begins, the heat generated by these organisisms compounds the problem.

One solution to the problems of mold infestation and moisture migration is grain aeration. Aeration is accomplished by attaching a fan to a bin constructed with a perforated floor and air plenum, such that ambient air may be forced through the grain bed. Aeration of grain immediately after harvest can quickly lower grain temperature to a level suitable for storage. This procedure limits mold growth, and there is evidence that a rapid lowering of temperature can cause insects already in the grain bed to die (Bloome, 1983a). Subsequent aeration on an intermittent basis can further lower grain temperature as ambient temperatures decrease through late fall and winter. Even relatively wet grain can be held through the winter season if temperatures are kept low (see Table I). Intermittent aeration also serves to equalize temperatures within the grain bed, preventing moisture migration (Shove, 1968).

One additional area in which aeration may play a role in saving the wheat producer money has its basis in the marketing system commonly employed in Oklahoma. Grain in Oklahoma is often purchased according to a moisture discount schedule. Figure 1 illustrates one form of such a discount schedule. Wheat at a moisture content above 13.5% is discounted by some amount, while wheat at or below this market standard moisture content is not given a premium. At first this would seem to encourage the marketing of dry grain, but this is not the case. Wheat is sold on a bushel basis determined by weight. For U.S. Grade 1 wheat, 60 lbs of grain makes one bushel. In one bushel of wet grain there is obviously less dry matter than in one bushel of dry grain. Figure 2 illustrates wheat market value as a function of moisture content, and it is apparent that wheat at 13.5% or 14.5% moisture content is worth the most, at least in the market determined by the example moisture discount schedule. A significant loss in revenue is sustained by the selling of wheat much below the market standard moisture content. As an example, 150 tonnes of U.S. Grade 1 wheat at 12% moisture content amounts to 5,510 market bushels, and at $4.00 per bushel, would be worth $22,040. If this same amount of wheat were raised to 13.5%, the market standard moisture content, the added weight in water would result in 152.6 tonnes of grain, or 5,605 market bushels, for a total



Moisture Content	Discount %
13.51	1.2
14.51	2.0
15.01	3.0
15.51	4.0
16.01	5.0

Figure 1. A Common Wheat Moisture Discount Schedule

Adapted from: Bloome, P. D. (1983b). Management implications of the market value of moisture in grain (ASAE Paper 83-3522). p. 8.

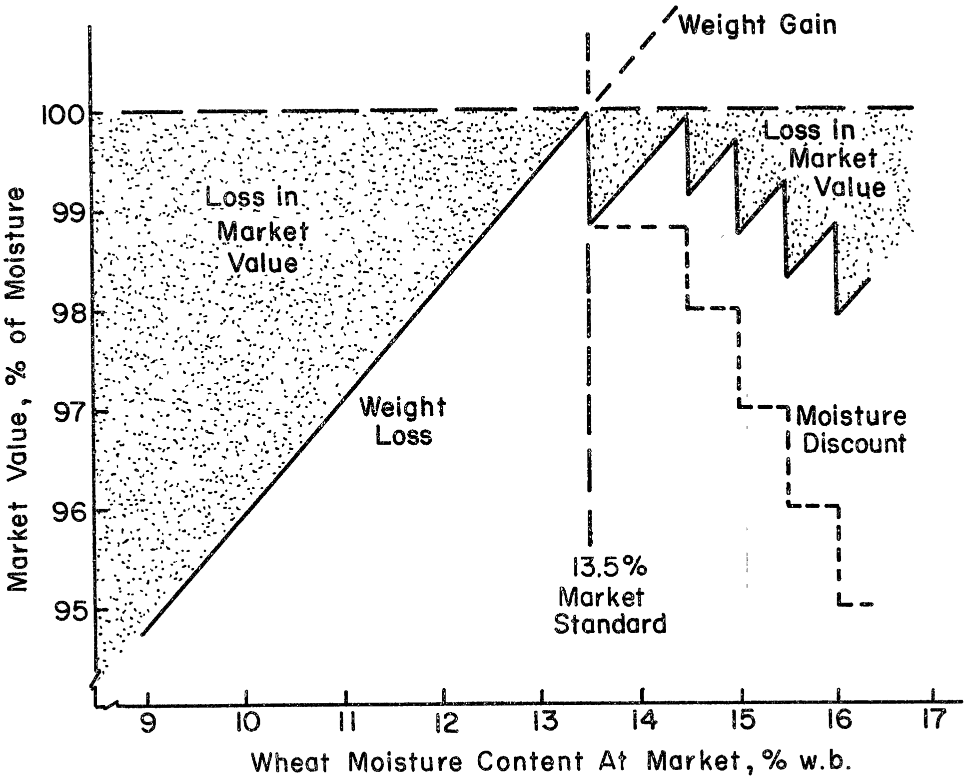


Figure 2. Market Value of Wheat by Moisture Content

Adapted from: Bloome P. D. (1983b). Management implications of the market value of moisture in grain (ASAE Paper 83-3522). p. 8.

selling price of $22,422, an increase of $382.

A farmer with the capability and opportunity to dry grain to the exact market standard before selling is a rarity. The expense of drying equipment is prohibitive, and wheat is not often harvested much above 14%, more often at 12% or below. Aeration systems, on the other hand, are much less expensive, and that capability to "fine tune" moisture content of wheat harvested within one or two points of the market standard may be a possibility. Aerating 150 tonnes of grain in a bin at a depth of about six m with airflow rate of one m^3/min-tonne would require a power output of approximately six kW from an average aerating fan (Midwest Plan Service, 1980). At six cents per kw-hr, it would cost 36 cents per hour to operate the fan. With a potential savings of $382 as calculated above, the 1.5% of moisture would have to be added within about 1,000 hours to be cost effective. This amounts to about 130 nights of aeration, since night air is cooler and more humid. Whether or not an aeration system can provide satisfactory moisture addition within such a time period given Oklahoma weather is a question that requires further study.

Simulation of Aeration

The possibility of aeration as a solution to the quality control and marketing problems experienced with on-farm storage of wheat is an area requiring much research. Testing actual aeration systems in the field is one possibility, and much information can be gained from such an approach. However, in testing such extreme cases as the holding of very high moisture grain at low temperatures, significant losses may occur. Laboratory experimentation may be performed, utilizing small physical models of grain storage buildings, but the length of time involved in investigating the performance of an aeration system over an entire winter storage period can be prohibitive. Perhaps the best tool in aeration research is computer simulation.

Computer simulation involves the use of mathematical models and associated physical properties data to predict the performance of grain aeration and drying systems. The advantage of simulation over field or laboratory testing is that many more experiments may be run in a far shorter time period. Recorded weather data is available for many locations, and any number of aeration configurations may be tested using several years of weather data in a fraction of the time required to make one test in the field or laboratory. The disadvantage of simulation is that in such a complex process as heat and mass transfer in a porous bed of biological material, simulation may only approach accurate prediction of system performance.

Scope of Investigation

Because of the inexact understanding of the processes involved in aeration/drying, many different approaches have been made in simulation. Each of the different approaches has its own set of simplifying assumptions that are only partially valid. The purpose of this investigation was to evaluate some of those approaches used in the simulation of the specific case of low airflow wheat aeration, to determine which techniques most accurately predict grain temperature and moisture content.

CHAPTER II

LITERATURE REVIEW

Types of Models

A large amount of research has been performed in an attempt to accurately model the transfer of heat and moisture involved in grain drying and aeration. A number of deep bed simulation programs have been developed and can be divided into four basic types. The first type of model has been called the batch, analog, or logarithmic model. In this type of model a single equation is used to predict a continuous moisture content profile in a deep bed of grain. In the other three types of models the deep bed of grain is discretized into a series of stacked thin layers and a solution technique is applied to predict temperature and moisture changes in each of these simpler elements. Models incorporating the thin layer approach may be categorized based on simplifying assumptions concerning heat and mass equilibrium between grain and air. In equilibrium simulation, both temperature and moisture equilibrium are assumed, while in semi-equilibrium simulation only temperature equilibrium is assumed. In nonequilibrium simulation no equilibrium assumptions are made.

Logarithmic Models

Perhaps the earliest work in deep-bed grain drying simulation was done by Hukill (1947). Hukill's work resulted in the development of an equation to predict the moisture ratio at any depth in the grain bed after a specified time:

$$MR = \frac{2^D}{2^D + 2^Y - 1}$$

where D = dimensionless depth variable,

and Y = dimensionless time variable (Hukill, 1954).

Barre et al. (1971) proceeded from this work to further define the dimensionless variables D and Y as:

$Y = K't$

D = a function of (L', M_o-EMC, air flow rate, C_a, T_o-T_e, depth in bed)

Sabbah et al. (1977) refined the model again in a series of tests against solar corn drying data. It was determined that Y should also be a function of air velocity. After this modification, the model produced acceptable results in the prediction of average grain moisture content at specified times.

The ease with which the logarithmic model's equations may be solved, either by hand or with the use of computational equipment, has caused the logarithmic model to be a popular alternative to more sophisticated techniques in applications where solution time is at a premium and a high degree of accuracy is not required. Baughman et al. (1970)

recognized the limited access of grain producers to the high speed digital computer equipment necessary in the solution of other types of models and implemented the logarithmic model on analog computer. Simonton et al. (1981) used the model to predict average batch moisture content as part of a microprocessor controlled combination dryer. Young and Dickens (1975) predicted fuel and fan costs for batch and crossflow dryers using the logarithmic model.

Keener et al. (1978) evaluated the logarithmic model in high temperature, high airflow drying tests and found that average batch moisture content could be predicted to within about 1.0 % w.b. absolute error.

Nonequilibrium Models

Nonequilibrium simulation is the most theoretically sound of all methods discussed herein, for both heat and mass transfer are described through rate equations, and simplifying equilibrium assumptions are not made. The most widely known of these types of models is the Michigan State University grain drying simulator, summarized by Bakker-Arkema et al. (1974) and Brooker et al. (1974). One rate equation each was used to determine grain temperature and moisture content, and air temperature and absolute humidity. Heat transfer was predicted through heat transfer coefficients, while mass transfer was predicted using a mass transfer coefficient and either an empirical thin layer drying rate equation or a theoretical diffusion rate equation. The MSU model, designed for high-temperature drying simulation, is not feasible for use in low-temperature, low-airflow simulation since the solution of the system of partial differential equations requires excessive computer time using the short simulation time intervals required (Morey et al., 1978b).

A validation test by Keener et al. (1978) compared performance of the MSU model and two variations on the model, the MSU model with a new moisture transfer equation, and a new partial differential equation model based on a two-lump, thin layer equation. All three models predicted moisture content within about 1.0% w.b. over a 100 hour drying test using airflow rates of 10 to 15 m^3/min-tonne. The two-lump model was about 60% faster in computational speed.

Semi-equilibrium Models

In low temperature drying and aeration simulation, modeling may be simplified by the equilibrium assumptions. In semi-equilibrium simulation, grain and air in each thin layer are assumed to come to temperature equilibrium over the simulation time interval, while moisture transfer is predicted through a thin layer or diffusion equation.

One of the first attempts at writing a semi-equilibrium model was made by Boyce (1966). This model was specifically limited to the processes of drying and heating, isothermal drying, and direct heat transfer. Boyce's model was thus inappropriate for natural air drying or aeration, where cooling and wetting are important processes. A validation test was made using barley, and errors of up to 4.0% d.b. were observed.

Henderson and Henderson (1967) developed a similar model using an empirical thin layer moisture transfer equation for rice. Errors observed in a validation test were attributed more to experimental errors than to errors in the numerical analysis. The model was insensitive to adsorption and did not appear to adequately predict rewetting in upper layers in the last stages of the experiment.

A widely used semi-equilibrium model was developed by Thompson et al. (1968) for shelled corn drying, based on temperature equilibrium and thin layer moisture transfer. The model accounted for condensation of moisture onto the grain surface but did not employ an adsorption equation or account for the difference between adsorption and desorption equilibrium moisture content (hysteresis). In addition to fixed bed simulation, the model was extended for use in the simulation of cross flow, concurrent flow, and counter flow dryers. Pierce and Thompson (1975) used an improved version of the model to examine energy efficiency of three types of cross flow dryers. This version included prediction of grain deterioration from the data of Steele et al. (1969).

Based on the work of Thompson et al. (1968), Sokhansanj et al. (1983) developed a semi-equilibrium model for low temperature drying of wheat. The model included a thin-layer rewetting equation and a procedure for the calculation of condensation of moisture onto the grain surface. Accuracy to within 2.0 %w.b. was obtained. The most remarkable characteristic of the model was that it was run on a desktop computer and drying fronts were graphically displayed on a CRT.

Pfost et al. (1977) tested two semi-equilibrium models, one using an empirical thin layer equation, the other a theoretical diffusion equation. By varying the moisture transfer coefficient acceptable results were obtained, but the coefficient was not determined as a function of pertinent system parameters (product temperature, air velocity, etc.) but was modeled as a constant. The diffusion rate method was found to be statistically more accurate than was the thin layer method, and was used to test various fan management schemes.

Morey et al. (1977) modified an equilibrium model presented by Thompson (1972) by incorporating thin layer techniques and hysteresis calculations. This semi-equilibrium model was used to evaluate several fan management schemes, including humidistatic, thermostatic, and clocked fan control (Morey et al., 1978a).

Equilibrium Models

The first full equilibrium model was presented by Bloome and Shove (1971) for shelled corn. Both temperature and moisture equilibrium were assumed to be reached over the simulation time interval. The model was restricted to low-temperature, low-airflow drying and aeration applications. Each possible combination of heating and cooling, wetting and drying was considered. The model was validated in a laboratory drying experiment and good agreement was obtained between experimental and predicted profiles, with largest errors observed in prediction of rewetting that occurred near the end of the test. The model was later modified to predict grain spoilage and was used by Bloome and Shove (1972) to optimize low-temperature drying of shelled corn.

Thompson (1972) simplified the Bloome and Shove (1971) model by employing a search technique for locating the zeros of unknown functions (Thompson and Peart, 1968). This model was used to examine the storage of high moisture corn using continuous aeration. Kranzler (1977) used this model in the development of a digital control system for the optimization of low temperature corn drying. Pfost et al. (1977) tested the model and found that the moisture equilibrium assumption did not hold, and speculated that equilibrium models would perform better using longer simulation time intervals.

Morey et al. (1977) evaluated the model of Thompson (1972) against field corn drying tests using airflow rates of 1-2 m^3/min-tonne. Again, errors were encountered that were attributed to the moisture equilibrium assumption. Acceptable results were obtained by adding a thin layer equation and hysteresis calculations, a semi-equilibrium version of the model.

CHAPTER III

OBJECTIVES

The objectives of this study were to:

1. Develop computerized simulation models for wheat aeration utilizing both equilibrium and semi-equilibrium techniques.

2. Obtain from a field test the necessary data for the validation and comparison of simulation models applied to low-airflow ambient aeration of wheat under Oklahoma weather conditions.

3. Evaluate the performance of simulation models in the prediction of heat and moisture transfer in wheat aeration.

4. Make recommendations for accurate modeling procedures.

CHAPTER IV

SIMULATION METHODOLOGY

Physical Properties

Extensive physical properties data are needed in the development of digital simulation programs. Because of the lack of precise knowledge concerning the physical makeup of biological products and the non-uniformity of structure, physical properties for grain are described by largely empirical means. In any empirical approximation, some error is associated with the use of the equations. In an iterative solution of heat and mass transfer equations in which the results of each iteration are based on the use of several empirical equations these errors may become quite pronounced. For these reasons the careful selection of physical properties data for use in a digital simulation is critical.

The physical properties needed for grain drying simulation have been determined most rigorously for corn. Data for wheat do exist, but the physical properties of wheat may vary considerably with wheat variety. Often empirical physical property equations for wheat are not specified as having been developed for any particular variety of wheat. For this study equations that were developed specifically for hard red wheat were used whenever a choice existed since verification data were taken from a bin of hard red winter wheat.

Specific heat of grain has been successfully modelled as a linear function of grain moisture content. Mohensin (1980) collected wheat data from several sources and presented the following equation:

$$C_g = 1.258 + 0.01131\ M_w \qquad (1)$$

Specific heat for air, water vapor, and water are well documented and values were taken from the CRC Handbook of Tables for Applied Engineering Science (1970).

