**專論**

# 熱力學模式應用於玉米貯存之研究

# A Study of Thermodynamic Model for Corn in Storage

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## 摘要

本研究應用不可逆熱力學原理推導的質傳與熱傳模式預測堆積玉米在貯存中的含水率與溫度變化，堆積玉米的水分擴散係數利用五種不同的混合模式以玉米粒與空氣中水蒸氣的擴散係數計算，傳遞水分的相態以五種不同程度的相態轉換係數估計試驗量所得含水率與溫度分佈將用以選擇最佳的混合模式與相態轉換係數組合，幾何平均模式爲最佳的模式用以計算堆積玉米的物性，低相態轉換係數表示水分的流動應爲液態，此與水分擴散係數估計的假設不合，此誤差主要來自水分的流失估計過速與呼吸熱被忽略不計，比較試驗與估計結果，高估的水分擴散係數須相伴一低値的相態轉換係數，反之低水分擴散係數應有高相態轉換係數。

## ABSTRACT

The heat and mass transfer equations based on the principle of irreversible thermodynamic processes were applied to simulating the storage process of corn. The bulk moisture diffusivity was determined by the combination of the moisture diffusivities of corn kernels and a mixture of air and vapor. Five mixing models were used to calculate the bulk moisture diffusivities respectively. The phase conversion factor was tested in five levels.

The experiment was primarily on measuring temperature and moisture distributions for corn in storage. The experimental data were used to select the suitable mxing model and phase conversion factor. The geometrical mean model was identified to explain and determine the bulk physical properties of corn. Most of moisture flow seemed to be in liquid state; however, it contradicted the assumption which estimated the moisture diffusivity. The exaggerated moisture flow and neglected respiration heat might lead this conclusion wrong. Comparing the experimental and predicted results from the various mixing models and phase conversion factors, it was drawn that a high bulk moisture diffusivity accompanied a low phase conversion factor and a low diffusivity was combined with a high value of factor.

## Introduction

There are two main approaches for mathematical simulation of heat and mass tansfer in stored grain. One approach is based on practical experimental results, while the second is derived from the theory of transport phenomena. In both cases, it is necessary to predict both the temperature distribution and the moisture distribution in the bulk grain.

Accurately predicting the mositure distribution in stored grain has been a difficult problem. One solution to this problem is based on the close relationship between the grain and the surrounding air. There are simultaneous respondent changes in the properties of the air when changes occur in the properties of the grain. Therefore, the properties of the grain can be predicted using the measured properties of the air. Most of the practical models of heat and mass transfer in stored grain are based on this approach of predicting the moisture distribution. These practical models are limited to applications in which the flow rate and other properties of air can be determined. In other cases, the theoretical approach must be used.

The theory of transport phenomena for a moist body was developed much earlier than the practical model. However, it has not been applied widely for actual cases of storage of agricultural products because it is difficult to accurately determine the physical coefficients related to heat and mass transfer. Modern scientific techniques and instruments for measuring the transfer properties have been improved significantly in recent years, thus making mathematical simulation based on the theory of transport phenomena more feasible than before. The early theoretical models based on simple independent heat and mass transfer for a porous hygroscopic body can only be applied to a few actual cases where the coupled effects of heat transfer and mass transfer can be neglected. In 1961, Luikov experimentally verified the coupled heat and mass transfer of capillary porous bodies using Onsager's (1931) reciprocal principle for irreversible thermodynamic processes. Since Luikov's investigation, mathematical simulation based on the theory of transport phenomena has become a powerful tool in the solution of drying problems.

The main objective of this study was to develop a mathematical model based on Luikov's theory to simulate the storage performance of a bulk of corn. A second objective was to choose a suitable mixing model, which determined the properties of the bulk corn by mixing the physical properties of air and corn kernels.

## Literature Review

### Mechanisms of Heat and Mass Transfer

Grain can gain or lose both moisture and heat during storage. Understanding the mechanisms of moisture and heat transfer will further help people optimize the quality of grain during the storage period.

The basic mechanisms for heat transfer are:

1. conductive heat flow within the interior of the body;
2. convective heat flow on the surface of the body; and
3. radiative heat flow on the surface of the body.

The effect of heat radiation can be neglected when the experiment is executed under controlled conditions. The free convective heat transfer of air is included to determine the boundary condition of heat transfer in this study.

Van Arsdel (1980) emphasized two major modes of moisture migration inside a moist porous body: one is molecular diffusion of vapor moisture and the other is capillary flow of liquid moisture. Marshall and Friedman (1950) identified five distinct mechanisms for mositure movement:

1. liquid movement by capillary force;
2. diffusion of moisture caused by a difference in concentration;
3. pressure gradients and shrinkage;
4. gravity; and
5. a vaporization and condensation sequence.

Goring (1985) added three more mechanisms for moisture removal:

1. surface diffusion in liquid layers absorbed at solid interfaces;
2. water vapor diffusion in air-filled pores, caused by a difference in partial pressure; and
3. water vapor flow under differences in

total pressure.

Onsager (1931) developed the principle of reciprocal relations in coupled irreversible thermodynamic processes. The principle is that when two or more irreversible transport processes, such as heat conduction and mass diffusion, take place simultaneously in a thermodynamic system, the processes might interfere with each other. According to Onsager's theory, the molecular transfer of heat and mass are related to each other and can be described by a system of linear equations:

$$J_m = L_{mm} F_m + L_{mT} F_T \tag{1}$$

and

$$J_q = L_{Tm} F_m + L_{TT} F_T \tag{2}$$

### Luikov's Coupled Heat and Mass Trasfer Equations

Lukiov (1966) experimentally investigated the Soret effect, which is thermal mass diffusivity, and the Dufour effect, which is diffusional thermal conduction, occurring in a drying process of hygroscopic materials.

