Modeling Aeration and Storage Management Strategies

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Abstract

Numerous experimental studies and modeling approaches have been documented in the literature that investigate stored grain ecosystems However, most numerical models have in the past assumed overly simplistic boundary conditions. Accurately predicting the heat and mass transfer in storage structures is necessary before biological and quality factors can be used to make informed management decisions. In addition to a comprehensive review of the literature, this paper presents data collected in a new pilot bin facility that documents the effects of these boundary conditions including wall and roof temperatures, ambient and headspace conditions, and convection currents on the heat and mass transfer in a stored grain ecosystem.

Introduction

Damage by insects, fungi, self-heating, and sprouting to wheat, oats, rice, corn, popcorn and other grains causes millions of dollars in economic losses to producers, handlers, and processors throughout the world every year Alternative pest control strategies must focus on limiting insect growth and reproduction, and on limiting the development of fungi during storage (Anon., 1995) Grain quality always deteriorates during storage, however it can be limited with proper management techniques

Two important physical parameters that affect grain deterioration are moisture content and temperature These can be controlled using ambient or chilled aeration Numerous additional methods are available to manage stored grain such as insect sampling, cost-benefit analysis of control strategies, crop resistance, biological controls, and improved facility design.

Previous Approaches to Modeling the Stored Grain Ecosystem

Numerous aeration studies have been conducted in the past to investigate engineering and entomological aspects of stored grain management. Arthur and Throne (1994) investigated the effects of pirimiphos-methyl degradation and insect development in aerated and non-aerated bins of corn in southeast Georgia. Lots of 229 kg of corn were infested with adults of the red flour beetle, *Tribolium castaneum* (Herbst); the maize weevil, *Sitophilus zeamais* Motschulsky; and eggs of the Indianmeal moth, *Plodia interpunctella* (Hubner), to determine the effects of aeration on insect control in southeastern Georgia from October 15 to August 4. Pirimiphos-methyl degradation was estimated using the method of Desmarchelier and Bengston (1979) Insects were introduced during storage every two months however, Indianmeal moth did not become established in unaerated or aerated bins, and beetle populations did not increase until the spring. No live insects were detected in treated bins Aeration regime did not significantly increase the rate of degradation of pirimiphos-methyl, but aeration regime and time interaction was significant. Although the bins were small and the temperatures within aerated and unaerated bins were approximately equal to the ambient temperature, aeration further delayed insect population development. Adams et al. (1993) used an elemental heat and mass transfer model to solve for the heat and mass transfer that occurred during storage in a cylindrical bin. Temperature distribution during non-aerated periods were approximated by assuming heat conduction. The model was based on finite-differences and considered effects due to solar radiation, wind, snow, and utilized hourly weather data to estimate the dry matter loss and the development rates of maize weevil. There are a number of related articles in the literature on this subject matter, including: Hellevang (1990), Subramanyam et al (1991), Gardner et al. (1988), Epperly et al. (1987), Noyes et al. (1987), Cuperus et al. (1986), Loschiavo (1985), Ghaly (1984), Elder et al. (1975), Shove (1969), Holman (1966), Kline and Converse (1961), Smith and Brown (1961), Foster and Stahl (1959), and Clayton (1956).

Additionally, numerous investigators have developed mathematical models to describe the heat and mass transfer in stored bulk grain Most models have only considered heat transfer during storage White (1988) solved for the temperature distribution within a flat storage by assuming transient heat conduction in a semi-infinite slab using finite differences The temperature of the top surface was set to the mean monthly temperature, and the temperature in the bottom was empirically estimated using field results. In one

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of the storage structures a heavy insect infestation raised the wheat temperature to over 40℃. Longstaff and Banks (1987) solved for the fluctuation in temperature near the surface of a grain bin in one dimension They determined that convection also played an important role in heat transfer near the surface. If convection was neglected the simulation model had a mean error of − 0.47℃, and when convection was included the mean error was 0.05℃. Yaciuk et al (1975) solved the heat conduction equation along the radial axis of a cylindrical bin using finite differences The outer wall was assumed to have heat transfer occurring due to convection and radiation. An analysis on the effect of various bin wall materials (galvanized steel, plywood, concrete, fiberglass insulation, white paint, and red paint) was conducted. For example, a 20 m diameter galvanized steel bin filled with wheat at an initial temperature of 25℃ took 1,637 days to cool to below 20℃ in Winnipeg, but only 1,299 days if the steel wall was painted white.