$C_a = 1.006$

$C_v = 1.871$

$C_w = 4.187$

The latent heat of vaporization of water within a hygroscopic material is greater than that of water from a free surface. Over the range of temperatures and moisture contents expected in this study, data for this ratio for wheat presented by Brooker et al. (1974) were best represented by the linear equation:

$L/L' = 1,258 - 0.01141\ M,$

where $L' = 2500.86 - 2.38\ T$ (2)

Equilibrium moisture content (EMC) of a hygroscopic material is that moisture content that the material will attain when exposed to air at a given relative humidity and temperature for a sufficient length of time. Obviously, the higher the relative humidity of the air, the greater the moisture content the material will reach at equilibrium. The EMC characteristics of grain are of prime importance in the simulation of heat and mass transfer and has been well investigated. Henderson (1952) derived a general form of equation for EMC of grains from thermodynamic principles:

$$ERH = 1 - EXP\ (-A\ T\ M^{N}) \tag{3}$$

As more data have become available Henderson's equation has been found to be a largely acceptable means for describing EMC in grains. Thompson (1972) modified the Henderson equation by adding a constant to temperature, and this modification was found to improve the performance of the equation:

$$ERH = 1 - EXP\ [-A\ (T + C')\ M^{N}] \tag{4}$$

The coefficients A, C', and N vary with material. Pfost et al. (1976) evaluated the constants in the Henderson-Thompson equation for hard red wheat in the desorptive condition. Using data presented by Day and Nelson (1965) and Brooker, et al. (1974) the constants producing the best fit were found to be:

$A = 0.000023008$

$C' = 55.815$

$N = 2.2857$

Pfost's coefficients provided a close fit to the experimental data with a standard error of moisture content of 0.0071.

Specification of Pfost's results as appropriate for wheat in the desorption condition is important. Grain comes to a higher EMC when being dried than when being wetted. The difference between adsorption and desorption EMC has been called the "hysteresis gap." Most EMC data have been taken from experiments in which wet grain was dried. Desorption has received more attention because little adsorption occurs in grain drying. However, in the study of natural air drying and aeration, adsorption of moisture by the grain mass does occur. In this study the importance of hysteresis was determined by running the simulation models with and without hysteresis calculations.

Hubbard et al. (1957) presented data for hysteresis in the EMC of wheat versus relative humidity and temperature. Values for the difference in desorption and adsorption EMC are shown in Table II. Hubbard's values were subtracted from Day and Nelson's (1965) data for desorption EMC to obtain adsorption EMC values. The Henderson-Thompson equation was then fit to adsorption data by using the NLIN procedure under SAS (SAS User's Guide, 1979). The following coefficients were determined with an R^2 of 0.99:

$A = 0.0000651043$

$C' = 70.7337$

$N = 1.8973$

Figure 3 depicts desorption and adsorption isotherms as predicted by the Henderson-Thompson equation at 15 degrees Celsius.

Wilhelm (1975) presented a series of equations for calculation of psychrometric properties in SI units. These

TABLE II

HYSTERESIS IN THE EQUILIBRIUM MOISTURE CONTENT OF WHEAT

Temperature, degrees C	Relative Humidity, %								
	12	22	33	44	56	65	76	84	91
	Difference Between Desorption and Adsorption Equilibrium Moisture Content, %w.b.								
25	1.45	1.49	1.47	1.28	1.15	0.97	0.79	0.34	0.26
30	1.48	1.60	1.53	1.44	1.22	0.86	0.65	0.26	0.01
35	1.56	1.61	1.53	1.56	1.15	0.84	0.62	0.33	..

Source: Hubbard, J. E., F. R. Earle and F. R. Senti (1957). Moisture Relations in Wheat and Corn. Journal of Cereal Chemistry, 34, p. 427.

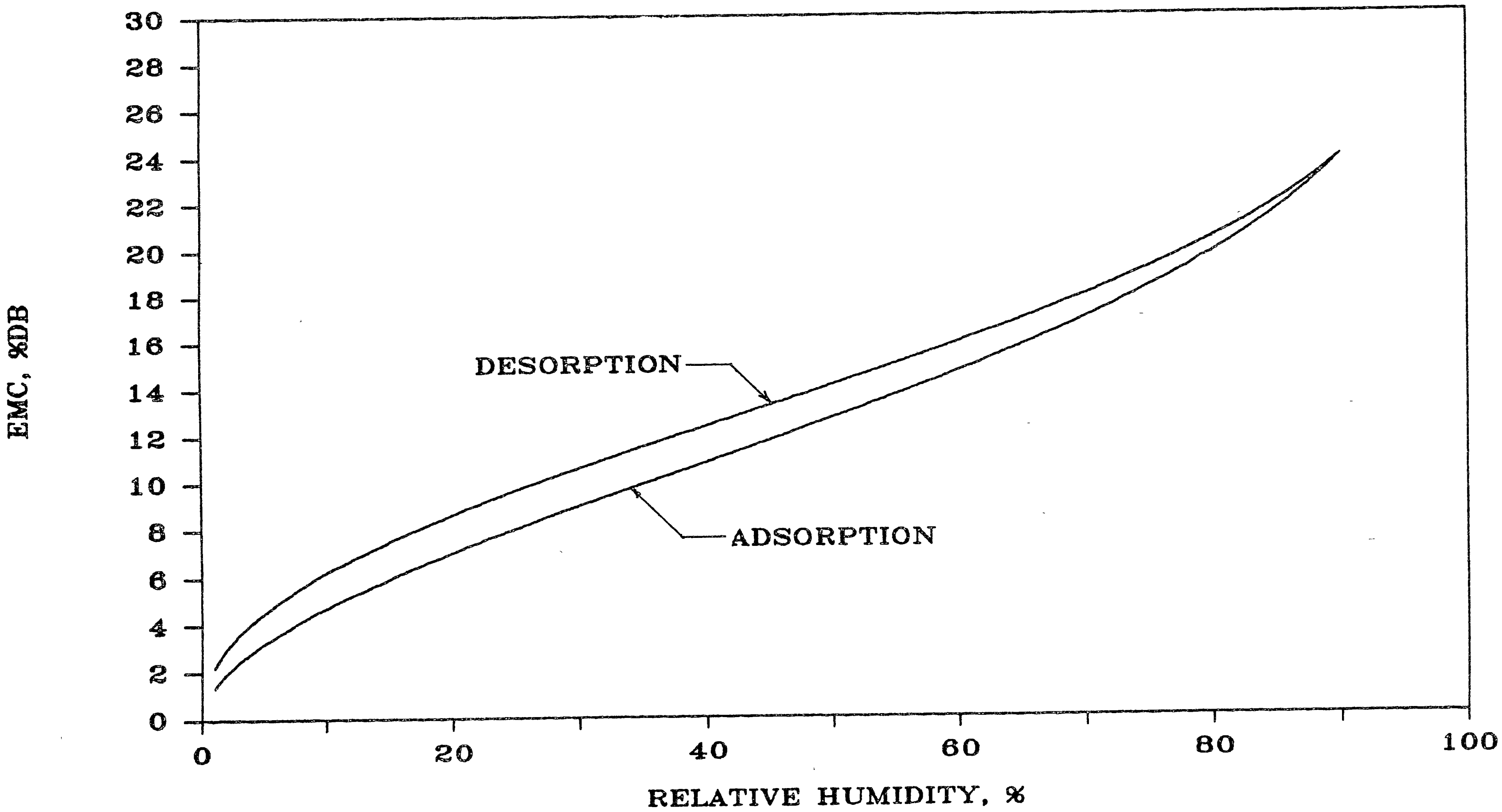


Figure 3. Hysteresis in the Equilibrium Moisture Content of Wheat at 15 Degrees Celsius

equations were used for calculation of air relative and absolute humidity and saturation vapor pressure. For the semi-equilibrium model, an empirical drying rate equation was needed. Empirical drying rate equations attempt to model the rate of moisture transfer to or from the grain mass as a function of a number of factors, often including initial moisture content, difference in current moisture content and EMC, air temperature, relative humidity, product temperature, and others. One form of equation with both a theoretical basis and proven correspondence to experimental data is:

$$dM / dt = K (M - EMC) \qquad (5)$$

The coefficient K is an estimation of the rate of moisture transfer and may be a function of any of the factors listed above. Many investigators have found acceptable results in limiting K to a function of only product temperature. However, separate equations for K are needed for desorption and adsorption. Watson and Barghava (1974) evaluated the coefficient for wheat in desorption as:

$$K_d = -2.4e8 \text{ EXP } (-6244/T^K) \qquad (6)$$

Dugal et al. (1982) obtained data for adsorption of moisture by very dry wheat and developed a thin layer rewetting equation from these data. However, Dugal's equation was not in the form of Equation (5) and was not easily applied to aeration simulation. Therefore Dugal's rewetting data were fit to Equation (5) using the NLIN procedure and the following equation for K was obtained with an R^2 of

0.83:

$$K_w = -24.327 \text{ EXP } (-1845/T^K) \qquad (7)$$

Deep Bed Modeling

In thin layer modeling, a layer of grain is assumed to have no moisture or temperature gradients in the direction of airflow. Whether this assumption holds true is a function of bed depth, airflow rate, air and grain temperature and moisture content, and other factors. The assumption is completely valid only when the layer of grain is only one kernel deep, a case seldom if ever found in real drying-aeration systems. With any depth of grain greater than one kernel, some transient gradients will exist in the layer of grain in the direction of airflow. However, the error in this assumption is small when applied to relatively thin layers of grain. A bin of grain filled to any significant depth cannot be accurately modelled in this fashion, for the depth of grain is too great and the airflow rate too low. The bin must therefore be divided into a series of stacked thin layers.

Both the equilibrium and semi-equilibrium models considered in this study were programmed using the same conceptual model of a deep bed of grain. Figure 4 illustrates a thin layer that was the control volume for heat and mass balance procedures. Incoming air temperature and absolute humidity (T_O and W_O), and initial grain temperature and moisture content (G_O and M_O) were known. Simulation

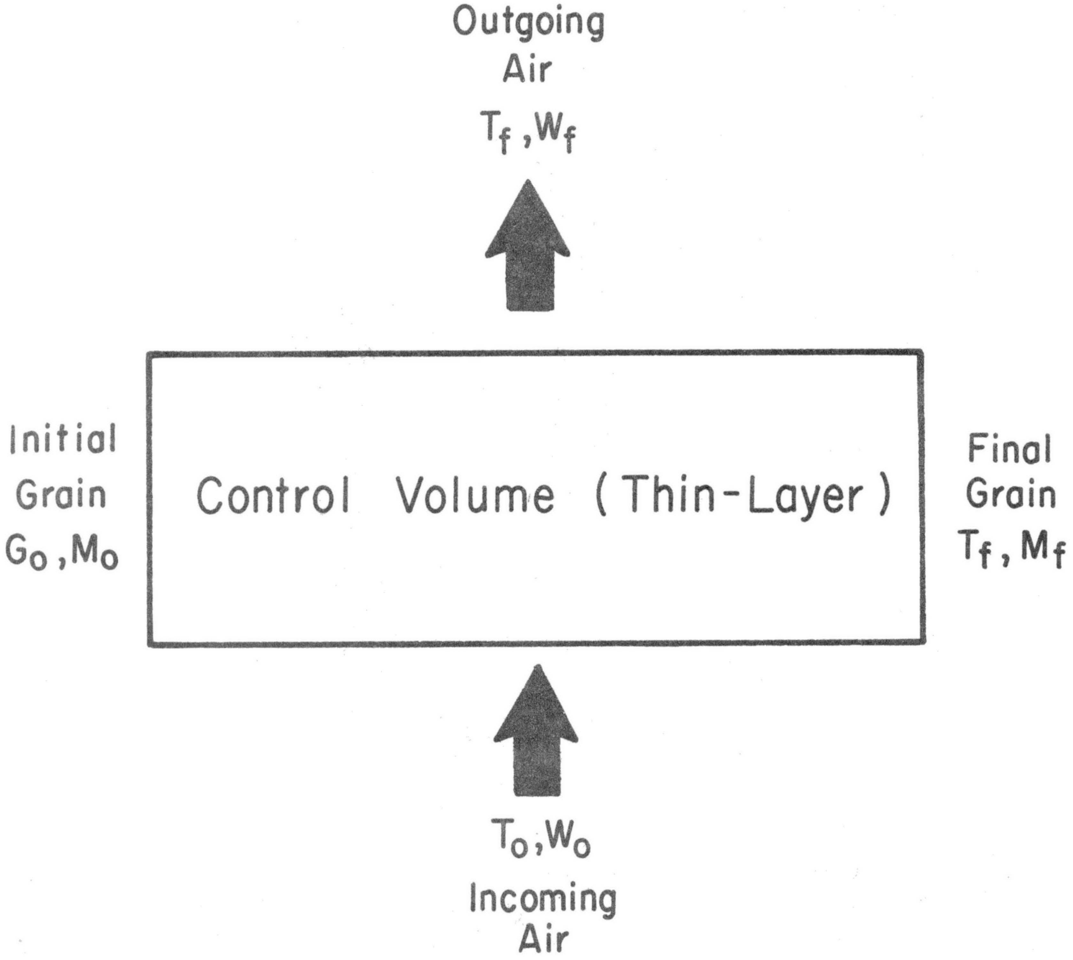


Figure 4. Simulation Control Volume

techniques were then used to solve for the exitting air absolute humidity and final grain moisture content (W_f and M_f), and final grain/air temperature (T_f) that existed after a specified time interval. Figure 5 shows how thin layers might be stacked to model the deep bed of grain. Incoming air conditions for the bottom (inlet) layer, shown as layer number one, were those of ambient air. Incoming air conditions for the layer just above, shown as layer number two, were the calculated exit air conditions from layer one. This process was carried out for each of the 20 layers. The selection of 20 thin layers was somewhat arbitrary. With an increase in number of layers comes greater accuracy due to a lessening of the errors involved in the thin layer assumption, and also an increase in computer time required. Twenty layers appeared to be a good compromise between these factors, while also corresponding well in location to readings taken from the validation bin.

After all 20 layers had been processed for the simulation time interval, time was incremented and the entire process was repeated using new ambient air conditions as input air conditions for the inlet layer.