Due to the Soret effect and Dufour effect, the simple heat and mass transfer laws can not fully simulate a storage process. Therefore, coupled heat and mass transfer equations systems are more widely accepted. Norden and David (1967) derived coupled differential equations of heat and mass transfer for a hygroscopic textile-wood. The equations include a simplified mass diffusion equation without the Soret effect and a heat transfer equation with the Dufour effect. They also indicated that the thermal mass diffusion in a moist textile body was important only for high temperature drying. Whitney and Porterfield (1973) used equations similar to Norden and David's to describe the drying process for corn meal. Using Whitney and Porterfield's equations, Young (1969) defined a modified Lewis number to evaluate the effect of temperature gradients on moisture transfer in the drying process. Fortes and Okos (1981) also applied the theory of coupled heat and mass transfer to simulation of drying for corn kernels.

Luikov (1961) was the first one to apply the principle of non-equilibrium thermodynamics to drying of a hygroscopic capillary-porous solid. Luikov derived the simultaneous coupled heat and mass transfer equations for hygroscopic capillary solids, based on Onsager's principle, the law of conservation, Fourier's law of heat diffusion and Fick's law of mass diffusion. The equations are

$$\frac{\partial M}{\partial t} = D_m \nabla^2 M + D_m \delta \nabla^2 T \tag{3}$$

and

$$\frac{\partial T}{\partial t} = \frac{\varepsilon h D_m \delta}{Cp} \nabla^2 M + \left(\alpha + \frac{\varepsilon h D_m \delta}{C_p}\right) \nabla^2 T \tag{4}$$

Because few of the coefficients of basic physical phenomenological transport equations and coupled mass and heat tranfer equations for grain drying and storage have been determined, Brooker et al. (1974) stated that the applicability of Luikov's coupled equations was limited to most grain drying cases. Husain et al. (1970) presented an analytical method, developed from non-equilibrium thermodynamics, to evaluate the thermodynamic parameters for coupled heat and mass transfer equations, which included the thermal gradient coefficients and isothermal mass capacities of rough rice, shelled corn and potato. These parameters were highly sensitive to moisture content and temperature. Husain et al. also proposed a mathematical model of coupled heat and mass transfer for a porous moist body, derived from Luikov's equations. They emphasized that it was very difficult to draw any general conclusion as to the behavior of these thermodynamic parameters for biological materials.

Experiments conducted by Eckert and Faghri (1980) expressed the transport properties of a porous body as functions of moisture content, temperature, and the body's structure. They concluded that a detailed study of the transport process occurring within an unsaturated porous body was complicated even for a regularly shaped solid matrix, and was almost impossible for the irregular void configurations in general for most porous media. Therefore, the normal approach in the analysis is to consider the media involved as a continuum.

### Mixing Properties of Heat and Mass Diffusion for Granular Materials

The transport physical properties of a kernel of corn or a bed of corn have been studied by many researchers. Kazarian and Hall (1965) measured the thermal properties of wheat and corn; Brooker et al. (1974) summarized specific heats, specific weights and thermal diffusivities of grains and vegetables; Vemuganti and Pfost (1980) experimentally determined the specific heat and test weights of 20 grains. Henderson and Pabis (1960) evaluated the moisture diffusivity for a kernel of corn and suggested that diffusivity is a function of the absolute temperature only. Chu and Hustrulid (1968) studied and obtained the mass diffusivity of a kernel of corn as a function of moisture content and temperature. Husain et al. (1970) conducted experiments to determine the thermal gradient coefficient and specific mass capacity of a kernel of corn.

Because the mechanisms of moisture movement in bulk grain are unclear, it is very difficult to develop a rational theory to predict the effective properties of granular materials found in conjuction with various fluids. But some formulae derived to describe the thermal conductivity of fractional volumes of component phases in granular materials can be used to compute the mass diffusivity because Fick's equation for moisture diffusion obeys the same mathematical laws that Fourier used to derive the equation for conductive heat transfer.

Most porous hygroscopic granular materials have more than two phases. Because the evaluation of the combined thermal properties of a mixture including more than two phases is very complicated, the simplified case considers a porous material in two phases: one is a solid component, and the other is a single phase fluid that occupies the pore space. The following five models have been developed for this simplified case:

1. Parallel Model (Woodside and Messmer, 1961)
   Solids and fluids within the interior of the system construct two independent paths for the heat fluxes.
2. Series Model (Woodside and Messmer, 1961)
   Solid and fluid, when arranged in series, form a heat flow path; then, heat flux flows through solid and fluid sequentially.
3. Geometric Mean Model (Lichtenecker, 1926)
   The geometric mean model is applied to a random distribution of the phases.
4. Equivalent Resistor Model (Willie and Southwick, 1954)
   Two distinct paths exist for heat fluxes: a continuous path through the major portion of the fluid, and a series path through the solid particles that are bridged by a small portion of the liquid.
5. Modified Maxwell Model (Brailsford and Major, 1964)
   Using Maxwell's result for a random distribution, the average conductivity of solid spheres in a continuous medium is computed.

McGaw (1968) investigated these five mixing models for calculating the conductivities of granular materials and compared his results with experimental data. He found each model could predict the data to a fair degree for a few cases. If a storage bin with grain is assumed to be a system with granular materials then these models can be used to calculate the mixture properties of heat and mass transfer for the storage bin.

## Experimental Procedures

The objective of this research was to describe and constructed and moisture content distributions in the interior of a storage bin. Experimental data was collected to validate Luikov's coupled equations (Equations (3) and (4)).

Three laboratory bins and eight grain columns were designed and constructed, and three experiments were conducted in the processing laboratory. The bins were placed on a stand, 79 cm high, to lessen the interference of the ground. Considering the natural convective heat transfer occurring on the wall of a bin, an interval of 15 cm was maintained between the bins. No moisture flux could flow through the metal wall of the bin. The measuring instruments were arranged close to the bins so that the measured data could represent the actual state of the experimental environment. The temperature and relative humidity of the surrounding air were recorded and calculated with a hygro-thermograph and a psychrometer.