Chang et al. (1993) solved the two-dimensional heat conduction equation in cylindrical coordinates that included solar radiation, windspeed, and simulated soil temperature under the bin. Two bins were equipped with aeration, bin-A was manually controlled with temperature limit settings and bin-B used a programmable microprocessor (Digigrain II, Pertech Inc., Timont, MN) using temperature and moisture content of the grain and temperature and humidity of the ambient air as control parameters. Predicted and measured temperatures were in close agreement The standard error of estimate ranged from 0.9 to 1.8℃ over the 32-month storage period. The effects of solar radiation in 6.6m diameter bins filled with wheat to a depth of 3.66m, and measured at a distance of 0.3m from the wall was determined. The average wheat temperature was 3.5℃ warmer along the south wall compared to the north wall. During the summer months, the average temperature of grain 0.3m from the top surface was 9 to 10℃ higher than the average temperature of the grain 0.3m from the floor. The time lag was about two months between the peak wall and bin center temperatures.

Metzger and Muir (1983) solved the two-dimensional heat conduction and forced convection problem. Temperatures, moisture content changes and deterioration in wheat were simulated and experimentally verified for 40-tonne bins. At the bottom, surface heat transfer was modeled for the aeration plenum, and not for a concrete or soil foundation as in Muir et al. (1980). The equilibrium drying model developed by Thompson (1972) was used to simulate periods of forced convection. Their results indicated that at an airflow rate of 0.54 $m^3/m^3/min$ (0.67 cfm/bu) the assumption of equilibrium conditions between the air and the grain may not be applicable. The predicted moisture loss at the floor was 1.6 percentage points less than the experimental data. The model predicted slightly higher moisture contents (0.1 to 0.5 percentage points) in the top of the bin. Allowable safe storage time was calculated using the model developed by Fraser and Muir (1980).

Alagusundaram et al. (1990a) solved the three-dimensional heat conduction equation to simulate the temperature distribution in grain bins using the finite element method. Hourly weather data (solar radiation, wind speed, and ambient air temperature) was used to simulate the temperature distribution within the bin. Linear or quadratic elements were used and thermal material properties for the grain, bin wall, concrete, soil, and air were considered No biological or moisture aspects during storage were considered. Validation of the model was done using temperature data from Muir et al. (1980) for canola and barley stored in two 5.56m diameter bins. Alagusundaram et al (1990b) solved the three-dimensional heat conduction equation using the finite difference method. The model indicated that there was a significant temperature difference between the north and south walls of the bin. Bin heights of 3.0 and 4.0 m were used to investigate the effects of diameter to height ratio on the absolute temperature difference between the north and south wall when rapeseed at an initial temperature of 20℃ was stored in Winnipeg, Canada for one year starting January 1, 1974. If a diameter to height ratio of 1.0 was used with a bin depth of 3.0m the average absolute temperature difference was 8.5℃. However, if the bin depth was 4.0 m it was 10℃. If the diameter to height ratio was 4.0 with a bin depth of 3.0m, the average absolute temperature difference was 2℃. If the bin depth was 4.0 m the difference was 3℃ Chang et al (1994) solved for the temperature and moisture content changes that occurred during aeration and during periods of non-aerated storage. Hourly weather data and airflow rates during periods of aeration were used as model inputs The temperature model from Chang et al. (1993) and data collected during that experiment were used to validate the moisture model. Moisture changes during non-aerated storage were assumed to occur by diffusion only. Periods of aeration were simulated using a modified procedure originally developed by Thompson (1972). Predicted moisture contents were in close agreement with experimental results. The standard error of estimate ranged from 0.11 to 0.54 percentage points

Obaldo et al. (1991) verified a simulation model of moisture content changes during non-aerated storage in 5.49m diameter bins filled with 58.46t of corn. The model was based on Ficks' law of diffusion The experimental tests showed little moisture migration during the summer and early fall season of non-aerated storage when the corn was not rewarmed by aeration.