Equilibrium Methodology

Equilibrium simulation was patterned closely after methods presented by Thompson (1972) for shelled corn. The assumptions involved in the use of a full equilibrium model were discussed fully by Bloome and Shove (1971), but the

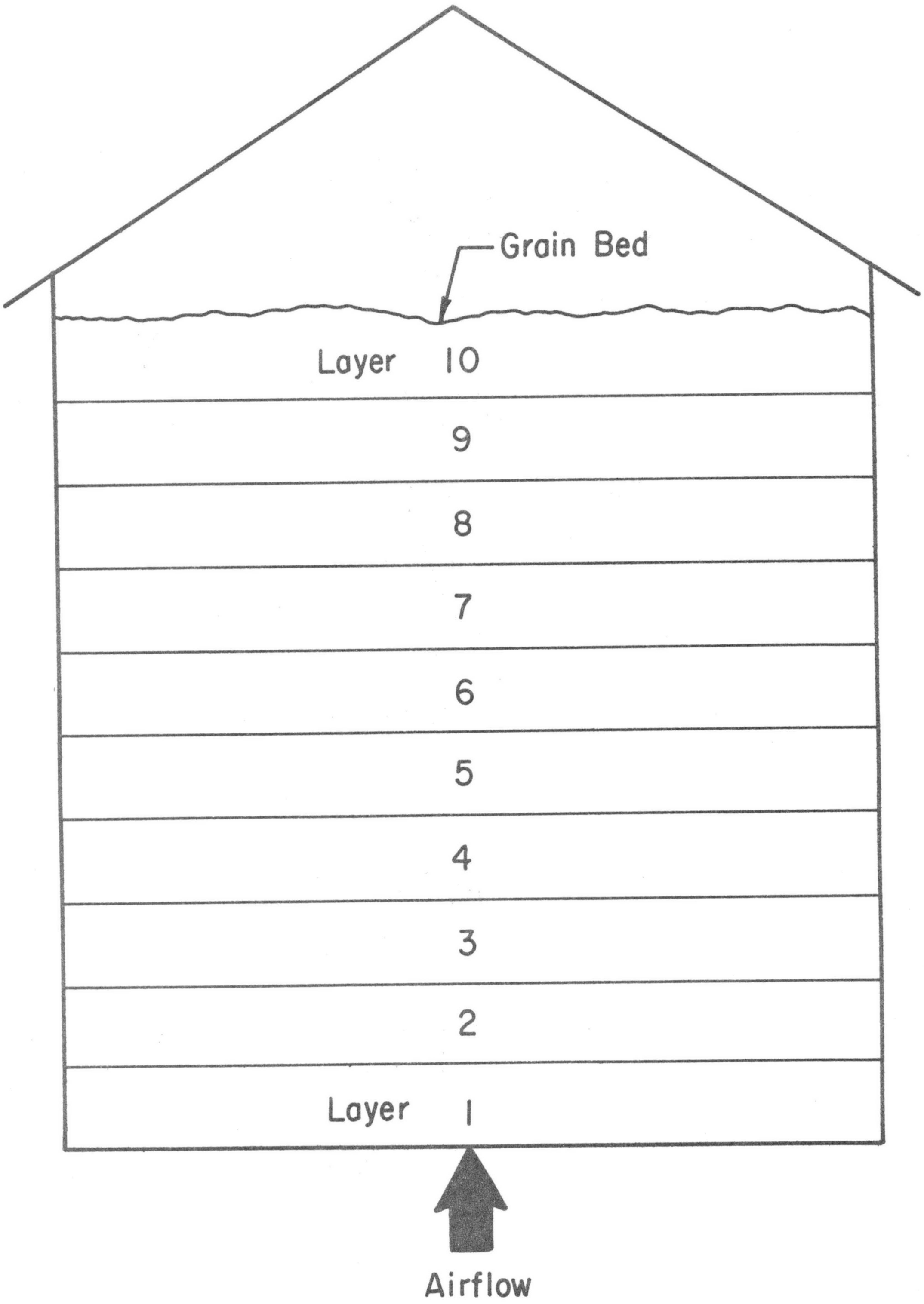


Figure 5. Thin Layers in Deep Bed of Grain

basis for this type of model is the assumption that temperature and moisture equilibrium are reached between air and grain in each grain layer over the simulation time interval. The equilibrium model was tested with and without the inclusion of hysteresis in equilibrium moisture content calculations. When hysteresis was considered, the first step was to determine whether wetting or drying was to occur in the layer. An intermediate equilibrium temperature accounting for only sensible heat transfer was calculated using the following heat balance:

$$C_aT_o + C_vT_oW_o + RC_gG_o = C_aT_e + C_vT_eW_o + RC_gT_e \tag{8}$$

Equilibrium relative humidity at T_e was calculated using both adsorption and desorption equations. Knowing the relative humidity of air entering the layer, the grain was identified as being wetted, dried, or in equilibrium (if the air relative humidity fell within the hysteresis gap). The appropriate equilibrium relative humidity equation was then used to complete the calculations. When hysteresis was not considered desorption equations were used exclusively, as is normally the case when adsorption is not considered.

Final equilibrium grain and air conditions were calculated by solution of the following three equations:

Heat balance:

$$C_aT_o + W_o(C_vT_o + L) + RC_gG_o + C_wG_o(W_f-W_o) = \\ C_aT_f + W_f(C_vT_f + L) + RC_gT_f \tag{9}$$

Mass Balance:

$$M_f - M_o = 100(W_o - W_f) / R \tag{10}$$

Equilibrium Relative Humidity:

Equation (4) with coefficients depending on sorption condition.

The first term on either side of Equation (9) represents the heat content of the dry air flowing through the layer. The second term represents the heat content of the moisture carried by the air, and the third term represents the heat content of the moist grain in the layer. The fourth term on the left side of Equation (9) represents the heat content of the water removed from or added to grain.

Solution for final equilibrium temperature, absolute humidity, and grain moisture content was obtained by use of a numerical search routine presented by Thompson and Peart (1968). The steps taken were as follows:

(1) Estimate W_f.

(2) Calculate T_f from Equation (9).

(3) Calculate M_f from Equation (10).

(4) Calculate ERH from Equation (4).

(5) Calculate final air relative humidity from psychrometrics.

(6) Estimate better W_f based on difference between ERH and RH_f, return to step (2), continue until $ERH-RH_f$ is sufficiently close to zero.

Normally this procedure enabled solution of the equilibrium equations within five or six iterations.

Semi-equilibrium Methodology

Semi-equilibrium simulation was patterned after Thompson et al. (1968). As in equilibrium simulation, temperature equilibrium is assumed between air and grain after the simulation time interval. However, moisture equilibrium is not assumed. Rather, moisture transfer between grain and air is predicted through empirical moisture transfer equations. The solution of the moisture transfer Equation (5) indicates that moisture equilibrium is approached in an exponential fashion, and if the simulation time interval is short, grain and air will not reach equilibrium.

As in the equilibrium model, an intermediate equilibrium grain/air temperature after sensible heat transfer was calculated to determine sorption condition. If the ERH of the grain fell within the hysteresis gap, no moisture transfer was calculated, otherwise the following approximation of Equation (5) was used, assuming EMC to be constant over the small time interval dt:

$$M_f = K\ (M_o - EMC)\ dt + M_o \tag{11}$$

where K was evaluated according to Equation (6) or equation (7), and EMC according to Equation (4) depending on sorption condition.

Final air absolute humidity after moisture transfer was calculated from:

$$W_f = W_o - R\ (M_f - M_o)/100 \tag{12}$$

Final equilibrium temperature was calculated from the equilibrium heat balance Equation (9).

Using this methodology, it was possible to arrive at a final air state point that was infeasible (i.e., $RH_f >$ 100%). This occurred when a greater amount of moisture transfer was calculated by Equation (11) than was possible without exceeding saturation of air. If this occurred, isenthalpic condensation of moisture back into the grain was simulated in a manner similar to that used by Sokhansanj, et al. (1983) by calculating the line of constant enthalpy

$$H = 1.006T_i + W_i(2502 + 1.775T_i), \qquad (13)$$

and using the numerical search routine to locate the temperature along this line at which air relative humidity was 99%. This procedure is illustrated in Figure 6.

Conversely, at times Equation (11) also indicated a greater amount of moisture adsorption than was present in the air. If this occurred, moisture transfer was reduced such that air absolute humidity was maintained at 0.001 kg water per kg dry air.

A listing of the FORTRAN implementation of the techniques discussed above is provided in Appendix B.

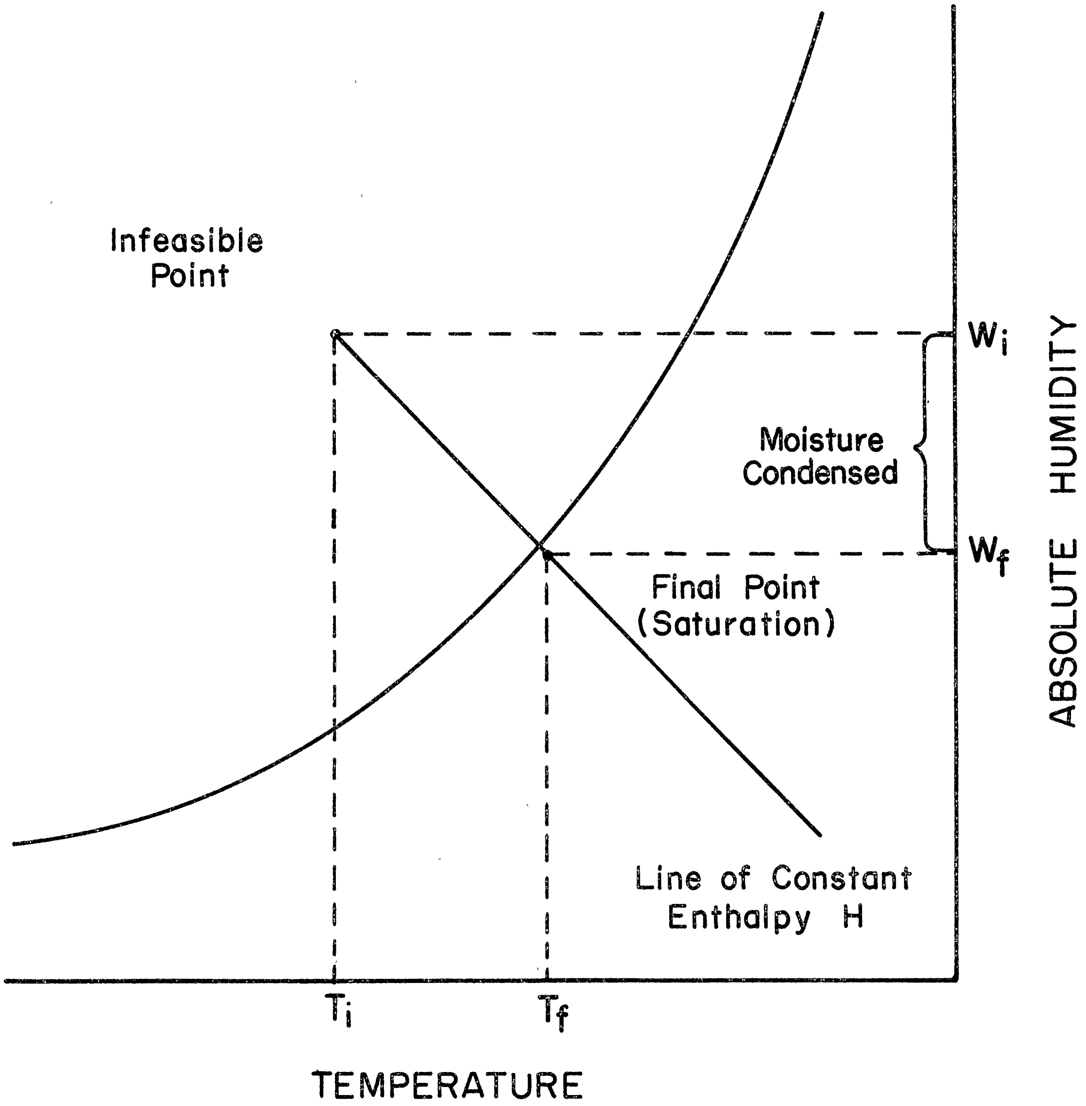


Figure 6. Procedure for Condensation Calculation

CHAPTER V

VALIDATION EXPERIMENTATION

Experimental data for verification and comparison of simulation techniques were obtained from a privately owned bin located in Morrison, Oklahoma, approximately 12 miles from Oklahoma State University (see Figure 7). The bin was already fitted with fan, perforated floor and air plenum and was half filled with approximately 68 tonnes of hard red winter wheat. The height of the grain bed was three meters.

Five parameters were measured in the experiment. Grain temperature and moisture content were measured at regular intervals. Air temperature and relative humidity were measured with a continuously recording instrument. Air velocity delivered by the fan was used to determine airflow rate.

A three m long, 35.6 cm diameter duct was attached to the fan outside the bin for air velocity measurement. Air velocity within the duct was measured with an Alnor velometer (Figure 8), using a ten point traverse at three locations along the duct. Airflow rate was calculated as approximately 0.4 m^3/min-tonne. Static pressure within the air plenum was measured with the velometer (Figure 9) and manufacturer's specified air flow rate was obtained. It

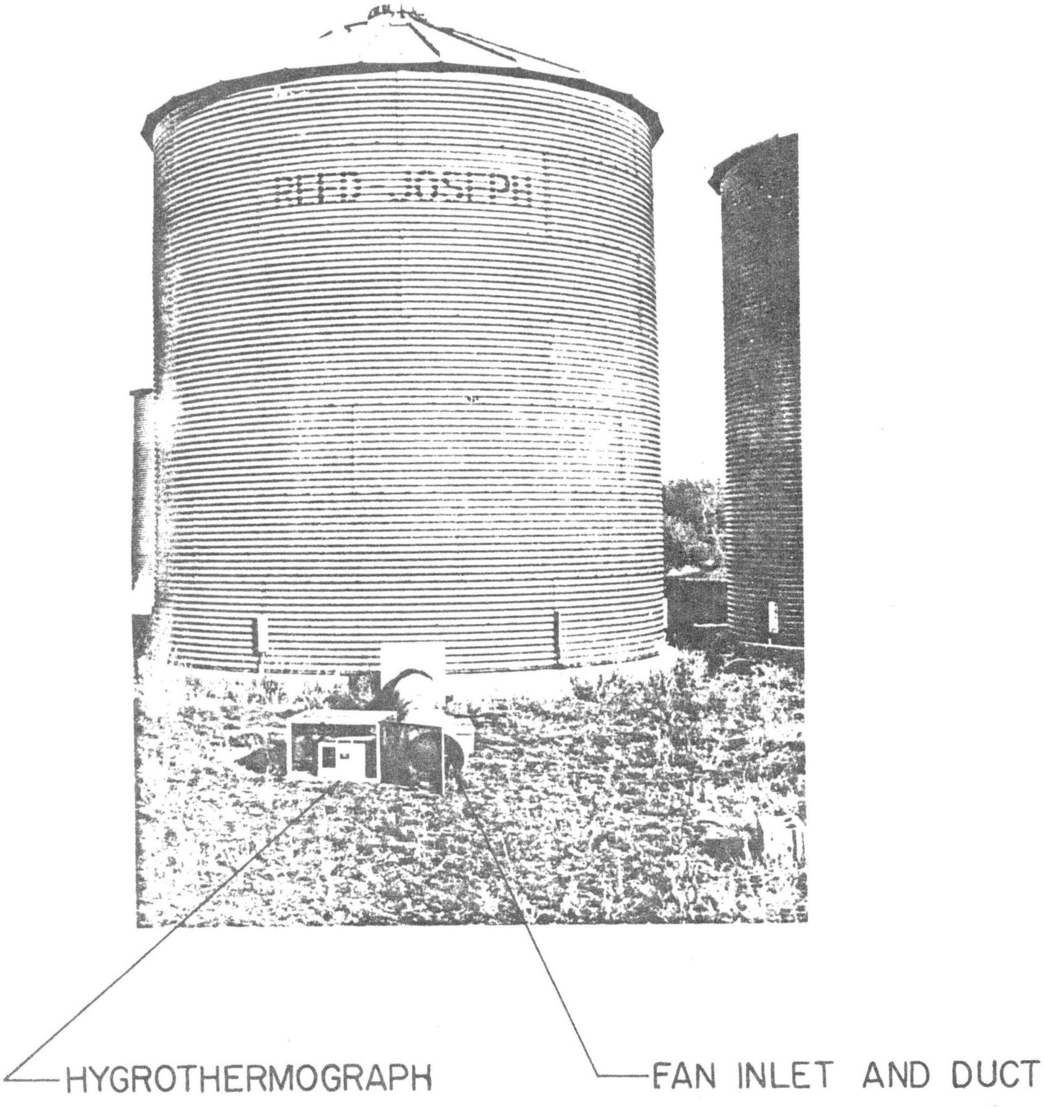


Figure 7. Experimental Grain Bin

Figure 8. Air Velocity Measurement

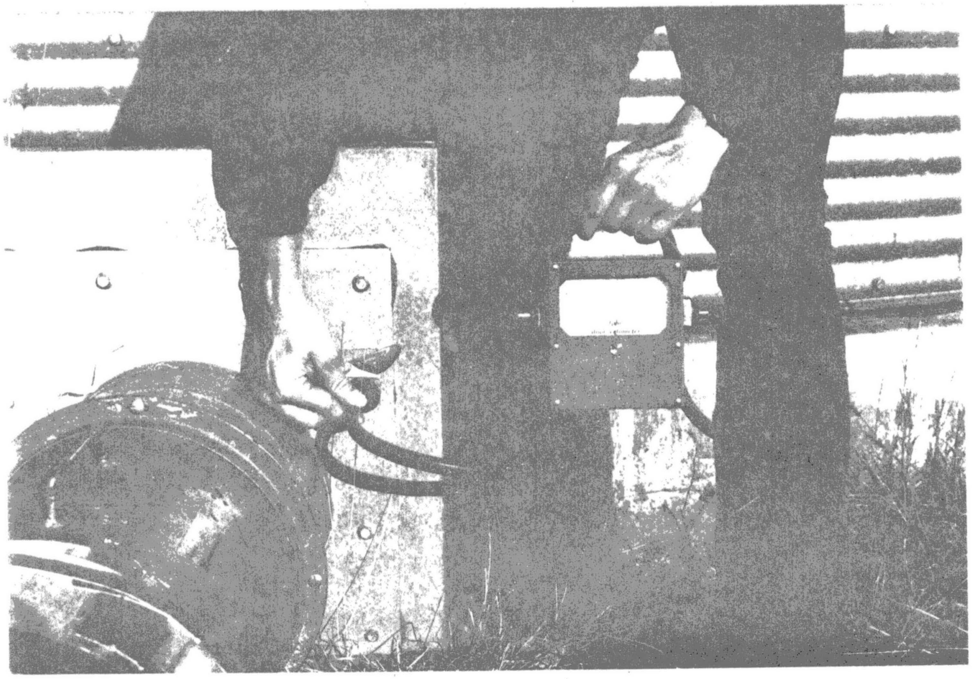


Figure 9. Static Pressure Measurement

was found that the fan delivered about 25% less air than specified by the manufacturer, probably because of the addition of the duct and safety shield.