### Moisture Content Determination

Five sets of moisture measurements were made: at start, after 4, 8, and 11 days and a termination (after 15 days) for the first and second experiments, and at start, after 2, 4, and 6 days and at termination (after 7 days) in the third test. Two sample columns at different locations were used in third test. Each column was divided into five subsamples: top surface to 5 cm, 5 to 10 cm, 10 to 15 cm, 15 to 20 cm, and 20 cm to bottom (25 cm). Subsamples were weighed, put into an evaporation disk and placed in an oven (Testlib Scientific Equipment Model TG3 .008) at 103 degree C for 72 hours.

### Temperature Measurement

Figure 1 is a schematic identifying the locations of the thermocouples, ASNI Type T, used to measure the temperature distribution within the interior of the bin. The data were collected hourly in the first two tests and at one half-hour interval in the last test. The data were recorded and stored on a magnetic tape using A. D. Data System ML-20A Data Loggers and subsequently placed into the digital computer.

### Temperature and Relative Humidity of The Surrounding Air

The temperature and relative humidity of the surrounding air were recorded with a hygrothermograph. Simultaneously, wet and dry bulb temperatures were measured with a motorized psychrometer. Data at one hour interval from the Charts (No.-207-WB) used in the hygrothermograph were digitized and subsequently printed and stored on a magnetic tape for use in the computer analysis. Data collected using a motorized psychrometer in the first test were also entered into a data file. Through the comparison between the values of these two resources for the first two tests, the accuracy of the hygrothermograph was validated. The hygro-thermograph data were used for all three tests.

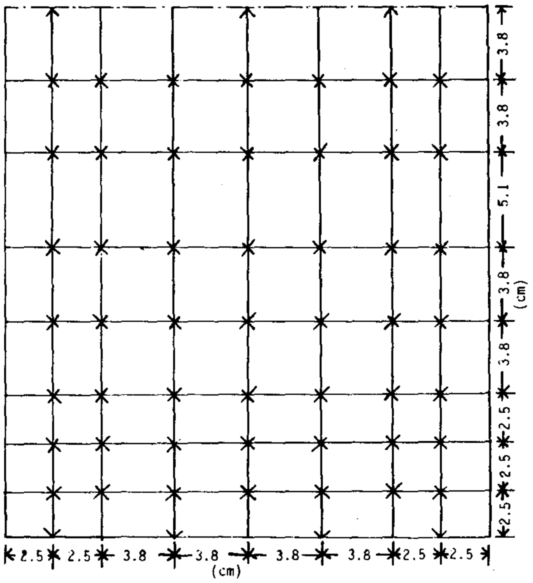

Fig. 1. A schematic illustrating the positions of the thermocouples placed in the storage bin.

## Model Development

A mathematical model based on the theory of coupled heat and mass transfer for a porous hygroscopic body was developed to simulate the temperature and moisture distributions of grain in a bin during the storage period. Luikov's equations (Equations (3) and (4)) were adopted in this study. Most of the variables in the model were chosen from the published data, but some of the needed information was not available.

The model was developed based on the following assumptions:

1. Shrinkage or expansion due to desorption or adsorption are, especially, small and negligible;
2. The gradient in moisture potential field produces moisture diffusion;
3. Diffusion is the only mechanism controlling mass transfer inside solids;
4. The temperature of the water vapor is equal

to the associated temperature of the surrounding solids;

5. Water vapor, air, and their mixture are ideal gases;
6. The moisture content in the vapor phase is negligible in comparison with the moisture content in the liquid phase; and
7. The properties of corn in the storage bin are isotropic.

**Coefficient Variables**

The required variables were defined in the model using the following equations:

1. Bulk density
In 1980, Vemuganti and Pfost reevaluated the bulk density of shelled corn and developed a formula to represent the relationship between the bulk density and moisture content:

$$\rho = 822.07 - 653.87 \frac{M}{1-M} \qquad (5)$$

2. Specific heat
Kazarian and Hall (1965) found the specific heat related to moisture, and presented the equation of specific heat as:

$$C_p = 1.4651 + 3.5623 \frac{M}{1-M} \qquad (6)$$

3. Latent heat
Strohman and Troeger (1967) developed the following equation to describe the latent heat of vaporization of water in moist corn:

$$h = (2502.1 - 0.7358\, T)(1 + a\, e^{bM}) \qquad (7)$$

Thompson (1969) also experimentally established a latent heat model for shelled corn, which has the same form as Strohman's equation, but has different coefficients: a= 5.34 and b= −28.5. Thompson's coefficients were slected in this work.

4. Thermal conductivity
In 1980, Fortes and Okos evaluated Kazarian and Hall's (1965) data and expressed the model of thermal conductivity as a function of moisture content and temperature:

$$\begin{aligned} \mathrm{Ln}(K) = {} & -1.1738 - 3.696\, M + 0.0475\, T \\ & + 0.0843\, M^2 - 0.0001499\, T^2 \\ & + 0.0006272\, M\, T \qquad (8) \end{aligned}$$

5. Thermal gradient coefficient
The thermal gradient coefficient is related to the Soret effect and can be determined experimentally, but the method is somewhat tedious and requires sophisticated instruments. A linear relationship exists between the coefficient and the temperature. Husain (1970) investigated the coefficient for a kernel of corn using the analytical method. Data from Husain's study is suitable for moisture contents of 4% to 20% (w.b.) and temperatures of 30 to 60 degrees C. If the method of linear extrapolation is applied to derive the thermal gradient coefficient, the equation is

$$\begin{aligned} \delta = {} & 0.0001\,(1.37625 + 2.56649\, M + 0.56685 \\ & (30-T) - 1.78632\, M^2) \qquad (9) \end{aligned}$$

6. Diffusivity of air and vapor
Since air and vapor occupy the common porous region of a storage bin, the mass diffusivity in the porous region can be treated as the molecular diffusivity of a binary gas. The molecular diffusivity of an ideal binary gas can be determined by Sherwood's (1936) model Sherwood recommended the following equation at pressures below 20 atm:

$$D_{ab} = \frac{0.0018583\, T^{3/2}}{P\,(A^\circ)^2\, C_i} \left( \frac{1}{M\rho_1} + \frac{1}{M\rho_2} \right)^{1/2} \qquad (10)$$