Khankari et al. (1994) developed a model to solve for the moisture diffusion due to temperature gradients using the control-volume method A unique aspect of their model was the incorporation of the sorption isotherm into the transport equations. Khankari et al. (1995a) extended their model to simulate the effects of natural convection during storage. Based on laboratory experimental studies they concluded that the moisture migration in wheat was governed by diffusion, while the effect of natural convection was more pronounced in corn Also, permeability within the grain bed was a critical factor in determining the extent of moisture migration due to natural convection. Heat transfer in wheat and corn was predominately governed by conduction

Khankari et al. (1995b) applied the model to investigate the moisture migration as affected by permeability, initial temperature of the stored grain, bin size, and bin aspect ratio The bin was modeled assuming symmetry about the centerline, the plenum was assumed to be insulated with respect to temperature and moisture transfer, the wall and headspace were assumed to be at the ambient temperature and insulated with respect to moisture transfer. Average daily dry-bulb temperatures over twenty-nine years for Minneapolis/St. Paul, Minnesota were used. The effects of moisture migration did not become evident until December or January when the gradients of temperatures were at the maximum value. This resulted in most of the moisture migration occurring during the winter. Increasing the permeability resulted in an increase in the natural convection flows, which resulted in faster cooling and an increase in the amount of moisture migration. Cooling grain to a temperature of 0℃ appeared to limit the amount of moisture migration that occurred during the year. Moisture migration occurred in all bin sizes. However regions of high moisture content built up quicker in smaller sized bins In tower silos moisture migration was primarily concentrated near the top surface of the silo

The natural convective heat and mass transfer equations have been solved in two-dimensions for arbitrarily shaped storage structures by Casada and Young (1994a). A two-energy model (fluid and solid) based on the finite difference method was developed to simulate natural convection and diffusion The finite difference solution was performed using a body-fitted coordinate system. This method transformed the irregular shaped geometry to a rectangular grid, which allowed for solution using the finite difference method. By using a two-energy equation model, temperature differences of nearly 0.5℃ occurred between the air and grain particles near the boundary. Natural convection currents contributed significantly to the temperature solution in the upper corners of the porous media. Casada and Young (1994b) applied the model to predict the heat and mass transfer that occurred during the shipment of peanuts in rail cars. An energy and mass balance was performed on the headspace of a sealed rail car. However, the model underpredicted the temperature in the headspace by 2 to 3℃. Short-term moisture migration due to diurnal heating and cooling in the headspace, which resulted in condensation, was the greatest source of moisture migration during transportation of peanuts in rail cars.

Abbouda et al. (1992a) modified Muir et al.'s (1980) finite difference heat transfer model for stored milo, and Abbouda et al. (1992b) added mass transfer to the model. Free convection was incorporated into the diffusion model by assuming an equivalent thermal conductivity coefficient. Heat generation was estimated using the dry matter loss equation for medium rough rice (Sukabdi, 1979). The heat produced by respiration was assumed to be equivalent to the combustion of the lost dry matter. Daily ambient air temperature and relative humidity were collected, and the net radiant heat flow into the bin wall was calculated using the method of Muir et al. (1980) and the modified equation by Metzger and Muir (1983) for the total radiation striking all sides of the cylindrical bin.