Thermocouples were used to measure grain temperature in the bin. Prior to aeration, thermocouples were buried in the grain at 0.31 m depth intervals beginning at 0.155 m above the bin floor. Nine thermocouples each were buried in three columns, one at the center of the bin, one near the wall, and one midway between the two (Figure 10). Temperature readings were made once daily for the duration of the test with a high impedance digital voltmeter calibrated for type T thermocouple wire.

Ambient air conditions were obtained using a hygrothermograph enclosed in a screened cage for protection against rodents (Figure 11). In the first week of the test it was found that the relative humidity arm of the instrument was defective. Hygrothermograph readings from Oklahoma State University at Stillwater, Oklahoma were obtained for comparison, and temperatures at the two locations were found to be in variance by only two degrees Celsius at most. Assuming absolute humidity at the two locations to be equal, relative humidity at Morrison was calculated based on Stillwater humidity and Morrison temperature. During the remainder of the test the hygrothermograph functioned correctly, corresponding well to wet and dry bulb temperatures taken once daily with a sling psychrometer. The hourly readings of temperature and relative humidity were entered into a

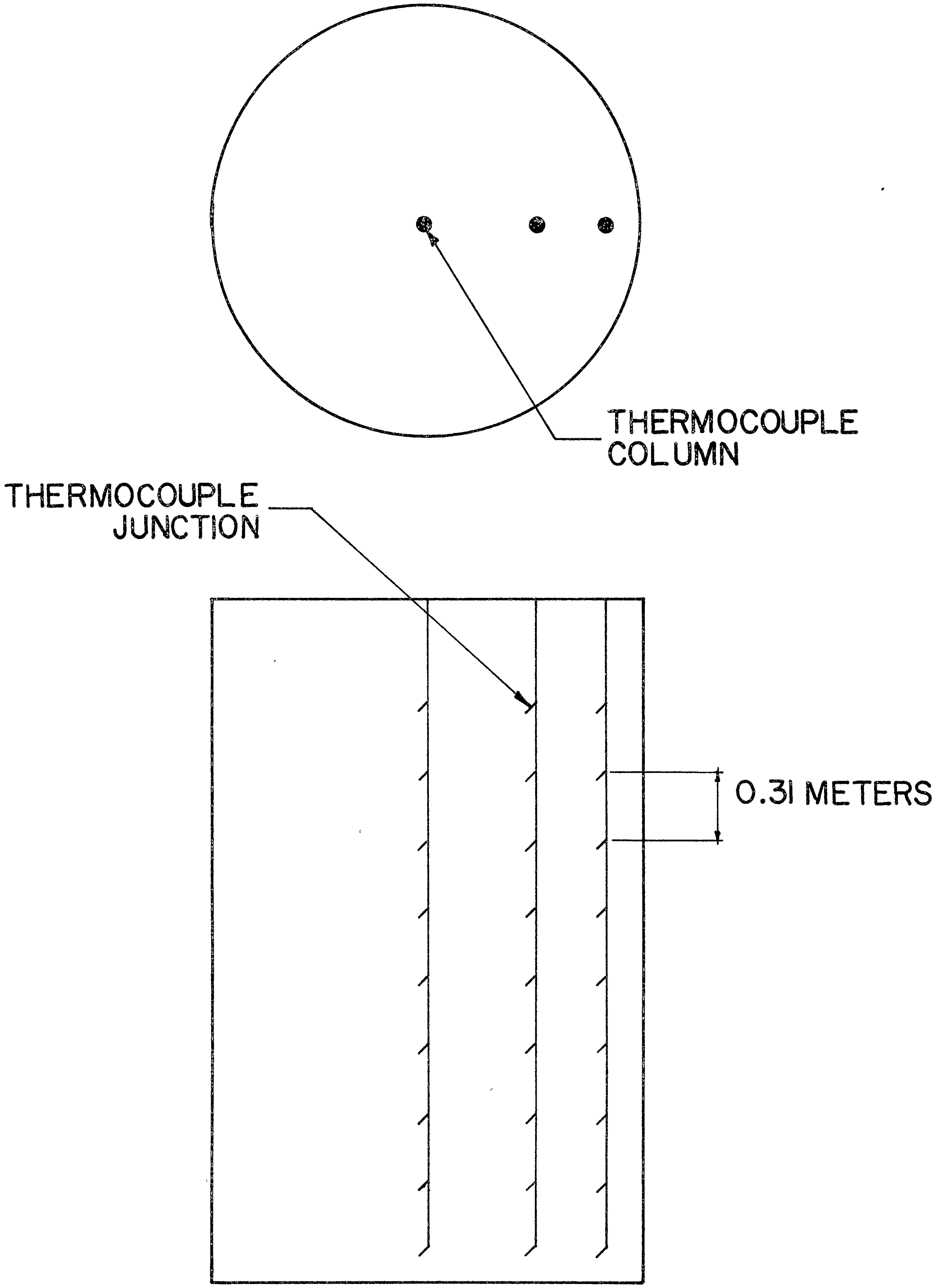


Figure 10. Thermocouple Placement

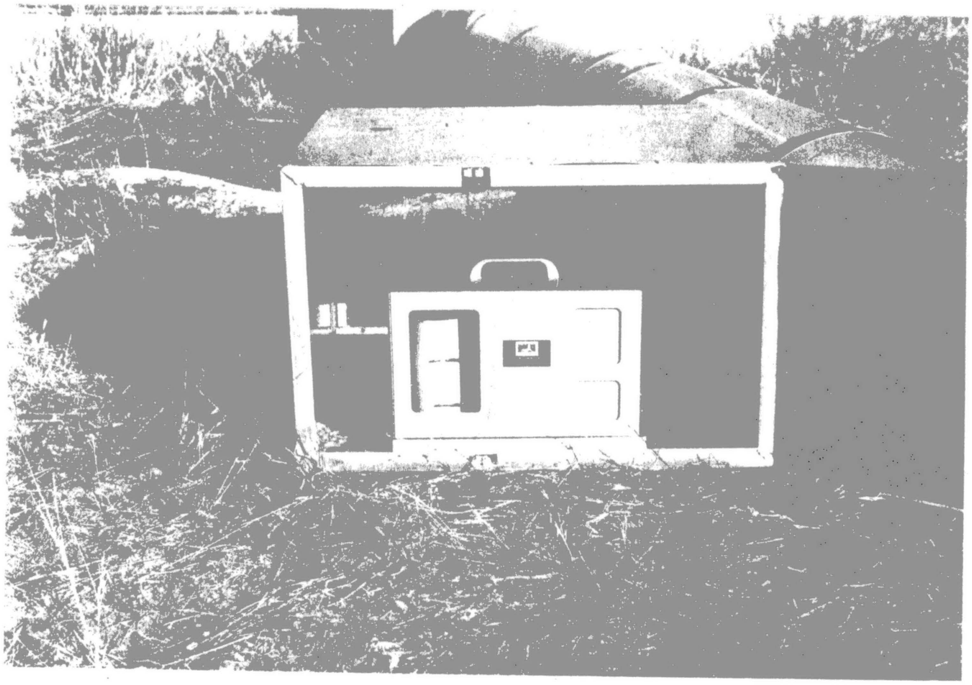


Figure 11. Hygrothermograph and Cage

computer data file for use as input to the simulation programs after modification to reflect a measured temperature rise of one degree Celsius across the fan in the pressure aeration system.

Moisture content readings were taken twice per week. Grain samples were extracted at 0.31 m depth intervals beginning at 0.155 m above the bin floor. Samples were taken at three locations near to thermocouple columns with a vacuum sampler (Figure 12). These samples were oven dried according to ASAE Standard S352 (1983) to determine moisture content.

Aeration was begun at 8:00 a.m. on November 14, 1983 and the fan was operated continuously until 4:00 p.m. on December 6, when the test was terminated so that the wheat could be sold. Moisture content readings were taken on the 17th, 22nd, and 26th of November, and on the 1st and 6th of December. However, moisture content readings taken on November 17 indicated that moisture gradients still existed in the radial direction within the bin due to the loading of at least two seperate batches of wheat with different moisture contents. By November 22 the difference between moisture content at the center of the bin and at the wall had decreased. Since the simulation techniques investigated herein made no provision for heat or moisture transfer in any direction other than that of airflow, 4:00 p.m. on November 22 was taken as the starting time for simulation. Complete listings of all data taken in the experiment are provided in Appendix A.

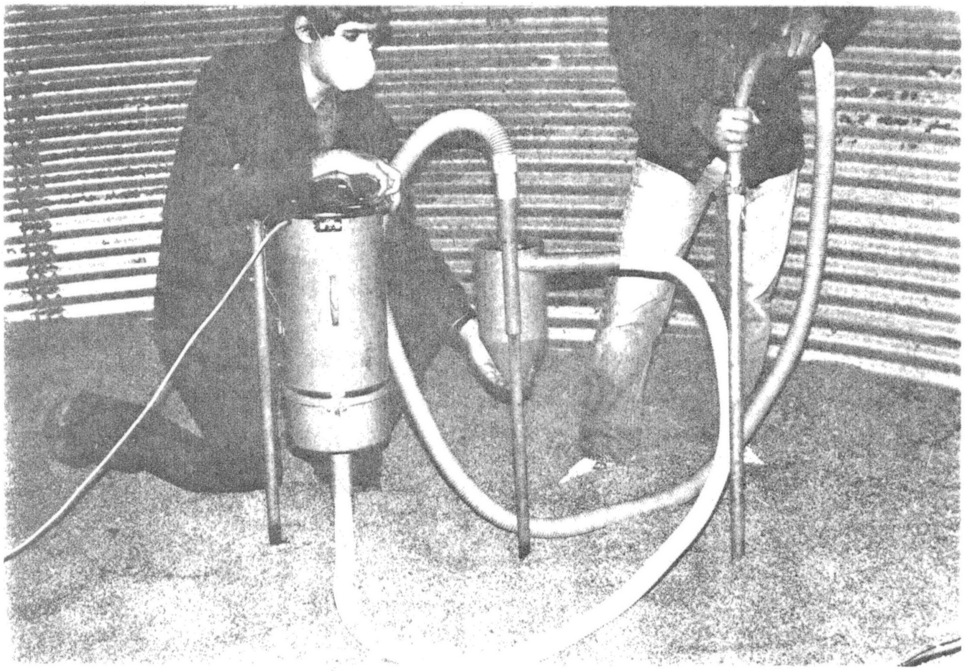


Figure 12. Vacuum Sampler

CHAPTER VI

DISCUSSION OF RESULTS

Field Test Results

Figure 13 illustrates experimentally obtained moisture content versus time of aeration at the bottom (inlet) and top of the grain bed, as well as average moisture content throughout the column of grain. At least two loads of wheat had been loaded into the bin prior to aeration, first a load of 11% wheat, then a load of 12.2% wheat. The average moisture content was about 11.25%, as can be seen from Figure 13. Initially a wetting front was set up, beginning in the lower layers of grain near the inlet, while the upper layers were dried due to dry air coming out of the lower portion of the bin. After approximately 192 hours of aeration a cool front passed through the northern Oklahoma area, and another wetting front began (see Appendix A for a complete listing of verification data, including hygrothermograph records).

Because of the initially dry grain used in the field test and the relatively humid air conditions, adsorption frequently occurred in the lower portion of the grain bed. Most verification work in the simulation modeling area has been done using drying experiments, where initial grain

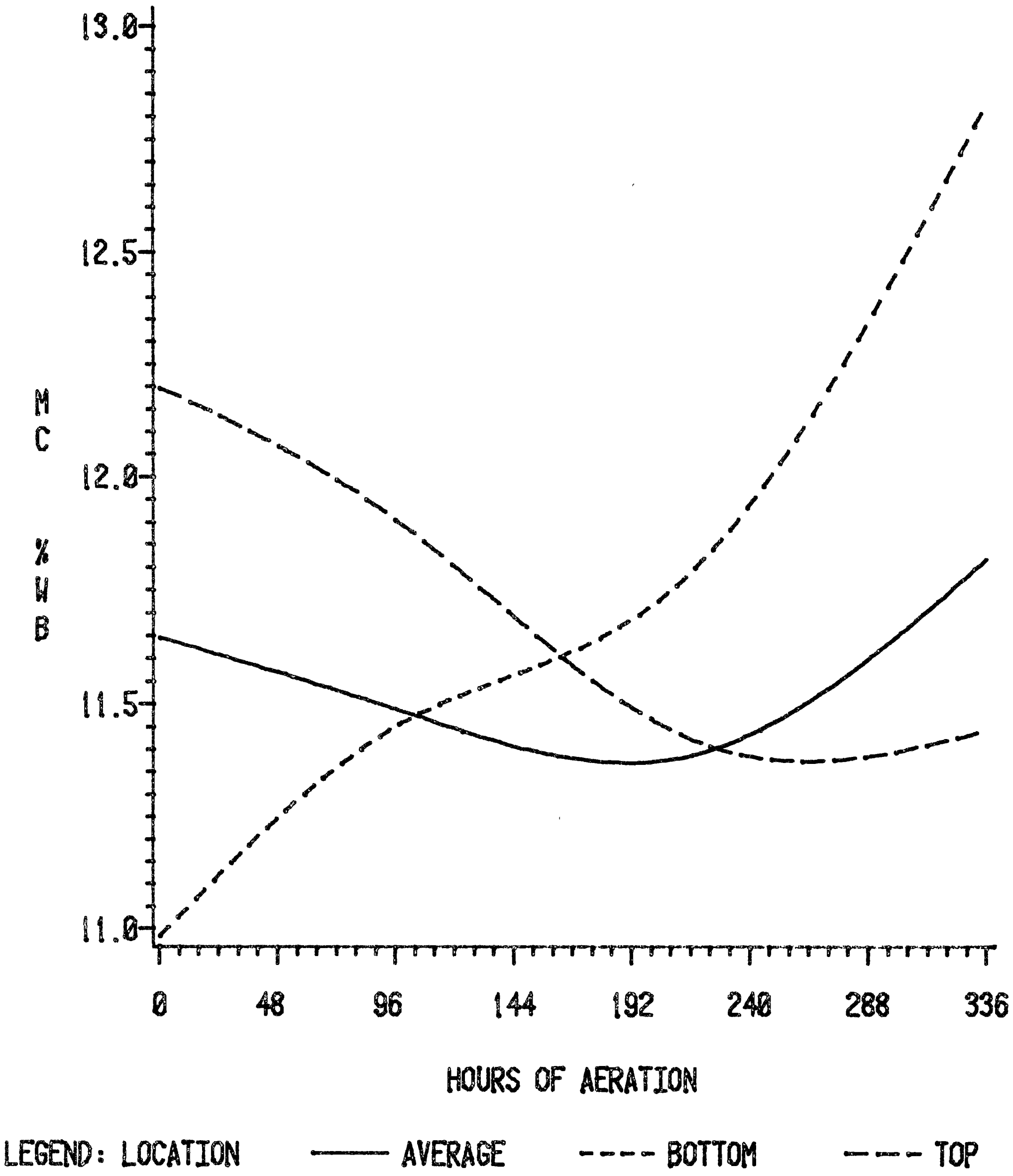


Figure 13. Experimental Moisture Content Versus Time

conditions are so wet that very little adsorption takes place. In grain storage, however, moisture content is low enough that continuous aeration through the night time period where relative humidity is greater will often result in some wetting. Field test data in this experiment provided the opportunity to test model performance in adsorption conditions likely to occur as often as desorption in aeration of wheat in Oklahoma.