7. Diffusivity of a kernel of shelled corn
Chu and Hustrulid (1968) evaluated the diffusivity of a corn kernel as

$$D_m = 0.0001(1.5134\, e^{(0.00045(T+273) - 0.05485)M - \frac{2514}{T+273}}) \qquad (11)$$

8. Porosity of a bulk of corn

Using an air-comparison pychrometer, Chung and Converse (1971) measured and calculated the porosity as a function of bulk density only

$$f = 1.01 - 0.000780359\,\rho \qquad (12)$$

9. Phase conversion factor
   The phase conversion factor is defined as the ratio of the amount of moisture flow in the vapor phase to the net amount of moisture flux. The phase conversion factor is an indication of the phase of moisture in the diffusive moisture flow. The domain of the factor is from zero to one. When the factor is zero, the total mass of moisture is transferred in the liquid phase. If the factor is equal to one, the mass is only in the vapor state. Since the mechanisms of moisture movement are uncertain, it is hard to determine a proper phase conversion factor in this research. Five values (0.0, 0.25, 0.5, 0.75 and 1.00) were chosen to determine the theoretical result which best compared with the experimental data.

### Boundary Conditions

Space boundary conditions reflect the law of interaction between a body surface and the surrounding medium. This interaction implies the processes of energy and mass transfer. The required boundary conditions for the system were derived from the law of conservation, the law of convective heat and mass transfer, Fourier's heat diffusion law and Fick's mass diffusion law.

The boundary condition for heat transfer is the boundary subjected to the convective heat flux with the environmental air and the conductive heat flux with the interior elements. The boundary condition for mass transfer is equal to the equilibrium moisture content.

## Model Verification

The mathematical model described the application of the theory of transport phenomenon to a storage process of corn. The data of a bed of shelled corn collected during the third test was used to validate the applicability of the model.

### Temperature Distribution

Figure 2 shows the predicted temperatures at wall distances of 8 cm using a geometric mean mixing model with a phase conversion factor of zero, and ambient air temperature is plotted as a reference. Although the ambient air temperature is unstable during the whole process, the figure strongly reveals the existence of a positive relationship between the grain and air temperatures. By viewing the temperature distribution curves, the experimental period can be divided into 3 stages: 0-80 hours, 80-125 hours, and 125-170 hours. In the first and third periods, the change of temperature is influenced largely by the moisture transfer. In the first period, the corn temperature is always lower than the ambient air temperature, no matter how low the air temperature is. Even with the rapid decrease in air temperature between 15-20 hours, it is still higher than the corn temperature; thus, the temperature of corn should continue to increase. However, the experimental results have a negative relationship to the change in ambient air temperature, which conflicts with the second law of thermodynamics. One possible reason for this phenomenon is that corn is always cooler than the surrounding air, because of the process of

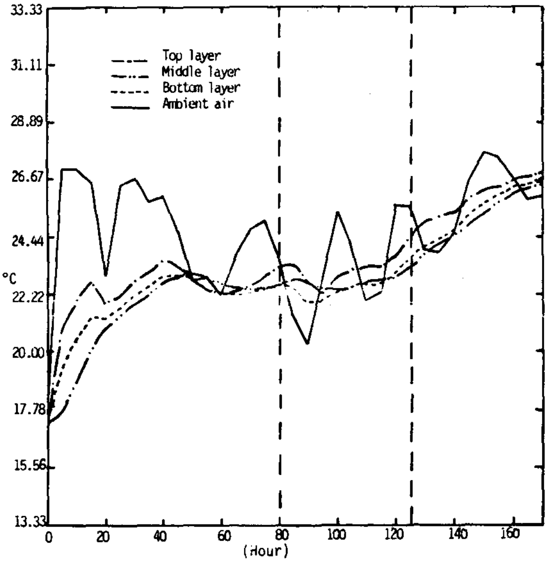

Fig. 2. Ambient and predicted temperatures from use of the geometric mean model with a phase conversion factor of zero for a wall distance of 8 cm in Test 3.

desorption which consumes heat to evaporate liquid moisture. In the third period, corn gets extra heat which is released from the process of absorption. This extra heat raises the corn temperature, even if the ambient air temperature has already been lower than the corn temperature. The second stage of the curve can be explained using the second law of thermodynamics and Fourier's law.

By observing the temperature distributions of three layers, the top layer and bottom layer are more sensitive to the changes of ambient air temperature. The temperature of the middle layer is lower than the temperatures of the top and bottom layers in the heating process, and higher than in the cooling process. But the temperature of the middle layer could be between the temperatures of the top and bottom layers in a transition period from absorption to desorption or from desorption to absorption.

**Moisture Distribution**

The moisture content measurements for experiment 3 are presented in Table 1. Figure 3 illustrates the predicted moisture distributions from a geometric mean model with a phase conversion factor of zero at wall distances of 8 cm. The figure indicates that the direction of moisture migration in corn is toward the equilibrium moisture content. The curves in Figures 3 can be divided into at least four distinct periods:

1. Starting point to 20 hours

   The internal moisture is almost uniform throughout the bin. The amount of external moisture flow is negligible, and internal moisture migration does not occur in this stage. As corn was moved into the room, the initial vapor pressure was close to the air vapor pressure; thus, the gradient of potential field of moisture migration did not exist. During this time period, a potential field was being created for later internal moisture migration. Because the initial temperature was far below the surrounding air temperature, the heat could be transported from the ambient air into the bin via convective heat

Table 1. Moisture contents in five layers at wall distances of 8 and 20 cm for Test 3.