Smith and Sokhansanj (1990) showed that natural convection could significantly affect heat transfer in the presence of moisture movement. An approximate analysis was conducted to determine when natural convection would become significant. As a result of their approximate analysis they determined that natural convection was significant when the Rayleigh (Ra) number was greater than 1.4×10^3. Therefore, a primary factor that determined the magnitude of natural convection was the term $(L/R + R/L)^2$. The smallest value occured for a ratio of $L/R = 1$. The finite element method was used to solve the equations governing heat, mass, and momentum transfer. Experimental data from Buretta and Berman (1976) was used to partially verify the numerical simulations. Buretta and Berman used beds of glass beads and water that was heated from the bottom. The sides were insulated and the top was held at a constant temperature until steady-state conditions were reached. Smith and Sokhansanj were able to accurately model Buretta and Berman's data, except at Ra numbers greater than approximately 70. They theorized that it was numerical errors that built up due to the large number of iterations required to reach steady-state. The model was applied to the data collected by Schmidt (1955) that showed mass transfer occurring in 35.24 m^3 (1000 bu) bins of wheat over a 30-month period. A sine function was fitted to the ambient weather data and was used as the temperature boundary condition for the walls and top of the bin. The bottom of the bin was assumed to be insulated. They concluded that the model would have more accurately modeled the heat and mass transfer within the bins if the solar radiation, wind speed, and heat flux from the ground were included Also, they concluded that the natural convection currents in wheat were so small that natural convection could be neglected due to the low permeability of wheat However, the higher permeability of corn, resulted in a higher airflow rate due to natural convection They concluded that methods to reduce the effects of natural convection could include periods of forced aeration or venting at the tops or sides of the bin to alter air currents

Tanaka and Yoshida (1984) developed a two-dimensional simulation model of conduction and natural convection of moisture migration and temperature distribution The heat and moisture balance equations were solved using the alternating direction implicit (ADI) method. The stream function was solved by the successive over-relaxation method Temperature data was collected in a 140-ton soybean bin with a diameter of 3.78m and a height of 25m Daily fluctuations of the ambient temperature were ignored and the wall and headspace temperatures were set equal to the average ambient temperature. The wall was assumed impermeable to moisture and the headspace humidity was set equal to the average ambient humidity It was assumed that the plenum of the bin was insulated with respect to temperature and moisture transport They determined that natural convection caused a moist region in the headspace to develop that would condense on the grain when the air was cooled at night. The introduction of dry air into the headspace was shown to be effective in minimizing water condensation

Nguyen (1987) solved the two-dimensional heat and moisture transfer by natural convection for rectangular storage structures Results were generated for storage structures with and without a headspace. The finite difference equations were solved using the ADI method A combined Fourier analysis – Fast Fourier Transform method was used to solve the elliptic Poisson equation in the case of a rectangular bin. The boundary conditions were handled as: at the solid boundaries the stream function and velocity components were zero, and the temperature was specified or calculated assuming adiabatic conditions.

Beukema et al. (1983) investigated the effects of natural convection in a porous media with natural convection in three dimensions, when moisture transfer was neglected. By including natural convection, cooling was accelerated, produced a lower average temperature and moved the location of the maximum temperature from the center of the container upwards Although, all data was collected in small containers (0.76m × 0.76m × 0.50m) and the walls were held at constant temperatures, they found that compared to conduction only, natural convection produced accelerated cooling of the porous medium

Bloome and Shove (1970) were among the first researchers to investigate forced convection drying with natural-air using a numerical model that assumed equilibrium conditions between the air and grain. Thompson (1972) modified the model and included dry matter loss as a method to estimate the amount of mold growth that occurred during storage Thompson's model divided the grain bed up into a number of layers and solved for the temperature and humidity of the air entering and exiting each layer. The model assumed that true equilibrium existed between the air and grain for the given time interval during drying, that heat and mass transfer between the air and grain was adiabatic, and that no hysteresis existed between the sorption and desorption isotherms relating the equilibrium moisture contents.

Thompson's model consisted of three algebraic equations that were iteratively solved to determine the temperature and humidity of the air entering and exiting each layer of the bin. Assuming equilibrium between the air and the grain a heat balance and an energy balance were derived The third equation needed was an equilibrium relative humidity (ERH) equation. Therefore, there were three equations and three unknowns (temperature, absolute humidity, and moisture content) that were solved using a search technique.

Unfortunately, only few have combined the heat and mass transfer analysis with insect population development and dry matter loss predictions Zink (1998), Adams (1994), and Maier (1992) worked with the Post-Harvest Aeration and Storage Simulation Tool (PHAST), a model that solved the two-dimensional heat conduction equation during non-aerated storage, and simulated a number of drying and storage strategies. PHAST has been experimentally verified for the drying, storage, and conditioning of a number of crops and strategies. Currently a number of drying, storage, and conditioning strategies can be simulated The primary storage strategies simulated are listed in Table Hourly weather data is used, including solar radiation and wind speed, to investigate the effects of various aeration strategies on insect development rates and dry matter loss predictions.