Introduction to Simulation Results

Three factors were to be examined in the comparison of simulation performance: method of solution (equilibrium or semi-equilibrium), hysteresis (inclusion of hysteresis calculations or not), and the length of the simulation time interval.

Initially, only equilibrium and semi-equilibrium models were to be tested. Results from the two standard models, when compared to field test data, indicated that a third type of approach warranted investigation. A combination of equilibrium and semi-equilibrium simulation was developed, an approach called combination methodology. Results from each of the three types of models will be discussed.

The effect of hysteresis calculations in each of the three types of simulation models was studied. Inclusion of hysteresis calculations was found to be similarly important in the prediction of adsorption in all three types of models. Hysteresis will be discussed in detail only in conjunction with equilibrium simulation, but the conclusions derived apply equally to semi-equilibrium and combination simulation.

Length of the simulation time interval was found to be an important factor in both equilibrium and semi-equilibrium simulation. The amount of computer time required for solution is directly proportional to the length of the simulation time interval, so it is desirable to lengthen the time interval. The effect of variation of the time interval differed considerably between equilibrium and semi-equilibrium simulation. In equilibrium simulation, increasing the time interval from one to three hours, for example, amounts to averaging the effect of aeration over three hours of time. In semi-equilibrium simulation, however, solution is based on linear approximation of a nonlinear rate equation over the simulation time interval. The approximation to the rate equation becomes less accurate with longer time intervals. The effect of variation of the simulation time interval in both equilibrium and semi-equilibrium simulation will be discussed.

Equilibrium Simulation Results

Table III lists moisture content values after 336 hours of aeration as predicted using equilibrium techniques with and without hysteresis calculations using a simulation time interval of one hour. These data are presented in graphical form in Figure 14.

TABLE III

MOISTURE CONTENT DATA FOR EQUILIBRIUM SIMULATION *

Depth from inlet, cm	Actual	With Hysteresis		Without Hysteresis	
		Pred.	Error	Pred.	Error
	Moisture Content, % w.b.				
15.5	12.83	15.00	2.17	15.79	2.96
46.5	11.93	12.74	0.81	13.46	1.53
77.5	11.61	11.70	0.09	11.93	0.33
108.5	11.83	11.50	-0.33	11.19	-0.64
139.5	11.93	11.47	-0.47	11.03	-0.90
170.5	11.77	11.43	-0.34	11.15	-0.62
201.5	11.49	11.54	0.05	11.35	-0.14
232.5	11.50	11.74	0.23	11.58	0.08
263.5	11.44	11.86	0.41	11.82	0.37
Average Absolute Error			0.54		0.84

* Using simulation time interval of one hour.

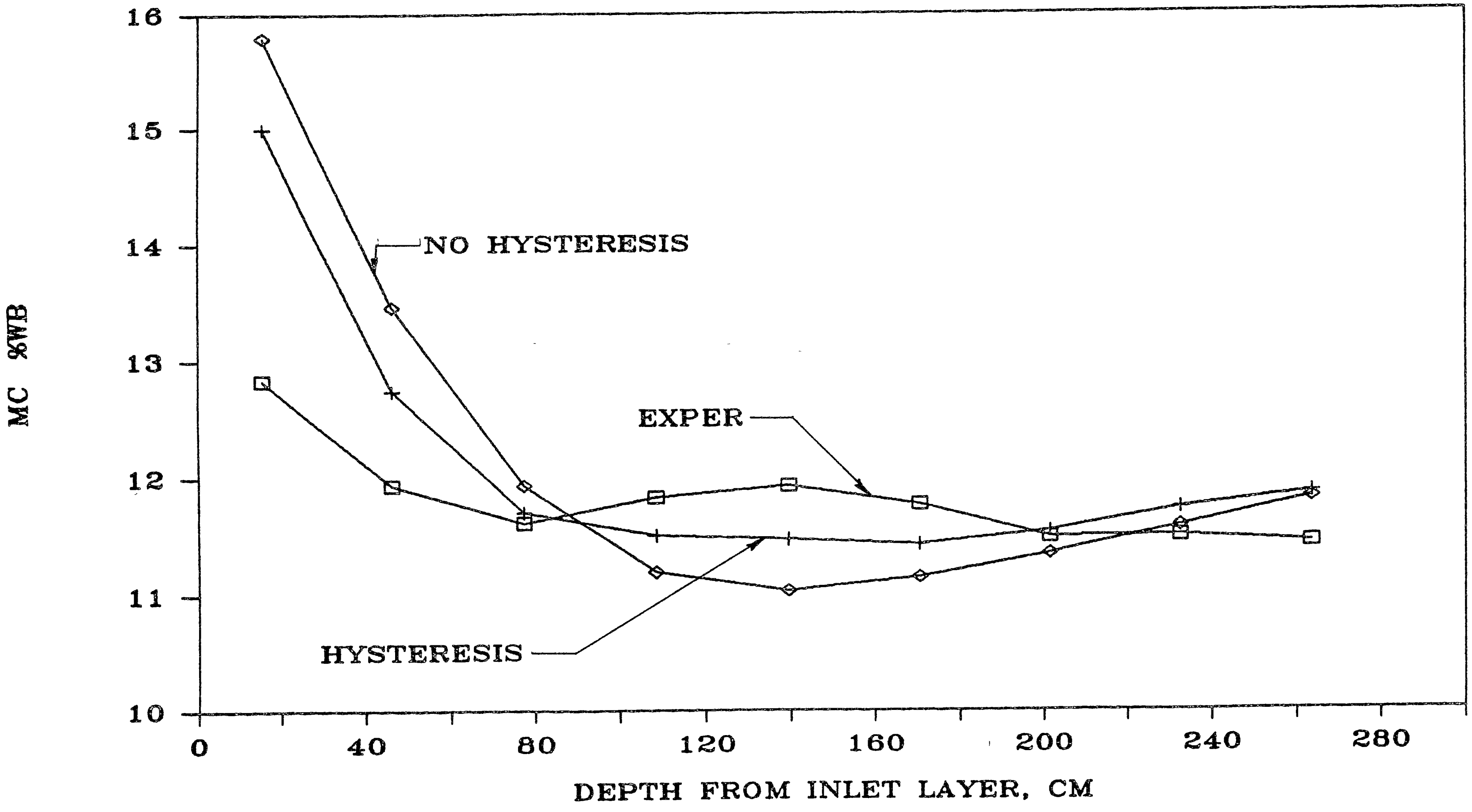


Figure 14. Moisture Content Profiles for Equilibrium Simulation

Equilibrium simulation predicted greater moisture changes in lower layers than were actually observed. Air entering layers just above was thus predicted to be drier than was actually the case, causing an overprediction of drying in middle layers. An underprediction of drying in the upper layers was observed, but each of the latter two deviations arises from the overprediction of moisture adsorption in the layers near the inlet. The maximum error in predicted moisture content was 2.96% in the bottom layer, with an average absolute error of 0.84%. The inclusion of hysteresis calculations reduced this error by as much as half in some layers, with the maximum error being 2.17% and an average absolute error of 0.54%. Although this value of absolute error is not large, a maximum error of over two points is unacceptable for the purposes discussed in Chapter I.

Overprediction of moisture change in the lower layers supports the results of Morey et al. (1977), who found that the moisture equilibrium assumption of Thompson's (1972) model resulted in prediction of greater moisture changes than were observed. If at any location air and grain do not reach equilibrium, it would be in the lower portion of the bin, where the greatest initial difference may be expected between grain and air conditions. In addition, desorption and adsorption rate data would seem to indicate that wetting is a slower process than is drying (see Equations (6) and (7)). Therefore equilibrium is approached more slowly, since adsorption dominates in the bottom layers when ambient air conditions are humid. Since the addition of hysteresis calculations only partially alleviated the problem in the lower layers, it may be speculated that the moisture equilibrium assumption was the more significant source of error.

Table IV shows the effect of variation of the simulation time interval in equilibrium simulation. The effect of this variation was found to be negligible, indicating that greater simulation time intervals, at least up to six hours, may be used with little increase in error. A greater simulation time interval reduces computer time required.

Semi-equilibrium Simulation Results

Table V lists moisture profiles predicted by semi-equilibrium techniques using a one hour simulation time interval. Overprediction of adsorption in bottom grain layers was again observed, though to a lesser degree than with equilibrium simulation. Drying in subsequent layers was, however, greatly overpredicted. There are several possible reasons for this error.

The first possible source of error lies in the empirical nature of the description of the moisture transfer coefficient (see Equations (6) and (7)). This coefficient might not be adequately described as a function only of grain temperature. These equations may need to be reevaluated for use in low airflow simulation.

The second possible reason for overprediction of

TABLE IV

MOISTURE CONTENT DATA FOR EQUILIBRIUM SIMULATION USING EXTENDED SIMULATION TIME INTERVAL

	Simulation Time Interval, hrs					
	1		3		6	
Depth from inlet, cm	Pred.	Error	Pred.	Error	Pred.	Error
	Moisture Content, % w.b.					
15.5	15.00	2.17	15.00	2.17	15.07	2.24
46.5	12.70	0.78	12.74	0.81	12.78	0.85
77.5	11.70	0.09	11.70	0.09	11.70	0.09
108.5	11.54	-0.29	11.50	-0.33	11.50	-0.33
139.5	11.39	-0.55	11.47	-0.47	11.47	-0.47
170.5	11.35	-0.42	11.43	-0.34	11.43	-0.34
201.5	11.47	-0.02	11.54	0.05	11.62	0.13
232.5	11.70	0.20	11.74	0.23	11.74	0.23
263.5	11.82	0.37	11.86	0.41	11.89	0.45
Average Absolute Error		0.54		0.55		0.57

TABLE V

MOISTURE CONTENT DATA FOR SEMI-EQUILIBRIUM SIMULATION *

Depth from inlet, cm	Actual	Pred.	Error
	Moisture Content, % w.b.		
15.5	12.83	14.24	1.41
46.5	11.93	11.19	-0.74
77.5	11.61	10.67	-0.93
108.5	11.83	10.75	-1.08
139.5	11.93	11.19	-0.74
170.5	11.77	11.35	-0.42
201.5	11.49	11.50	0.02
232.5	11.50	11.78	0.27
263.5	11.44	11.86	0.41
Average Absolute Error			0.67

* Using time interval of one hour.

drying is that Equation (5) and Equation (11) constitute a linear approximation of moisture transfer over the small time interval dt. Moisture transfer actually varies in a non-linear fashion over time (Brooker et al., 1974). A possible solution to this problem is a more rigorous solution of a full drying equation, such as was used by Bakker-Arkema et al. (1974). At low airflow rates and low simulation time intervals, computer time required in such a solution might be prohibitive. Another solution is to reduce the simulation time interval.

Table VI lists moisture content profiles predicted by semi-equilibrium techniques using 1.0, 0.5, and 0.25 hour simulation time intervals. Reduction of the time interval decreased errors in predicting adsorption in the bottom layer, but increased overprediction of drying in layers just above. The average absolute error was not significantly changed by varying the time interval, but the shape of the profile was altered extensively (Figure 15). Even though the lowest average absolute error was obtained using a 0.5 hour time interval, a 0.25 hour time interval must provide the least numerical error in solution, and thus provides the best indication of model performance. Since numerical errors decrease using short time intervals, overprediction of drying must be attributed to inaccuracy in the description of the empirical moisture transfer coefficient.

TABLE VI

MOISTURE CONTENT DATA FOR SEMI-EQUILIBRIUM SIMULATION USING REDUCED SIMULATION TIME INTERVAL

	Simulation Time Interval, hrs					
	1.0		0.5		0.25	
Depth from inlet, cm	Pred.	Error	Pred.	Error	Pred.	Error
	Moisture Content, % w.b.					
15.5	14.24	1.41	13.19	0.36	12.23	-0.60
46.5	11.19	-0.74	10.91	-1.02	10.67	-1.26
77.5	10.67	-0.93	10.67	-0.94	10.71	-0.90
108.5	10.75	-1.08	10.87	-0.96	10.95	-0.88
139.5	11.19	-0.74	11.35	-0.58	11.47	-0.46
170.5	11.35	-0.42	11.58	-0.19	11.78	0.01
201.5	11.50	0.02	11.82	0.33	12.12	0.63
232.5	11.78	0.27	12.05	0.55	12.32	0.82
263.5	11.86	0.41	11.97	0.53	12.09	0.65
Average Absolute Error		0.67		0.61		0.69

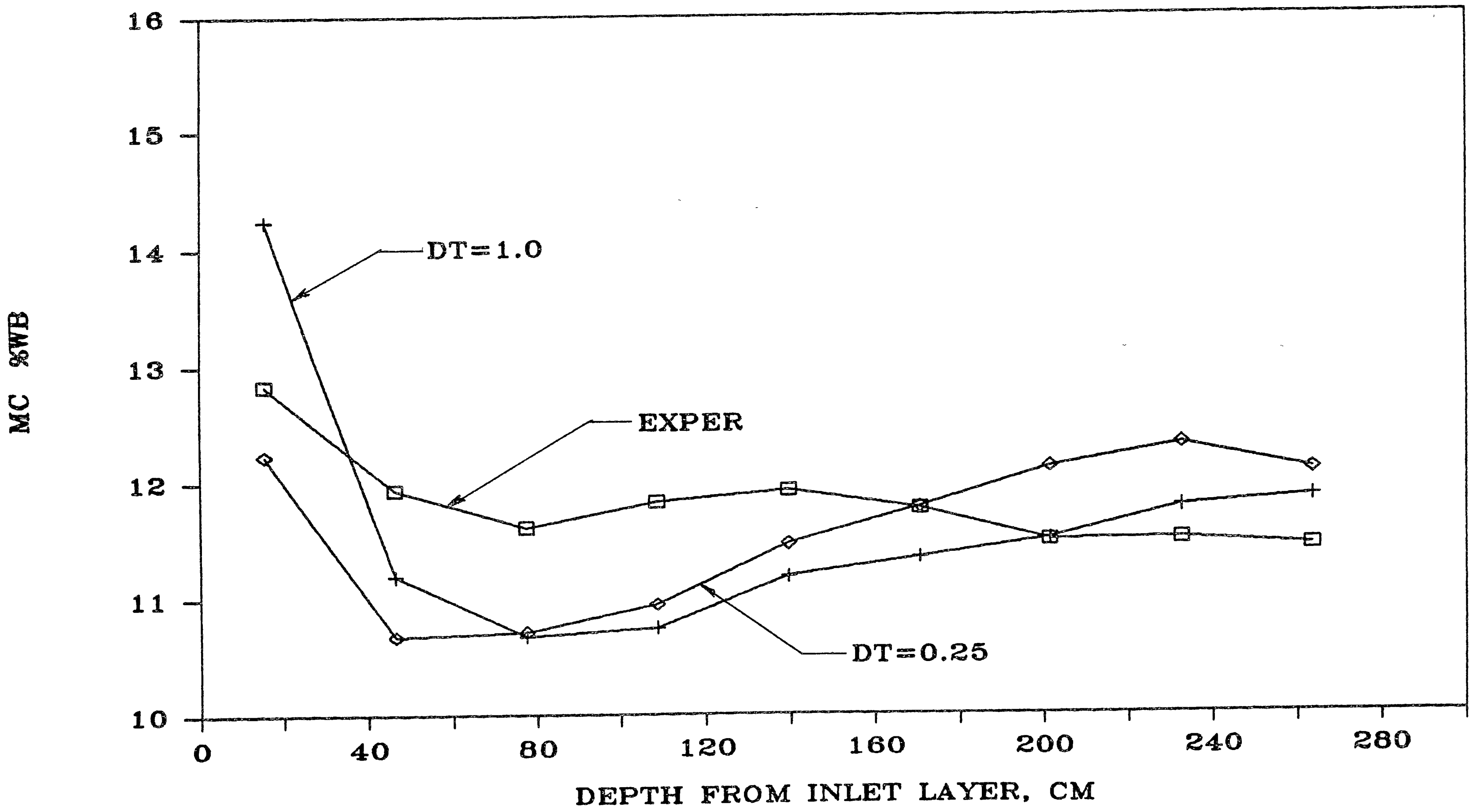


Figure 15. Moisture Content Profiles for Semi-equilibrium Simulation

Combination Simulation Results

Noting the relatively good performance of equilibrium methods in layers where drying was the predominant process, and the better performance of semi-equilibrium methods in layers in which adsorption predominated, a combination of the two methods was used. Equilibrium solution was used in drying situations, and semi-equilibrium solution for wetting situations. Predicted moisture content profiles for this combination model are tabulated in Table VII and illustrated in Figure 16 along with profiles from equilibrium and semi-equilibrium models. All models were run with hysteresis calculations and a simulation time interval of one hour for the equilibrium model, of 0.25 hours for the semi-equilibrium and combination models.