| Time (hr) | M.C. (top) | M.C. (n.t.) | M.C. (mid) | M.C. (n.b.) | M.C. (bot) |
|---|---|---|---|---|---|
| R=8 | | | | | |
| 0 | 12.450 | 12.450 | 12.450 | 12.450 | 12.450 |
| 48 | 10.850 | 11.210 | 11.760 | 11.340 | 11.100 |
| 96 | 10.310 | 10.530 | 10.730 | 10.460 | 10.420 |
| 144 | 11.370 | 10.820 | 10.740 | 10.830 | 10.740 |
| 170 | 11.260 | 11.340 | 11.110 | 11.230 | 11.350 |
| R=20 | | | | | |
| 0 | 12.450 | 12.450 | 12.450 | 12.450 | 12.450 |
| 48 | 10.910 | 11.320 | 12.010 | 11.510 | 11.270 |
| 96 | 10.370 | 10.690 | 10.910 | 10.820 | 10.670 |
| 144 | 11.150 | 10.910 | 10.860 | 10.900 | 11.103 |
| 170 | 11.150 | 11.310 | 11.160 | 11.370 | 11.350 |

top : layer at the top surface
n.t. : layer next to the top layer
mid : layer at the middle
n.b. : layer next to the bottom layer
bot. : layer at the bottom surface
R : the interval from the wall

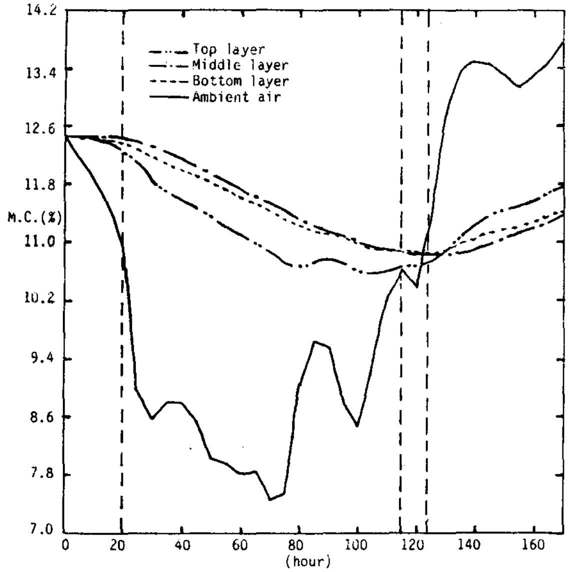

Fig. 3. Equilibrium moisture content and predicted moisture contents for the grometric mean model with a phase conversion factor of zero for a wall distance of 8 cm during Test 3.

transfer. This heat was spent to build a potential field for moisture migration by vaporizing the internal liquid moisture. Before the potential field had been constructed, the internal moisture flux was negligible.

2. 20 to 115 hours

   Vapor pressure is the chief driving force for moisture diffusion in the porous portion of the bin and the internal moisture gradient is the major motivation for the moisture migration in the solid portion of the bin. The internal moisture migration became important. Corn lost moisture into the surrounding air. This period ended when the corn moisture was equal or close to the equilibrium relative humidity of the surrounding air.

3. 115 to 125 hours

   Although the moisture content was almost equal to the equilibrium relative humidity of ambient air during this period, this did not mean that internal moisture flux did not occur during this period. An observation of the moisture curve indicated that the slope of the curve was not equal to zero in this period. In other words, the moisture changes inside the corn could not be neglected.

   The gradient of vapor pressure, as a result of the temperature gradient, was one of the driving forces for moisture migration. The moisture transport theory emphasized that the driving forces of moisture movement were both the moisture gradient and temperature gradient. This moisture transfer phenomena could not be simulated just using the simple moisture diffusion theory; hence, the theory of coupled heat and mass transfer was used.

4. 125 hours to termination

   Due to rain, the equilibrium relative humidity of the environmental air increased to break the equilibrium state. Firstly, corn absorbed moisture from the ambient air; then, moisture condensed from vapor to liquid and released the latent heat to increase the temperature of the whole system. Figures 2 and 3 showed that the temperature rised with the increase of the moisture.

By observing the relationships among the top, middle and bottom layers, one may conclude that the moisture content of the middle layer is higher than the moisture levels of the other layers in desorption, and lower than the other layers during the absorption period. But if the moisture content of middle layer is between the other layers, the process is in a transition period which is from absorption to desorption or from desorption to absorption.

**Parameter Comparison**

Since the heat and mass transfer model was used to describe the storage behavior in a bulk of corn, the bulk properties were needed. Through reviewing the publications, all physical properties except the moisture diffusivity and phase conversion factor are available. Although the bulk moisture diffusivity has not been determined, a parametric value can be estimated using the mixing models based on the moisture diffusivity of a kernel of corn, the molecular vapor diffusivity of an air and water vapor mixture, and the porosity in a bulk of corn. The phase conversion factor can also be determined by a parameter study.

### Moisture Diffusivity

The second objective was to find an appropriate mixing model to estimate the properties of a bulk corn, based on the properties of corn kernels and the air-vapor mixture. Because the mixing models were developed for computing the heat diffusivity of solids only, the moisture diffusivity is assumed to be the main mechanism controlls the interior moisture migration. A high moisture diffusivity allows internal moisture flow to occur within the bin easily and quickly, but the internal moisture gradient is lowered at the same time. A small internal moisture gradient can reduce the rate of internal moisture flow. In most cases, the favorable effect of increasing moisture diffusion due to the high moisture diffusivity always exceeds the negative influence of a reduced moisture flow rate caused by the low internal moisture gradient. Conversely, the low moisture diffusivity generates a small internal moisture flow, but it amplifies the internal moisture gradient which can accelerate the rate of moisture migration inside the bin.

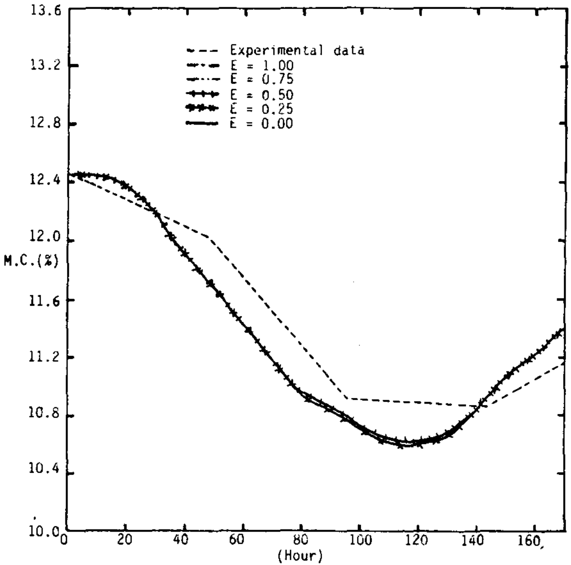

Fig. 4. Experimental and predicted moisture contents in the middle layer at a wall distance of 20 cm using the parallel model and five phase conversion factors for Test 3.