Table 1. Current storage strategies that can be simulated with PHAST

Aeration Strategy	Reference
Fixed temperature and Fixed EMC limits	
Adaptive EMC window	Sentry Technologies (1993)
Seed wet-bulb aeration	Wilson and Desmarchelier (1994)
Aeration below a fixed temperature and relative humidity	
Grain chiller	Maier (1992)

Singh et al. (1993) developed a three-dimensional model of free convective heat and mass transfer in stored grain Fumigant deterioration and dry matter loss were also estimated The non-dimensionalized finite difference equations corresponding to the temperature and concentration fields were written by utilizing the three-point difference scheme, which allows for non-uniform mesh sizes. For an incompressible fluid the momentum equation was rewritten by assuming that the velocity field was solenoid, which allowed for the velocity field to be defined in terms of a vector potential. The liberation of fenitrothion pesticide was also modeled. The equations were then solved using the ADI method. The temperature boundary condition was set to a non-dimensional temperature of 0 everywhere except on the floor, which was assumed to be insulated All boundaries were assumed to be impermeable to moisture and fumigant flow. Thorpe (1995) further refined the heat and mass transfer equations to consider moisture and energy release by mold development

Flinn et al (1992) used the temperature distribution of Metzger and Muir (1983) to estimate the population growth of the rusty grain beetle, *Cryptolestes ferruginues* (Stephens) Field tests were conducted in a 351m^3 (10,000 bu) bin of non-aerated wheat in Cloud County, Kansas The bin was sampled monthly from July to December 1987 for grain temperature, grain moisture content, and insect density. The bin was divided into sixteen compartments and the insect densities estimated by equations from Flinn and Hagstrum (1990) and Hagstrum and Flinn (1990). The model successfully predicted insect development within the bin, except for the last month when the predicted number of *C ferrugineus* decreased even though grain temperatures were favorable for insect growth (31.4 and 27.6℃) During the last two sample dates a parasitoid (*Cephalonomia waterstoni*) was found in the insect traps, however its effect on decreasing the population of *C ferrugineus* was not fully examined

Hagstrum and Flinn (1990) investigated the effects of aeration and fumigation on simulated population growth models of rusty grain beetle, *Cryptolestes ferrugineus* (Stephens); sawtoothed grain beetle, *Oryzaephilus surinamensis* (L); lesser grain borer, *Rhyzopertha dominica* (F); rice weevil, *Sitophilus oryzae* (L.); and the red flour beetle, *Tribolium castaneum* (Herbst). A simple temperature model was developed to simulate the effects of non-aerated storage and aeration Simulations were based on storing wheat under two temperatures, 27 and 32℃, and two initial moisture contents, 10 and 14%. No temperature changes during non-aerated storage were simulated until October 1, when it was assumed that the temperature decreased at a rate of 0.5℃ per week. It was assumed that no moisture changes occurred during storage or aeration. The population growth of the five insects differed depending on the moisture content and temperature of the wheat. Aerating early in the season was effective in limiting populations of *C. ferrugneus* and *O. surinamensis*. *R. dominica* (F) and *S. oryzae* were not as affected by malathion protectant as the other three species Fumigation was effective against all species

Current Approaches to Modeling the Stored Grain Ecosystem

A comprehensive stored grain ecosystem model is composed of a number of sub-models. An overall simulation model needs to incorporate: (1) location-specific weather conditions (dry-bulb temperature, relative humidity, windspeed, snow cover, and solar radiation) for use in choosing aeration strategies and determining their effect on the boundary conditions, (2) a grain aeration sub-model, which will predict grain temperature and moisture content due to forced aeration as a function of airflow rate, temperature, and relative humidity, (3) the effects of ambient conditions on the grain bulk during storage as a result of three-dimensional heat conduction, free heat and mass convection, and moisture transport due to diffusion, (4) estimates of grain deterioration as predicted by dry matter loss equations, (5) insect models based on temperature, moisture content, pesticide effects, and time, and (6) other relevant stored product quality predictions, such as residual pesticide breakdown, fumigation effects, mycotoxin development, and end use quality changes.