Combination methodology was more effective than equilibrium or semi-equilibrium methodologies with an average absolute error in moisture content of 0.36%. Overprediction of adsorption in lower layers was still present, but at much lower levels than with equilibrium simulation. Only in the very bottom and top layers were errors of any significance observed, and in no layer did error exceed 1.0%.

Temperature Prediction

Figure 17 illustrates average measured grain temperature versus time of aeration along with average temperatures predicted by each of the three types of models. Equilibrium techniques provided the least error in temperature predic-

TABLE VII

MOISTURE CONTENT DATA FOR COMBINATION SIMULATION COMPARED TO OTHER METHODS

	Simulation Method					
	EQ *		SEMI-EQ **		COMB **	
Depth from inlet, cm	Pred.	Error	Pred.	Error	Pred.	Error
	Moisture Content, % w.b.					
15.5	15.00	2.17	12.23	-0.60	13.64	0.81
46.5	12.74	0.81	10.67	-1.26	12.20	0.27
77.5	11.70	0.09	10.71	-0.90	11.93	0.32
108.5	11.50	-0.33	10.95	-0.88	11.74	-0.09
139.5	11.47	-0.46	11.47	-0.46	11.66	-0.27
170.5	11.43	-0.34	11.78	0.01	11.70	-0.07
201.5	11.54	0.05	12.12	0.63	11.78	0.29
232.5	11.74	0.24	12.32	0.82	11.97	0.47
263.5	11.86	0.42	12.09	0.65	12.09	0.65
Average Absolute Error		0.55		0.69		0.36

* Using simulation time interval of one hour.
** Using simulation time interval of 0.25 hours.

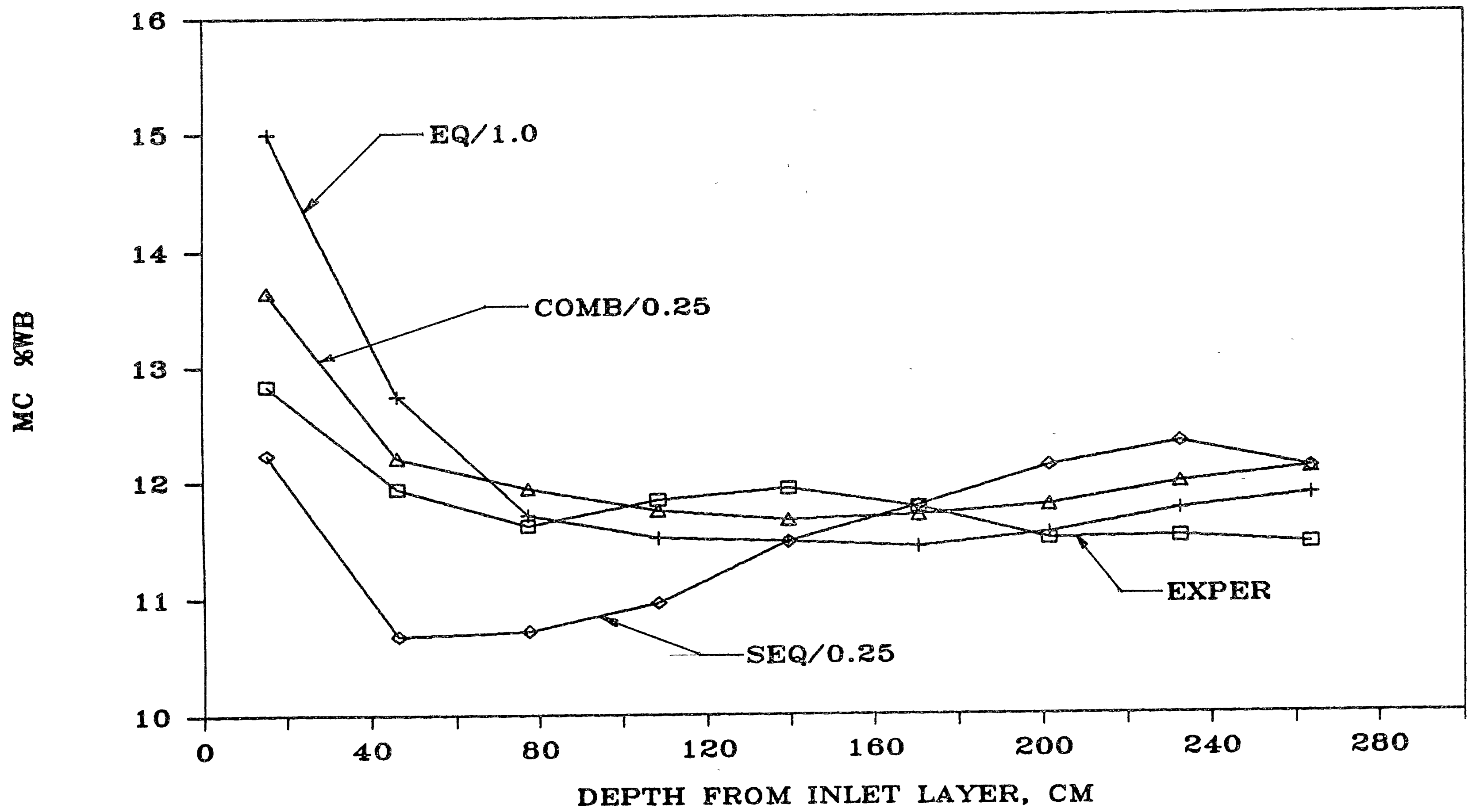


Figure 16. Moisture Content Profiles for Equilibrium, Semi-equilibrium, and Combination Methods

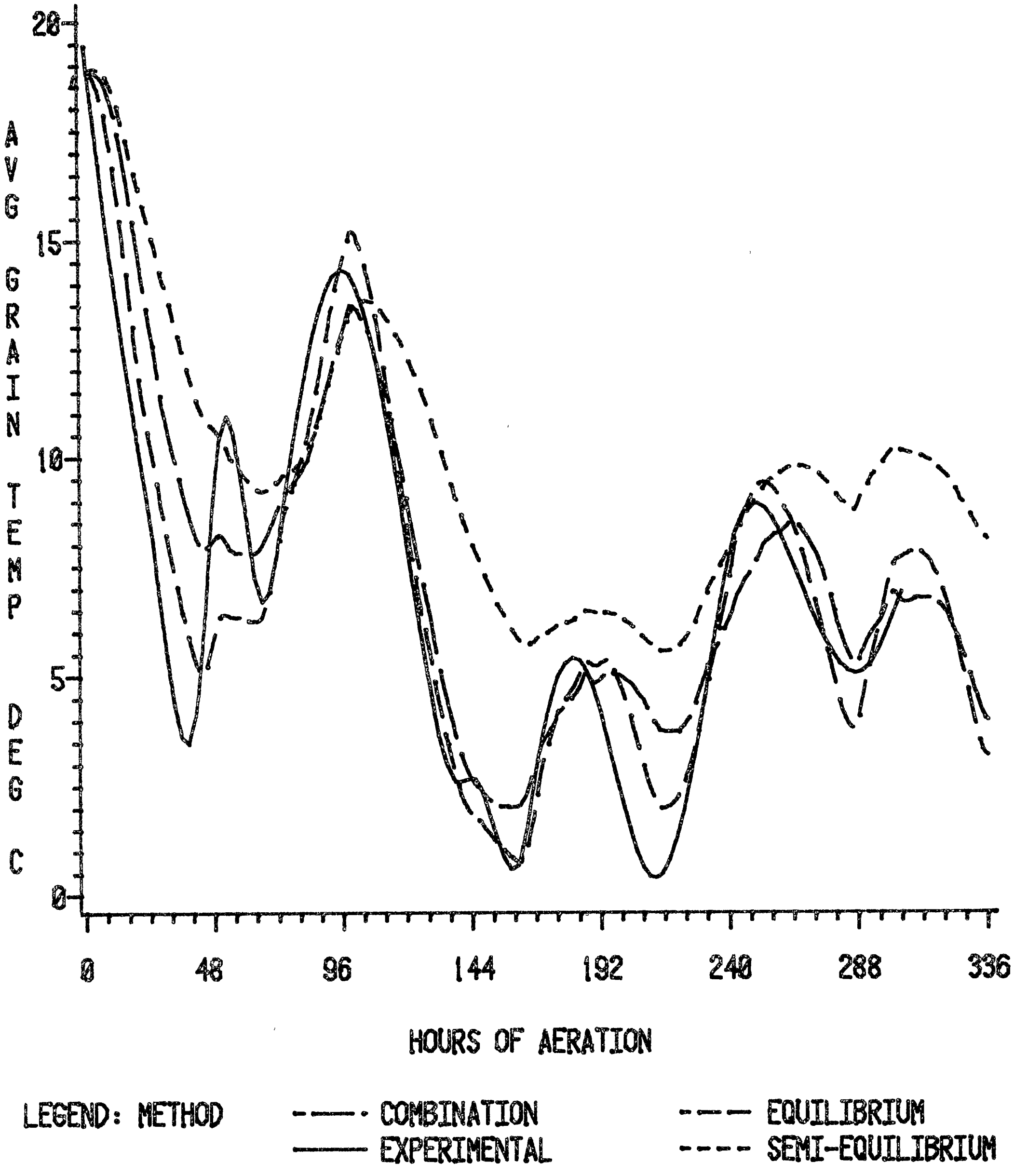


Figure 17. Predicted Grain Temperature Versus Time for All Simulation Methods

tion, with errors seldom larger than one degree Celsius, well within the margin of error in thermocouple measurement. Semi-equilibrium methodology produced much higher errors in temperature, further indicating that the empirical moisture transfer coefficient terms used were not accurate. Combination methodology did not perform as well as equilibrium methodology, but the errors were not large when considering type T thermocouple measurement error of one degree Celsius.

Summary of Results

Specification of the acceptable margin of error in simulation depends on what the model is to be used for. For the purposes outlined for simulation of aeration in Chapter I, more accuracy is required in moisture content prediction than is required in drying simulation.

In grain drying simulation, the major purpose is to predict the amount of time required to dry very wet grain to an average low moisture content. Large changes in moisture content occur, and errors in moisture content prediction of over 1.0% w.b. have been deemed acceptable (Bloome and Shove, 1970, Keener et al., 1978, Sokhansanj et al., 1983).

In aeration small changes in moisture content commonly occur, and these small changes may be highly significant, as was shown in Chapter I. Errors of over 1.0% in any given layer may lead to unexpected mold infestation in grain thought to be safely dry. In predicting average grain moisture content for marketing purposes, average errors of 1.0% are certainly unacceptable.

Based on these considerations neither the equilibrium nor semi-equilibrium models considered in this study produced acceptable moisture content prediction. Combination methodology moisture content prediction error was within acceptable limits. Temperature was quite accurately predicted by both equilibrium and combination techniques. Further experimentation is needed to verify the results of the single validation test used in this study.

CHAPTER VII

CONCLUSIONS

The following conclusions were drawn based on comparing simulation results to experimentally obtained data for one set of conditions:

1. Overprediction of moisture changes in layers close to the inlet indicates that the moisture equilibrium assumption upon which equilibrium methodology is based is not valid when grain and air are conditions are far from equilibrium, particularly in adsorption.

2. Relatively large errors in the prediction of adsorption compared with smaller errors in the prediction of drying indicate that adsorption should be considered separately and that the hysteresis effect should be considered in aeration simulation.

3. Equilibrium simulation performance was largely unaffected by lengthening the simulation time interval, indicating that time intervals of at least six hours can be used without serious performance problems.

4. Lack of semi-equilibrium techniques to accurately predict drying indicates that currently available empirical drying rate equations were not valid in application to this test, and that these equations may need to be reevaluated

for the lower air flow rates used in grain aeration.

5. When considering the accuracy needed in simulation of aeration, grain moisture content was not acceptably predicted by equilibrium or semi-equilibrium methods.

6. Moisture content was predicted with a maximum error of 0.81% w.b. and an average absolute error of 0.36% w.b. by using equilibrium methods for drying situations and semi-equilibrium methods for wetting situations (combination methodology). Moisture content error using combination methods was deemed acceptable for aeration simulation.

7. Grain temperature was acceptably predicted by equilibrium and combination methodologies, indicating that the temperature equilibrium assumption is valid at low air flow rates and that equilibrium or combination simulation may be used in the prediction of temperature changes in aerated wheat.

A SELECTED BIBLIOGRAPHY

American Society of Agricultural Engineers (1983). ASAE S352, Moisture measurement -- grains and seeds. In *Agricultural engineers yearbook*, St Joseph, MI 49085.

Anderson, Kim (1984). Personal interview. Stillwater, OK, October, 1984.

Bakker-Arkema, F. W., L. E. Lerew, S. F. DeBoer and M. G. Roth (1974). *Grain dryer simulation* (Agricultural Experiment Station Research Report 224). East Lansing: Michigan State University.

Barre, H. J., G. R. Baughman and M. Y. Hamdy (1971). Application of the logarithmic model to deep bed drying of grain. *Transactions of the ASAE, 14*, 864-867.

Baughman, G. R., M. Y. Hamdy and H. J. Barre (1970). Analog computer simulation of deep bed drying of grain (ASAE 70-326). Paper presented at the meeting of the American Society of Agricultural Engineers.

Bloome, P. D. and G. C. Shove (1971). Near equilibrium simulation of shelled corn drying. *Transactions of the ASAE, 14*, 709-712.

Bloome, P. D. and G. C. Shove (1972). Simulation of low temperature drying of shelled corn leading to optimization. *Transactions of the ASAE, 15*, 310-316.

Bloome, P. D. (1983a). Personal interview. Stillwater, OK, September, 1983.

Bloome, P. D. (1983b). Management implications of the market value of moisture in grain (ASAE Paper 83-3522). Paper presented at the meeting of the American Society of Agricultural Engineers.

Bloome, P. D. and G. H. Brusewitz (1974) Maintaining quality of stored grain (OSU Extension Facts No. 1100). Stillwater: Oklahoma State University.

Bloome, P. D., G. H. Brusewitz, and S. L. Harp (1974). Aeration and cooling of stored grain (OSU Extension Facts No. 1101). Stillwater: Oklahoma State University.

Brooker, D. B., F. W. Bakker-Arkema and C. W. Hall (1974). Drying cereal grains. Avi: Westport, CT.

Boyce, C. S. (1966). Heat and moisture transfer in ventilated grain. Journal of Agricultural Engineering Research, 11, 255-265.

CRC handbook of tables for applied engineering science (1970). CRC Press, Inc.: Boca Raton, FL.

Day, D. L. and G. L. Nelson (1965). Desorption isotherms for wheat. Transactions of the ASAE, 8, 293-297.

Dugal, A. K., W. E. Muir and D. B. Brooker (1982). Thin-layer rewetting of wheat straw and heads. Canadian Agricultural Engineering, 24, 11-14.