1. Parallel model

   In the theory of parallel models, two paths for moisture movement are formed inside the bin: one is through air completely, and the other is through corn only. Using the Sherwood's (1936) model, the calculated value of diffusivity of the air-vapor mixture is approximated as 0.032 mxm/hr which is almost one half of the moisture diffusivity for a mixture of air and water vapor and significantly higher than the moisture diffusivity of a kernel of corn. The mixing model yields a high bulk moisture diffusivity. High bulk moisture diffusivity means that most moisture fluxes flow through the air path. Because the state of moisture occupying the porous regions of the bin is vapor, the value of the phase conversion factor should be close or equal to one, but Figure 4 reveals that the moisture distributions are independent of the phase conversion factors. The high moisture diffusivity reduces the resistance for internal moisture removal. Uniform moisture distribution is a result of the high bulk moisture diffusivity. Therefore, the predicted moisture contents in the surface layers are usually higher, and the internal predicted results are lower than the experimental values in a desorption process. For an adsroption process, a reverse transport phenomenon exists when the predicted data are compared with the experimental results. Figure 5 explains that most of the predicted temperatures are lower in desorption and higher in adsorption when compared to the actual data. This may have been caused by either underestimating the convective heat transfer coefficient, or improperly neglecting conductive heat flow on the interface between the wall of the bin and the surrounding air.

2. Series model

   A series model has a relatively low calculated value of 0.000065 mxm/hr for the moisture diffusivity of the system, which is ten times the moisture diffusivity of corn and one-thousandth of the molecular diffusivity of an air and vapor mixture. By the mechanism of moisture convection, the surface corn releases its moisture to the surrounding air, and a portion of the moisture loss in the surface corn should be supplied

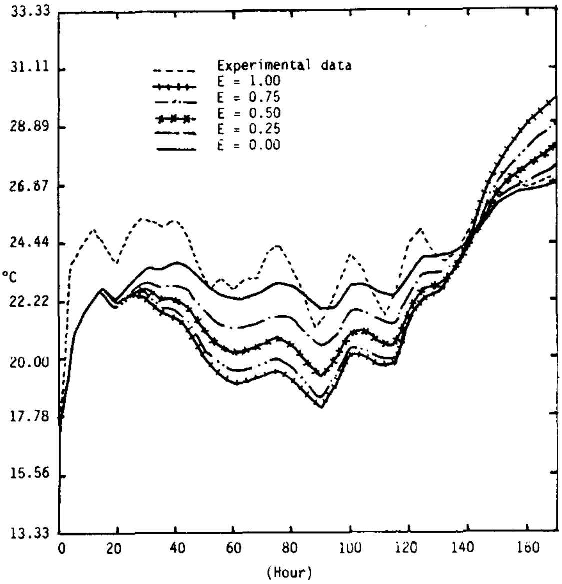

Fig. 5. Experimental and predicted temperatures in the top layer at a wall distance of 20 cm using the parallel model and five phase conversion factors for Test 3.

from the interior corn. A low bulk moisture diffusivity increases the internal resistance for moisture movement. From Figure 6, it is suggested that the rates of moisture migration on the surface elements are higher for the series model than for the other models because of the shortage of the internal moisture flow. The internal moisture content for the series model is stable regardless of what happens at the surface. The predicted moisture contents in the surface elements are higher in an absorption and lower in a desorption when compared to the actual data. The moisture of the interior layer is always much higher than the experimental results. Figure 7 shows that the predicted temperature distribution is rather uniform because the thermal diffusivity is almost a hundred times the bulk moisture diffusivity. The temperature changes in the surface elements are more fluctuant than the changes within the interior layers of the bin, partially because the surface moisture flux is much larger than the internal moisture flux for the series model.

3. Modified Maxwell model

The moisture diffusivity used for this model is approximately 0.024 mxm/hr which is close to the bulk moisture diffusivity in the parallel model. As a consequence, the transport behavior for a modified Maxwell model is almost identical to that of the parallel model.

4. Equivalent resistor model

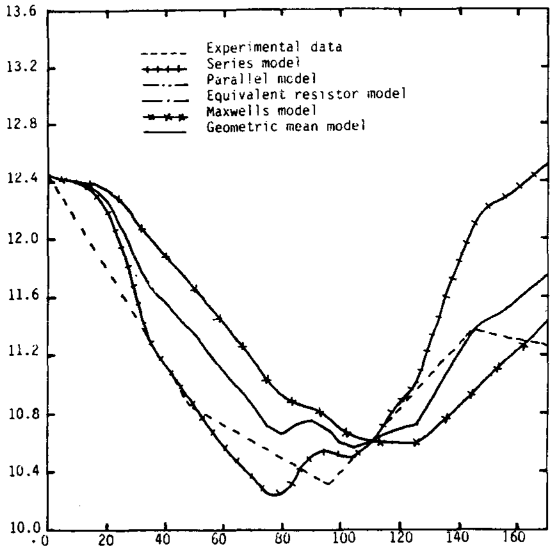

Fig. 6. Experimental and predicted moisture contents in the top layer at a wall distance of 8 cm using five mixing models with a phase conversion factor of 0.50.