Heat and mass transfer during non-aerated storage

There are three main equations that are needed to define heat, mass, and momentum transfer in a storage bin Derivations can be found in a number of references (Thorpe, 1995; Khankari et al., 1995a; Alagasundaram et al., 1990a, 1990b). The equations have been developed by applying elemental energy, mass, and momentum balances within the grain bulk

The temperature distribution can then be calculated due to heat conduction and free convection as (Khankari et al., 1995a):

$$\rho_p c_p \frac{\partial T}{\partial t} + \rho_a c_a u_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left(k \frac{\partial T}{\partial x_j}\right) + \rho_h h_{fg} \frac{\partial W_g}{\partial t} \qquad [1]$$

where

c_a – specific heat of air (J/kg ℃)
c_p – specific heat of grain (J/kg ℃)
h_{fg} – latent heat of vaporization (J/kg)
k – thermal conductivity (W/m ℃)
T – temperature (℃)
W_g – grain moisture content (kg water/kg of dry matter)
ρ_a – density of air (kg/m³)
ρ_p – density of grain (kg/m³)

The first term in equation [1] represents the change in enthalpy within the grain bed over time The second term is the result of heat transfer due to convection. This has to be equal to the heat transfer due to diffusion plus a source term. The source term is a result of water either condensing out of the air onto the grain or evaporating from the grain into the air.

Assuming that the vapor pressure within the air and grain are always at equilibrium (Khankari et al., 1995a):

$$\frac{\partial P_v}{\partial x_j} = \left(\frac{\partial P_v}{\partial W_g}\bigg|_T \frac{\partial W_g}{\partial x_j} \right) + \left(\frac{\partial P_v}{\partial T}\bigg|_{W_g} \frac{\partial T}{\partial x_j} \right) \quad [2]$$

If we let,

$$\sigma = \frac{\partial P_v}{\partial W_g}\bigg|_T \quad \text{and } \omega = \frac{\partial P_v}{\partial W_g}\bigg|_{W_g} \quad [3]$$

The mass balance can be written as (Khankari et al., 1995a):

$$\rho_g \frac{\partial W}{\partial t} + u_j \left(\frac{\sigma}{R_v T_{ab}} \right) \frac{\partial W}{\partial x_j} + u_j \left(\frac{\omega}{R_v T_{ab}} \right) \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j}\left[D_M \frac{\partial W}{\partial x_j} \right] + \frac{\partial}{\partial x_j}\left[D_T \frac{\partial T}{\partial x_j} \right] \quad [4]$$

where $D_M = \sigma D_{eff}$ and $D_T = \omega D_{eff}$.

Using the ERH relationships of various grains, the parameters σ and ω can be determined. If the Henderson ERH equation is used (Khankari et al., 1995a):

$$\frac{P_v}{P_s} = 1 - e^{[-K*(T+C)(100M)^N]} \quad [5]$$

where K, C, and N are parameters specific to various crops, M is the decimal dry basis moisture content and T is temperature in (℃) (Brooker et al., 1992). The saturation vapor pressure (P_s) is found by expressions given in Brooker et al. (1992).

The momentum equation is based on Darcy's law which describes the free convection currents that develop as a result of temperature gradients normal to the force of gravity. The buoyancy driven flows that occur within grain bulks are sufficiently small so that the pressure gradient is proportional to the velocity gradient. Mathematically this maybe expressed as (Thorpe, 1995):

$$\frac{\partial P}{\partial x_j} + \frac{\mu}{K} u + P_a g = 0 \quad [6]$$

where

g – gravity constant (m/s^2)
K – permeability (m^2)
p – pressure (Pa)
u – velocity (m/s)
x_j – Cartesian tensor notation for space coordinate
μ – dynamic viscosity of air (Pa s)