Henderson, J. M. and S. M. Henderson (1967). A computational procedure for deep bed drying analysis (ASAE Paper No. 67-316). Paper presented at the meeting of the American Society of Agricultural Engineers.

Henderson, S. M. (1952). A basic concept of equilibrium moisture. Agricultural Engineering, 33, 29-31.

Hubbard, J. E., F. R. Earle and F. R. Senti (1957). Moisture relations in wheat and corn. Cereal Chemistry, 34, 422-433.

Hukill, W. V. (1947). Basic principles in drying corn and grain sorghum. Agricultural Engineering 28, 335-338, 340.

Hukill, W. V. (1954). Grain drying. In J. A. Anderson and A. W. Alcock (Eds.), Storage of cereal grains and their products. American Association of Cereal Chemists, St Paul, MN.

Keener, H. M., G. E. Meyer, M. A. Sabbah and R. B. Curry (1978). Simulation of Solar Grain Drying (Agricultural Engineering Series 102). Wooster: Ohio Agricultural Research and Development Center.

Kranzler, G. A. (1977). A digital electronic control system for low temperature drying of shelled corn. Unpublished doctoral dissertation, Ames: Iowa State University.

Midwest Plan Service (1980). Low temperature and solar grain drying (MWPS-22). Ames: Iowa State University.

Mohensin, N. N. (1980). Thermal properties of foods and other agricultural materials. Gordon and Breach: New York, NY.

Morey, R. V., H. A. Cloud, R. J. Gustafson and D. W. Peterson (1977). Evaluation of the feasibility of solar energy grain drying (ASAE Paper No. 77-3013). Paper presented at the meeting of the American Society of Agricultural Engineers.

Morey, R. V., H. A. Cloud, R. J. Gustafson and D. W. Peterson (1978a). Fan management systems for ambient air drying systems (ASAE Paper No. 78-3003). Paper presented at the meeting of the American Society of Agricultural Engineers.

Morey, R. V., H. M. Keener, T. L. Thompson, G. M. White and F. W. Bakker-Arkema (1978b). The present status of grain drying simulation (ASAE Paper No. 78-3009). Paper presented at the meeting of the American Society of Agricultural Engineers.

<u>Oklahoma Agriculture 2000</u> (1982). College of Agriculture, Stillwater: Oklahoma State University.

Pfost, H. B., S. G. Maurer, D. S. Chung and G. A. Milliken (1976). Summarizing and reporting equilibrium moisture data for grains (ASAE Paper No. 76-3520). Paper presented at the meeting of the American Society of Agricultural Engineers.

Pfost, H. B., S. G. Maurer, L. E. Grosh, D. S. Chung and G. Foster (1977). Fan management systems for natural air dryers (ASAE Paper No. 77-3526). Paper presented at the meeting of the American Society of Agricultural Engineers.

Pierce, R. O. and T. L. Thompson (1975). Energy utilization and efficiency of crossflow grain dryers (ASAE Paper No. 75-3020). Paper presented at the meeting of the American Society of Agricultural Engineers.

Sabbah, M. A., H. M. Keener, and G. E. Meyer (1977). Simulation of solar grain drying using the logarithmic model (ASAE Paper No. 77-3012). Paper presented at the meeting of the American Society of Agricultural Engineers.

<u>SAS User's Guide</u> (1979). SAS Institute, Inc., Gary NC 27511.

Shove, G. C. (1968). Aerating stored dry grain (Circular 984). College of Agriculture, Cooperative Extension Service, Urbana: University of Illinois.

Simonton, H. R., J. M. Allison, and B. D. McLendon (1981). A microprocessor based grain drying control system (ASAE Paper No. 81-5027). Paper presented at the meeting of the American Society of Agricultural Engineers.

Sokhansanj, S., D. Singh and P. Gebhardt (1983). Low temperature system design and analysis using desktop computers. Proceedings of the National Conference on Agricultural Electronics Applications, 2, 682-691.

Steele, J. L., R. A. Saul and W. V. Hukill (1969). Deterioration of shelled corn as measured by carbon dioxide production. Transactions of the ASAE, 12, 685-689.

Thompson, T. L. and R. M. Peart (1968). Useful techniques to save research time. Transactions of the ASAE, 11, 461-467.

Thompson, T. L., R. M. Peart and G. H. Foster (1968). Mathematical simulation of corn drying -- a new model. Transactions of the ASAE, 11, 582-586.

Thompson, T. L. (1972). Temporary storage of high moisture corn using continuous aeration. Transactions of the ASAE, 15, 333-337.

Watson, E. L. and V. K. Barghava (1974). Thin layer drying studies on wheat. Canadian Agricultural Engineering, 16, 18-22.

Wilhelm, L. R. (1975). Numerical calculation of psychrometric properties in SI units. Transactions of the ASAE, 18, 318-325.

Young, J. H., and J. W. Dickens (1975). Evaluation of costs for drying grain in batch or crossflow systems. Transactions of the ASAE, 18, 734-739.

APPENDIX A

EXPERIMENTAL DATA

TABLE VIII

AMBIENT AIR TEMPERATURE FOR AERÂTION TEST

	Date											
Hour of Day	NOV 14	15	16	17	18	19	20	21	22	23	24	25
	degrees Celsius											
0	.	7	3	9	6	18	6	10	17	4	-1	3
1	.	6	2	9	8	17	4	11	17	3	-1	3
2	.	6	2	9	7	14	4	11	17	3	-1	3
3	.	6	2	9	6	13	4	10	17	1	-1	3
4	.	4	3	8	6	13	3	9	17	2	0	2
5	.	4	3	8	4	12	3	9	17	1	-1	2
6	.	3	3	8	5	12	2	9	17	1	-1	2
7	.	3	3	8	6	11	2	9	17	1	-2	3
8	12	4	3	9	9	11	2	9	17	1	0	4
9	12	7	7	11	13	11	6	11	17	2	3	9
10	12	4	11	15	17	9	9	13	18	1	6	12
11	13	12	14	17	19	11	11	17	21	3	9	14
12	13	14	17	19	21	11	15	19	22	4	11	17
13	16	16	19	19	23	10	18	23	23	5	14	18
14	18	17	22	24	23	9	19	25	12	6	16	18
15	15	18	24	22	23	8	22	27	12	7	17	20
16	14	18	22	21	26	7	20	27	11*	6	14	19
17	12	13	17	18	22	7	17	27	11	3	9	14
18	11	8	12	12	21	8	14	22	10	2	5	13
19	10	6	10	9	19	8	11	18	10	1	3	13
20	8	5	9	8	18	8	11	18	10	1	3	12
21	7	4	9	7	20	8	11	18	9	0	3	13
22	7	3	9	7	13	8	11	18	8	0	3	13
23	7	3	9	6	18	7	10	18	6	-1	3	12

TABLE VIII (continued)

Hour of Day	Date											
	NOV 26	27	28	29	30	DEC 1	2	3	4	5	6	7
	degrees Celsius											
0	12	4	-2	-2	1	-3	6	6	-1	8	-1	.
1	12	3	-2	-3	1	-4	7	5	-2	8	-1	.
2	12	3	-2	-3	1	-4	7	4	-2	8	-1	.
3	12	2	-2	-3	1	-4	7	4	-2	6	-1	.
4	11	2	-2	-3	1	-4	7	4	-3	3	-2	.
5	12	1	-2	-3	2	-4	7	3	-3	2	-2	.
6	13	1	-2	-3	2	-4	7	3	-2	2	-2	.
7	12	1	-2	-3	2	-4	7	3	-2	2	-4	.
8	12	1	-2	-2	2	-4	7	2	-2	2	-4	.
9	13	1	-2	1	1	-2	8	2	0	2	-4	.
10	13	1	-1	4	1	-1	8	2	1	2	-2	.
11	13	2	-1	7	1	1	10	2	1	2	-1	.
12	13	2	0	9	2	1	10	2	3	2	1	.
13	12	1	1	11	4	6	9	2	7	2	3	.
14	12	1	1	13	6	5	9	1	11	2	6	.
15	13	1	2	14	5	4	9	1	14	2	8	.
16	13	1	2	13	6	4	9	1	16	2	10**	.
17	13	1	1	9	2	4	8	1	16	2	.	.
18	12	0	-1	6	-1	4	7	0	11	2	.	.
19	7	0	-2	6	-2	4	7	0	11	1	.	.
20	6	0	-2	5	-2	4	6	0	10	1	.	.
21	6	0	-2	4	-3	4	6	0	9	1	.	.
22	6	0	-2	3	-3	6	6	0	9	0	.	.
23	4	-1	-2	1	-3	6	6	-1	8	0	.	.

* Simulation test start.
** Simulation test end.

TABLE IX

AMBIENT AIR RELATIVE HUMIDITY FOR AERATION TEST

	Date											
Hour of Day	NOV 14	15	16	17	18	19	20	21	22	23	24	25
	relative humidity, %											
0	.	76	83	56	92	65	73	65	88	92	89	70
1	.	79	83	58	92	70	76	60	90	91	83	71
2	.	81	83	56	92	87	78	63	92	91	83	69
3	.	81	83	56	92	90	77	62	92	91	80	74
4	.	84	77	59	92	92	79	63	92	91	77	76
5	.	85	80	57	92	92	86	58	92	91	83	83
6	.	89	83	60	92	92	90	66	92	91	83	84
7	.	87	87	61	92	92	87	64	92	91	90	84
8	83	86	91	66	92	82	91	75	92	87	87	85
9	88	83	82	62	92	72	88	64	92	79	82	64
10	89	87	58	47	73	92	64	59	92	81	71	48
11	88	46	42	41	57	90	52	48	85	67	56	41
12	82	39	33	37	54	77	35	41	73	64	51	30
13	63	35	26	36	44	71	29	30	65	56	39	28
14	49	34	20	28	39	69	26	26	91	55	32	28
15	43	32	19	29	40	72	22	23	81	46	26	24
16	44	30	21	34	33	92	22	22	77*	49	29	25
17	50	36	27	34	37	87	27	23	77	55	37	30
18	54	58	39	61	38	80	42	36	81	64	54	36
19	67	75	50	84	44	76	61	52	77	83	59	44
20	70	83	57	85	76	80	54	65	75	85	62	47
21	76	85	54	89	65	77	62	76	80	87	70	47
22	75	89	57	88	92	74	61	80	85	87	64	48
23	75	83	56	85	88	68	63	84	92	87	78	55

TABLE IX (continued)

	Date											
Hour of Day	NOV 26	27	28	29	30	1	2	3	4	5	6	7
	relative humidity, %											
0	59	79	64	91	91	90	79	91	88	83	69	.
1	61	74	64	91	91	90	87	91	86	85	69	.
2	68	70	65	91	91	90	91	91	87	87	69	.
3	76	69	64	91	91	90	91	91	87	90	69	.
4	89	72	61	91	91	90	91	91	84	90	69	.
5	92	70	58	91	91	85	91	91	87	86	67	.
6	84	69	58	91	90	83	91	91	87	86	70	.
7	91	67	57	91	90	83	76	91	87	88	81	.
8	87	64	57	91	90	82	83	90	87	88	85	.
9	85	63	55	91	81	74	78	90	87	90	86	.
10	85	60	57	65	56	65	70	90	83	90	80	.
11	86	56	60	56	57	54	62	90	85	90	67	.
12	84	54	59	51	54	46	58	90	80	89	56	.
13	89	55	54	46	46	39	61	90	69	81	48	.
14	87	50	55	42	46	45	70	89	52	78	44	.
15	86	51	55	39	48	52	78	89	42	76	37	.
16	91	54	54	41	49	57	77	83	41	76	30**	.
17	89	63	57	50	59	61	86	83	45	73	.	.
18	59	65	65	61	76	65	85	79	60	76	.	.
19	80	76	75	68	89	71	83	79	65	78	.	.
20	88	69	78	72	87	77	84	79	68	76	.	.
21	79	63	81	85	90	78	83	79	73	75	.	.
22	74	63	76	81	90	74	85	79	78	74	.	.
23	85	60	75	91	90	76	86	83	82	72	.	.

* Simulation test start.
** Simulation test end.

TABLE X

GRAIN MOISTURE CONTENT FOR AERATION TEST

	Depth from inlet, cm								
Date	15.5	46.5	77.5	108.5	139.5	170.5	201.5	232.5	263.5
	Moisture content, % w.b.								
Nov 8	9.3	9.4	9.9	10.8	12.0	12.2	12.3	12.2	13.2
17	10.5	10.4	10.5	10.7	11.4	12.1	12.2	12.3	12.7
22	11.0	11.0	11.3	11.5	11.6	11.9	12.2	12.1	12.2
26	11.4	11.5	11.2	11.3	11.4	11.5	11.4	11.7	11.9
Dec 1	11.8	11.6	11.2	11.4	11.2	11.3	11.3	11.2	11.4
6	12.8	11.9	11.6	11.8	11.9	11.8	11.5	11.5	11.4

TABLE XI

GRAIN TEMPERATURE FOR AERATION TEST

		Depth from inlet, m								
Date	Time	0.16	0.47	0.78	1.09	1.40	1.71	2.02	2.33	2.64
		Temperature, degrees Celsius								
Nov 14	17	14	18	18	17	16	16	17	17	18
15	17	13	13	13	12	11	10	11	11	12
16	8	7	8	9	9	10	11	11	11	10
16	17	14	13	12	11	8	8	8	9	10
17	8	11	11	12	13	12	12	11	10	9
17	16	17	14	13	13	12	11	11	11	11
18	8	11	11	12	13	13	13	13	12	11
18	16	17	19	18	17	13	13	12	12	12
19	9	13	16	17	19	20	19	17	17	15
19	17	11	13	14	16	17	17	17	17	17
20	9	8	7	8	9	11	12	12	12	12
20	17	12	12	11	10	9	9	10	10	11
21	8	10	10	11	12	13	12	11	9	8
21	16	17	14	13	12	12	12	11	11	11
22	9	21	21	21	21	21	20	16	15	13
22*	16	15	19	21	22	22	22	19	18	17
23	9	4	6	8	10	12	14	15	16	16
23	17	5	6	6	6	8	9	12	11	9
24	10	3	2	3	4	5	6	6	6	6
24	18	10	9	9	10	11	12	14	6	13
25	10	6	5	6	6	7	8	8	7	6
25	18	12	11	11	9	7	7	7	8	8

TABLE XI (continued)

		Depth from inlet, m								
Date	Time	0.16	0.47	0.78	1.09	1.40	1.71	2.02	2.33	2.64
		Temperature, degrees Celsius								
Nov 26	16	16	16	16	16	16	15	13	12	11
27	17	3	3	4	5	7	9	12	12	13
28	10	-1	0	1	2	3	4	5	5	5
28	17	2	2	2	1	2	3	4	4	4
29	10	1	-1	-1	0	1	2	2	2	2
29	16	7	6	4	1	1	1	2	2	2
30	10	3	4	4	5	6	7	7	6	3
30	16	3	2	2	3	4	5	6	7	6
Dec 1	10	-2	-3	-3	-2	1	2	3	4	4
1	15	2	-1	-2	-3	-1	0	3	3	3
2	9	8	9	9	8	7	5	2	1	-1
2	16	9	9	9	9	9	9	6	5	3
3	17	3	4	6	6	7	8	10	11	11
4	18	10	9	6	3	2	2	4	4	6
5	8	4	6	7	9	11	11	6	5	6
6	10	-1	-1	0	1	-1	4	6	7	7
6	16**	3	2	1	0	1	3	5	6	6

* Simulation test start.
** Simulation test end.