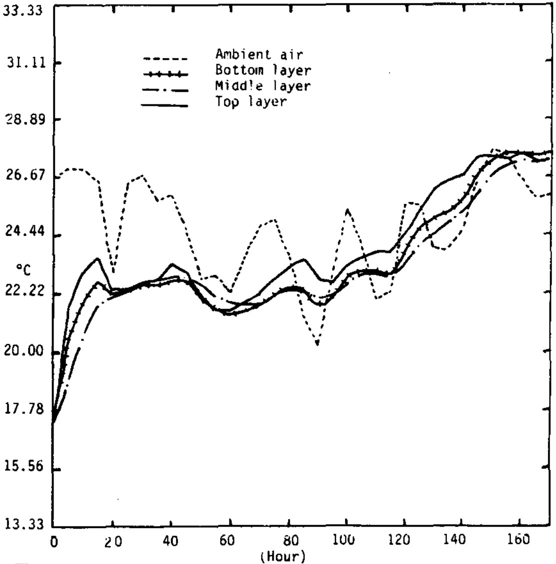

Fig. 7. Ambient and predicted temperatures at a wall distance of 8 cm using the series model with a phase conversion factor of 0.25 for Test 3.

The bulk diffusivity calculated using the equivalent resistor model is 0.029 mxm/hr. In a comparison of the bulk moisture diffusivities of the equivalent resistor model, the parallel model and the modified Maxwell model, one may conclude that the predicted moisture distributions of these three models in Figure 8 are almost identical and the predicted temperature distributions are also similar.

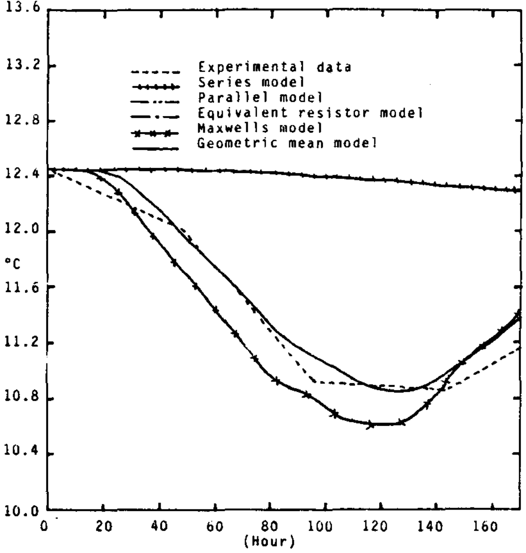

Fig. 8. Experimental and predicted moistue contents in the middle layer at a wall distance of 20 cm using five mixing models with a phase conversion factor of 0.75.

5. Geometric mean model

The bulk moisture diffusivity, calculated from the geometric mean model, is approximately 0.00025 mxm/hr, or fifty times the moisture diffusivity of a kernel of corn and one-hundredth of the molecular diffusivity of a vapor and air mixture. The bulk thermal diffusivity from Eqs. (10) is 0.00067 mxm/hr. A comparison of the bulk moisture diffusivity of the geometric mean model and the bulk thermal diffusivity demonstrated neither to be negligible; in other words, moisture and heat transfer must interact with each other in the storage process. As a consequence, in Figure 9, the predicted moisture curve for the geometric mean model is located between the curves for the series and the parallel models.

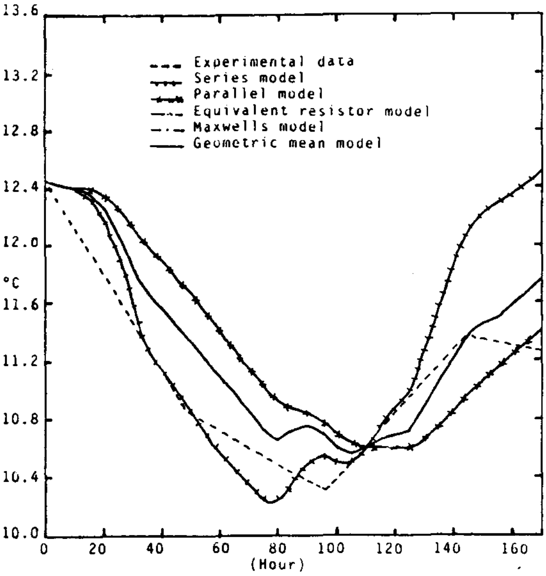

Fig. 9. Experimental and predicted moisture contents in the top layer at a wall distance of 8 cm using five mixing models with a phase conversion factor of 0.25.

**Phase Conversion Factor**

The moisture flow is accompanied by largest amount of heat flow at a value of one, and the amount of the accompanying heat flow is a minimum at zero. The theory of coupld transport phenomenon states that both heat and mass transfer are influenced by the temperature gradient and the moisture gradient. The effect of the temperature gradient on the moisture flow rate is influenced by both the moisture diffusivity and the thermal gradient coefficient. If the thermal gradient coefficient is too small, the moisture diffusivity is the only mechanism to control moisture removal. In 1970, Husain et al. investigated the thermal gradient coefficient of a kernel of corn and found that it was less than 0.0000442. Due to the relatively low gradient coefficient, the moisture curves does not show the noticeable deviations that occur with different phase conversion factors. It is suggested that the phase conversion factor is directly determined by the temperature distribution. Figure 10 shows that the changes of temperature are highly related to the mixing models and phase conversion factors. Comparing the experi-

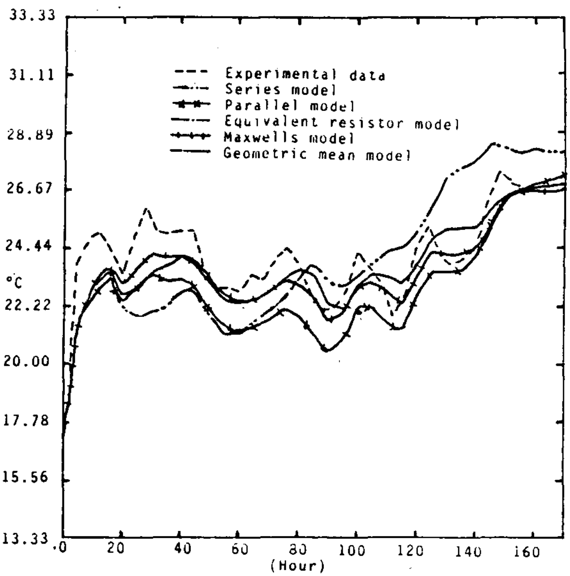

Fig. 10. Experimental and predicted temperatures in the top layer at a wall distance of 8 cm using five mixing models with a phase conversion factor of zero.

mental results and the predicted results from the various mixing models, one conclusion is that a high bulk moisture diffusivity accompanies a low phase conversion factor, and a low moisture diffusivity is combined with a high phase conversion factor. The high bulk moisture diffusivity may underestimate the moisture fluc; then, the accompanying heat flux is exaggerated.