APPENDIX B

LISTING OF COMPUTER SOURCE CODE

```
C
C ***********************************************************************
C ** WHEAT AERATION MODEL -- VERIFICATION VERSION -- LARRY SCHULTZ     **
C ** OKLAHOMA STATE UNIVERSITY -- STILLWATER, OK  74078                **
C ** LAST MODIFIED, 22  OCT 84                                         **
C ***********************************************************************
C
      DIMENSION A(4), GT(20), GM(20), TPRT(10)
      DATA A/4*0.0/
      WB(DB)=100.0*DB/(100.0+DB)
C
C     *** READ SYSTEM PARAMETERS
C
      READ (5,20) NLYR,AIRATE,DT,TLIM,EQLIM,METH,IHYST
      READ (5,21) (GT(ILYR),ILYR=1,NLYR)
      READ (5,21) (GM(ILYR),ILYR=1,NLYR)
      READ (5,22) TPRT
C
C     *** INITIALIZE PHYSICAL CONSTANTS
C
      CA=1.006
      CV=1.871
      CW=4.187
      GAR=1000.0/(AIRATE*60.0*DT*1.21*NLYR)
      CKL=1.0/DT
C
C     *** PRINT TITLE
C
      WRITE (6,23)
C
C     *** READ AMBIENT AIR CONDITIONS, BEGIN TIME LOOP
C
      TIME=0.0
1     READ (10,24) TA,RHA
C
C        *** CALCULATE WA FROM PSYCHOMETRIC EQUATIONS
C
         WA=WAIR(TA,RHA)
C
C        *** SET INLET CONDITIONS TO AMBIENT AIR CONDITIONS
C
         TO=TA
         WO=WA
C
C        *** BEGIN LOOP FOR LAYERS
C
         DO 17 ILYR=1,NLYR
            J=1
            N=0
            A(1)=0
            A(2)=0
            A(3)=0
            A(4)=0
            GTO=GT(ILYR)
```

```
           GMO=GM(ILYR)
C
C          *** CALCULATE SPECIFIC HEAT FOR GRAIN LAYER
C
           CG=1.258+0.01131*WB(GMO)
C
C          *** CALCULATE LATENT HEAT OF VAPORIZATION OF WATER IN WHEAT
C
           HVF=1.258-0.01151*GMO
           HVA=2500.86*HVF
           HVB=-2.38*HVF
C
C          *** DETERMINE WHETHER DRYING OR REWETTING IS TO TAKE PLACE
C
           TE=((CA+WO*CV)*TO+GAR*CG*GTO)/(CA+WO*CV+GAR*CG)
           RHE=RHAIR(TE,WO)
           IF (RHE.GT.99.9) RHE=99.9
           IDRY=1
           IF (IHYST.EQ.0.AND.METH.EQ.1) GO TO 2
           ERHD=(1.0-DEXP(-2.30080D-5*(TE+55.815)*GMO**2.2857))*100.
           ERHA=(1.0-DEXP(-6.510426D-5*(TE+70.7337)*GMO**1.8973))*100.
           IDRY=3
           IF (RHE.LE.ERHD) IDRY=1
           IF (RHE.GE.ERHA) IDRY=2
           IF (IDRY.EQ.3) ERRAT=(RHE-ERHD)/(ERHA-ERHD)
C
C          *** SELECT SOLUTION METHOD TO USE
C               METH=1 -- EQUILIBRIUM
C               METH=2 -- SEMIEQUILIBRIUM
C               METH=3 -- COMBINATION
C
2          GO TO (4,7,3), METH
3          IF (IDRY.EQ.2) GO TO 7
C
C          ***** EQUILIBRIUM METHODOLOGY *****
C
C          *** ESTIMATE WF TO BE EQUAL TO WO AS FIRST GUESS
C
4          WF=WO
C
C             *** CALCULATE TF FROM HEAT BALANCE EQUATION
C
5             TF=(CA*TO+WO*(CV*TO+HVA+HVB*GTO)+GAR*CG*GTO+CW*GTO*
     1          (WF-WO)-WF*HVA)/(CA+WF*(CV+HVB)+GAR*CG)
C
C             *** CALCULATE MF FROM MASS BALANCE EQUATION
C
              GMF=GMO-100.*(WF-WO)/GAR
              IF (GMF.LT..001) GMF=.001
C
C             *** CALCULATE RHF FROM PSYCHOMETRIC EQUATIONS
C
              RHF=RHAIR(TF,WF)
C
```

```
C              *** CALCULATE EQUILIBRIUM RELATIVE HUMIDITY
C
               IF (IDRY.EQ.1)
     &          ERH=1.0-DEXP(-2.30080D-5*(TF+55.815)*GMF**2.2857)
               IF (IDRY.EQ.2)
     &          ERH=1.0-DEXP(-6.510426D-5*(TF+70.7337)*GMF**1.8973)
               IF (IDRY.NE.3) GO TO 6
               ERHD=1.0-DEXP(-2.30080D-5*(TF+55.815)*GMF**2.2857)
               ERHA=1.0-DEXP(-6.510426D-5*(TF+70.7337)*GMF**1.8973)
               ERH=ERRAT*(ERHA-ERHD)+ERHD
6              ERH=ERH*100.0
C
C              *** CALL ZEROING ROUTINE, REPEAT UNTIL ERH EQUALS RHF
C
               Y=ERH-RHF
               CALL ZERO (J,0.0,WF,Y,A,.025,K,N,M)
            GO TO (5,16), K
C
C           ***** SEMI-EQUILIBRIUM METHODOLOGY *****
C
7           GO TO (8,9,11), IDRY
C
C           *** CALCULATE MASS REMOVED
C
8           CK=2.4E8*EXP(-6244/(TE+273))
            IF (CK.GE.CKL) CK=CKL
            EMC=(LOG(1-RHE/100.)/(-2.30080D-5)/
     &        (TE+55.815))**(1./2.2857)
            DELM=CK*(GMO-EMC)*DT
            GMF=GMO-DELM
            GO TO 12
C
C           *** CALCULATE MASS ADSORBED
C
9           CK=24.327*EXP(-1845/(TE+273))
10          EMC=(LOG(1-RHE/100.)/(-6.510426D-5)/
     &       (TE+70.7337))**(1/1.8973)
            IF (IHYST.EQ.0)
     &       EMC=(LOG(1-RHE/100.)/(-2.30080D-5)/
     &        (TE+55.815))**(1/2.2857)
            DELM=CK*(GMO-EMC)*DT
            GMF=GMO-DELM
            GO TO 12
C
C           *** NO MASS CHANGE
C
11          GMF=GMO
C
C           *** CALCULATE FINAL AIR CONDITIONS
C
12          WF=WO-(GMF-GMO)/100.0*GAR
            IF (WF.GE.0.0005) GO TO 13
            CK=CK/2.0
            GO TO 10
```

```
13          TF=(CA*TE+WO*(CV*TE+HVA+HVB*GTO)+GAR*CG*GTO+
     &       CW*GTO*(WF-WO)-WF*HVA)/(CA+WF*(CV+HVB)+GAR*CG)
C
C           *** CHECK FOR INFEASIBLE STATE POINT (RHF>100%)
C
            RHF=RHAIR(TF,WF)
            IF (RHF.LE.99.99) GO TO 16
C
C           *** SIMULATE CONDENSATION OF EXCESS MOISTURE
C
            WI=WF
            TI=TF
C
C           *** CALCULATE ENTHALPY AT INFEASIBLE POINT
C
            H=1.006*TI+WI*(2502.+1.775*TI)
C
C           *** CONVERGE TO SATURATION POINT ON CONST. ENTHALPY LINE
C
            TF=TI+2.0
14          WF=(H-1.006*TF)/(2502.+1.775*TF)
               RHF=RHAIR(TF,WF)
               CALL ZERO (J,99.,TF,RHF,A,.5,K,N,M)
            GO TO (14,15), K
C
C           *** CALCULATE HEW HUMIDITY RATIO AND FINAL MOISTURE CONTENT
C
15          WF=WAIR(TF,99.99)
            GMF=GMF+(WI-WF)*100.0/GAR
C
C           *** FINAL STATE POINT FOUND, SAVE CONDITIONS
C
16          TO=TF
            WO=WF
            GT(ILYR)=TF
            GM(ILYR)=GMF
17       CONTINUE
C
C        *** INCREMENT TIME
C
         TIME=TIME+DT
C
C        *** PRINT STATE OF BIN
C
         DO 18 I=1,10
            IF (TIME.NE.TPRT(I)) GO TO 18
            WRITE (6,25) TIME,(GT(ILYR),ILYR=1,NLYR)
            WRITE (6,26) (GM(ILYR),ILYR=1,NLYR)
            GO TO 19
18       CONTINUE
C
C        *** RETURN IF TIME LIMIT NOT REACHED
C
19    IF (TIME.LT.TLIM) GO TO 1
```

```
C
C     *** FIN
C
      STOP
C
20    FORMAT (I8,4F8.0,2I8)
21    FORMAT (10F8.0,/,10F8.0)
22    FORMAT (10F8.0)
23    FORMAT (51H1WHEAT AERATION MODEL -- LARRY SCHULTZ -- OCT, 1984,/)
24    FORMAT (2F5.0)
25    FORMAT (1H ,F8.2,8H TEMP:  ,20F5.1)
26    FORMAT (1H ,8X,8H M.C.:  ,20F5.1)
C
      END
C
C
      FUNCTION WAIR (T,RH)
C
C **********************************************************************
C ** WAIR -- RETURNS ABSOLUTE HUMIDITY OF AIR GIVEN DRY BULB TEMP.    **
C **         AND RELATIVE HUMIDITY. -- LARRY SCHULTZ                  **
C **********************************************************************
C
      DOUBLE PRECISION P,PWS,TA,RHA,PW,PSAT
C
      TA=T+273.16
      RHA=RH
      P=101.325
      IF (RHA.GT.1.0) RHA=RHA/100.0
C
C     *** CALCULATE SATURATION VAPOR PRESSURE
C
      PWS=PSAT(TA)
C
C     *** CALCULATE VAPOR PRESSURE AT T
C
      PW=RHA*PWS
C
C     *** CALCULATE ABSOLUTE HUMIDITY
C
      WAIR=0.62198*PW/(P-PW)
      RETURN
      END
C
C
      FUNCTION RHAIR (T,W)
C
C **********************************************************************
C ** RHAIR -- RETURNS RELATIVE HUMIDITY OF AIR GIVEN DRY BULB TEMP.   **
C **          AND ABSOLUTE HUMIDITY. -- LARRY SCHULTZ                 **
C **********************************************************************
C
      DOUBLE PRECISION P,PWS,TA,PW,WA,PSAT
C
```

```
      TA=T+273.16
      WA=W
      P=101.325
C
C     *** CALCULATE SATURATION VAPOR PRESSURE
C
      PWS=PSAT(TA)
C
C     *** CALCULATE VAPOR PRESSURE AT T
C
      PW=P*WA/(0.62198+WA)
C
C     *** CALCULATE RELATIVE HUMIDITY
C
      RHAIR=PW/PWS*100.0
      RETURN
      END
C
C
      FUNCTION PSAT (T)
C
C *********************************************************************
C ** PSAT -- RETURNS SATURATION VAPOR PRESSURE OF AIR GIVEN ABSOLUTE **
C **        DRY BULB TEMPERATURE. -- LARRY SCHULTZ                   **
C *********************************************************************
C
      DOUBLE PRECISION T,PSAT,A,B,C,D,E,F,G,AA,BB,CC
C
      DATA A,B,C,D/-7511.52D0,89.63121D0,0.023998970D0,-1.1654551D-5/
      DATA E,F,G/-1.2810336D-8,2.0998405D-11,-12.150799D0/
      DATA AA,BB,CC/24.2779D0,-6238.64D0,-.344438D0/
C
      IF (T.GE.273.16)
     & PSAT=DEXP(A/T+B+C*T+D*T*T+E*T**3+F*T**4+G*DLOG(T))
      IF (T.LT.273.16) PSAT=DEXP(AA+BB/T+CC*DLOG(T))
      RETURN
C
C
      END
      SUBROUTINE ZERO (J,YD,X,Y,A,DEL,K,N,M)
C
C *********************************************************************
C ** ZERO -- NUMERICAL SEARCH ROUTINE FOR SOLUTION OF UNKNOWN FXN    **
C **        PROGRAMMED BY T. L. THOMPSON         LAST UPDATE 7/76    **
C *********************************************************************
C
      DIMENSION A(4), IJ(4,3)
      DATA IJ/1,2,3,4,4,3,2,1,3,4,1,2/
      J1=1
      IF (N.LE.0) M=1
 1    JP=J
      J=IJ(J,J1)
      IF (J.LE.2.AND.JP.LE.2) GO TO 2
      IF (J.GE.3.AND.JP.GE.3) GO TO 2
```

```
      Z=A(1)
      A(1)=A(3)
      A(3)=Z
      Z=A(2)
      A(2)=A(4)
      A(4)=Z
2     IF (J1.EQ.3) GO TO 7
      IF (J.LE.2) GO TO 3
      X=-X
      A(1)=-A(1)
      A(3)=-A(3)
3     IF (J.EQ.1.OR.J.EQ.4) GO TO 4
      YD=-YD
      Y=-Y
      A(2)=-A(2)
      A(4)=-A(4)
4     J1=1
      CALL TYPE1 (J1,YD,X,Y,A,DEL,K,N,M)
      IF (M.EQ.2.AND.J.GE.3) X=A(1)/2.5
      IF (M.EQ.3.AND.J.GE.3) X=A(1)*4.0
      IF (M.EQ.4.AND.J.GE.3) X=A(1)/100.
      IF (J.LE.2) GO TO 5
      X=-X
      A(1)=-A(1)
      A(3)=-A(3)
5     IF (J.EQ.1.OR.J.EQ.4) GO TO 6
      YD=-YD
      Y=-Y
      A(2)=-A(2)
      A(4)=-A(4)
6     IF (K.EQ.2) RETURN
      IF (J1.NE.1) GO TO 1
7     IF (N.LT.15) RETURN
      K=2
      WRITE (6,8) YD,X,Y,A
      RETURN
C
8     FORMAT (19H DOES NOT CONVERGE ,7F10.5)
      END
C
C
      SUBROUTINE TYPE1 (J,YD,X,Y,A,DEL,K,N,M)
      DIMENSION A(4)
      XL=A(1)
      YL=A(2)
      XU=A(3)
      YU=A(4)
      K=1
      IF (ABS(Y-YD)-ABS(DEL)) 1,1,2
1     K=2
      M=1
      GO TO 7
2     N=N+1
      GO TO (3,4,8,12,5,5), M
```

```
3      XL=X
       X=2.5*X
       YL=Y
       M=2
       GO TO 7
4      YU=Y
       XU=X
5      IF (YL-YU) 6,9,9
6      J=2
       N=N-1
       M=6
7      A(1)=XL
       A(2)=YL
       A(3)=XU
       A(4)=YU
       RETURN
8      YL=Y
       XL=X
9      IF (YL-YD) 10,13,13
10     X=XL/100.
       M=3
       XU=XL
       YU=YL
       GO TO 15
11     K=2
       M=1
       GO TO 7
12     YU=Y
       XU=X
13     IF (YD-YU) 14,16,16
14     XL=XU
       YL=YU
       X=XU*4.
       M=4
15     IF (N-6) 7,7,11
16     IF (M-5) 17,18,18
17     W=(YL-YD)/(YL-YU)*(XU-XL)+XL
       X=(XL+W)/2.
       M=5
       GO TO 7
18     Y4=YL-(YL-YU)*(X-XL)/(XU-XL)
       IF (Y4-Y) 19,20,20
19     J=3
       M=6
       IF (Y.GT.YD.AND.Y.LT.YL) XL=X
       IF (Y.GT.YD.AND.Y.LT.YL) YL=Y
       IF (Y.LT.YD.AND.Y.GT.YL) XU=X
       IF (Y.LT.YD.AND.Y.GT.YL) YU=Y
       X=XL+(YL-YD)*(XU-XL)/(YL-YU)
       GO TO 7
20     IF (Y-YD) 24,21,21
21     IF (YL.NE.Y) GO TO 22
       S=XU
       GO TO 23
```

```
22    S=(X-XL)*(YL-YD)/(YL-Y)+XL
23    W=((Y-YD)/(Y-YU))*(XU-X)+X
      IF (S.GT.XU) S=XU
      XL=X
      YL=Y
      X=(S+W)/2.
      GO TO 7
24    W=((X-XL)*(YL-YD))/(YL-Y)+XL
      IF (YU.NE.Y) GO TO 25
      S=XU
      GO TO 26
25    S=((YD-YU)*(X-XU))/(Y-YU)+XU
26    IF (XL-S) 28,28,27
27    S=XL
28    XU=X
      YU=Y
      X=(S+W)/2.
      GO TO 7
C
      END
```

VITA 2

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Master of Science

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