## Results and Discussions

With only five data points available to plot each experimental moisture curve, the unknown moisture contents between any two experimental data points were determined using the linear interpolation scheme. Due to the unstable nature of the experimental environment, the linear interpolation does not seem to be a good approximation. When the predicted data are compared with the experimental results, it is hard to identify the best combination of the mixing models and the phase conversion factors.

The moisture distributions in the surface layers for the higher moisture diffusivity models, which are the parallel model, modified Maxwell model and equivalent resistor model, are matched to the experimental results, but the predicted internal moisture contents of these models were lower in a desorption process and higher in an abosrption process than the experimental data. In other words, the rates of moisture migration in the high moisture diffusivity models are always larger than the actual moisture flux. It should be emphasized that a heat flux accompanies a moisture flux, and even a small moisture flow in the vapor phase can carry a lot of heat. The moistue fluxes of the models with high moisture diffusivity are exaggerated; therefore, the curves of temperature distribution are distorted by the extra gain or loss in heat.

The low moisture diffusivity model predicts better temperature when the model is accompanied with a higher value of the phase conversion factor. However, the predicted interior moisture distribution from this model is poor. The interior moisture flow rate for the series model is close to zero, and that conflicts with the experimental results. Figure 3 indicates that the region of the equilibrium relative humidity of the surrounding air from 7.5% to 13.8% (d.b.), and the moisture content region of corn is from 10.2% to 12.5% (d.b.) in Test 3. Although the amount of moisture flow due to the equilibrium moisture gradient is low, the magnitude of the interior moisture flow still can not be neglected as shown by reviewing the experimental results (Figure 3).

After making a comparison of the mixing models and the phase conversion factors, it is concluded that the change of the moisture distribution is independent of the value of the phase conversion factor, but the change of temperature distribution is very sensitive to the factor. Based on the predicted temperature distribution, the geometric mean model is better than the others at the low value of the factor, and the series model is the best choice at the high value. Considering both temperature change and moisture change throughout the entire bin at the same time, the model based on the combination of the geometric mean model and the phase conversion factor equal to zero is the best selection.

## Summary and Recommendations

The experiments were undertaken to develop a mathematical model for the heat and mass transfer in a bulk of corn. The emphasis was primarily on measuring temperature and moisture distributions in a corn storage bin. Although the study has been confined to a single class of grain, corn, the method of analysis can be useful for other grains. Predicted and experimental data were interpreted and correlated with the existing theories.

A number of conclusions regarding the effects of moisture and temperature in a bulk of corn during the storage period are supported by these investigations:

1. The geometric mean model, the best of the five models, is identified to explain and determine the bulk physical properties in a bed of corn, based on the physical properties of individual components of air and corn.
2. Most of moisture flow within the interior of the bin seems to be in liquid state, so that the range of the phase conversion factor is from 0.0 to 0.25. This may conflict with the suggestions of other researchers. The moisture flux may be exaggerated is one of the reasons.
3. Many problems may occur when an experiment is conducted to validate a grain model based on the theory of heat and mass transfer, for example
   - A. Inaccurate measurements of the rates of heat flow and moisture migration.
   - B. Inaccurate determinations of the moisture gradients.
   - C. An unstable experimental environment.
   - D. Difficulties in measuring the physical properties, such as the moisture diffusivity, the phase conversion factor and the natural convective moisture transfer coefficient.

### Recommendations

Not all of the above problems are uncontrollable, but it is not easy even to deal with one of them. Although it is very difficult to build a mathematical model to describe and predict a storage process of grain based on the theory of coupled heat and mass transfer exist, there are sufficient reasons to continue the work:

1. The moistue transfer equation for storage in a bed of grain can be simplified as Fick's second law of mass diffusion because of small temperature fluctuation and a negligible temperature gradient coefficient during the storage period.
2. A moisture diffusion equation for a bed of grain can be derived following the same mathematical analogy which was used by Fick to develop the law of heat diffusion. The bulk moisture diffusivity must be determined with experiments.

## Nomenclature

**Letter Symbols**

| | |
|---|---|
| $A^{\circ}$ | Lennard-John's force constant, Angstron |
| $A$ | area normal to the direction of heat or mass flow, mxm |
| $C_i$ | collision integral |
| $C$ | concentration of water vapor, kg/mxmxm |
| $C_p$ | bulk specific heat of corn, k-joule/kg-C |
| $D$ | moisture diffusivity, mxm/hr |
| $D_m$ | molecular diffusivity, mxm/hr |
| $F$ | thermodynamic force |
| $f$ | porosity in a bed of corn, decimal |
| $h$ | latent heat for water vaporization in moist corn, k-joule/kg |
| $J_m$ | moistue flux, kg/hr-mxm |
| $J_q$ | heat flux, k-joule/hr-mxm |
| $K$ | bulk thermal conductivity, k-joule/hr-m-C |
| $L$ | coupled coefficient of Onsager's equation |
| $M$ | moisture content, decimal (d.b.) |
| $M_e$ | equilibrium moisture content, decimal (d.b.) |
| $M\rho$ | molecular weight, gm/mole |
| $P$ | atmospheric pressure, atm |
| RH | relative humidity, decimal |
| $T$ | temperature, C |
| $t$ | time, hr |

**Greek Symbols**

| | |
|---|---|
| $\alpha$ | thermal diffusivity, mxm/hr |
| $\varepsilon$ | phase conversion factor, decimal |
| $\delta$ | thermal gradient factor, 1/c |
| $\rho$ | bulk density, kg/mxmxm |

**Subscript**

| | |
|---|---|
| a | ambient air |
| m | mass |
| q | heat |
| T | temperature |

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