The momentum equation can be solved using Boussinesq's approximation and the definition of stream functions (Thorpe, 1995; Potter and Wiggert, 1991). A stream function, Ψ, can be defined such that the velocity is:

$$u = \frac{\partial \Psi}{\partial y} \quad \text{and } v = -\frac{\partial \Psi}{\partial x} \quad [7]$$

If the velocity definitions in equation [7] are differentiated, than the definition of the stream function can be determined (Thorpe, 1995):

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = -\frac{K_g (\rho_a)_0 \beta}{\mu} \frac{\partial T}{\partial x} \quad [8]$$

An existing two-dimensional transient FE model from Comini et al. (1994) is currently being modified to solve equations [1], [4], and [8]. The original model solved the advection equation associated with general field problems. The model equations are weakly coupled, meaning that there is an interrelation between the temperature, moisture equation, and momentum equation A direct simultaneous solution of the equations is not possible and therefore an iterative solution scheme is used. The general solution scheme is:

1. Read in current hourly weather data,
2. Determine material properties based on current estimates of temperature and moisture content,
3. Update the boundary conditions,
4. Solve the moisture equation using the most recent estimates of the temperature and free convection currents,
5. Solve the temperature distribution based on the most recent values for the moisture content and free convection currents,
6. Solve for the stream function based on the current estimated temperature, and calculate the velocities from the stream functions,
7. Check accuracy, if the desired convergence has not been reached repeat steps 2 through 6, if it has been reached proceed to the next hour.

At least two other previously developed numerical models use a similar iterative approach to successfully handle the coupled equations (Khankari et al., 1995; Thorpe, 1995).

Heat and mass transfer during aerated storage

A number of researchers have investigated the airflow distribution within grain stores as a result of forced aeration (Shedd, 1953; Jayas et al., 1990; Sinicio et al., 1992; Dalpasquale et al., 1994). Jayas et al. (1990) developed a mathematical model of anistropic airflow through stored grain that can be written as:

$$\frac{\partial}{\partial x}\left(K_{xx} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y}\left(K_{yy} \frac{\partial P}{\partial y} \right) = 0 \quad [9]$$

$$K_{xx} = A_x \left[\left(\frac{\partial P}{\partial x} \right)^2 + \left(\frac{\partial P}{\partial y} \right)^2 \right]^{\frac{B-1}{2}} \quad [10]$$

$$K_{yy} = A_y \left[\left(\frac{\partial P}{\partial x} \right)^2 + \left(\frac{\partial P}{\partial y} \right)^2 \right]^{\frac{B-1}{2}} \quad [11]$$

$$B = \frac{B_x + B_y}{2} \quad [12]$$

where P is the static pressure (P_a), x, y are the horizontal and vertical distances (m), and A_x, B_x, A_y, B_y, B are product and direction-dependent constants that are determined by regression of experimental data. Sinicio et al. (1992) solved equation [9] using the finite element method and verified the accuracy of the model using laboratory tests. A total of 47 laboratory experiments were conducted and the model accurately predicted the static pressures except for points close to the grain surface.

Equation [9] can be used to determine the airflow distribution during aeration, and equations [1] and [4] can be used to determine the heat and mass transfer during forced aeration. The effects of conduction heat transfer and mass diffusion during periods of aeration can be estimated. If heat conduction appears to have a limited role during periods of forced aeration, equation [1] can be modified to neglect heat conduction. If mass diffusion plays a limited role during forced aeration, equation [4] can be modified to neglect mass diffusion.

Deterioration due to dry matter loss

Production of carbon dioxide has been a method used for many years by engineers to predict the storability of grains (Stroshine and Yang, 1990; Thompson, 1972; Steele et al., 1969). Saul and Lind (1958) related CO_2 production from storage fungi to DML in corn, and developed the allowable storage time concept (AST). Thompson (1972) incorporated the AST principle into his low temperature drying model and was able to predict grain temperature, MC and DML changes of high-moisture shelled corn under continuous aeration

Dry matter loss is estimated by measuring the amount of carbon dioxide that has been produced by the grain during storage. A general rule of thumb is that when corn experiences a dry matter loss of 0.5% then it will lose one US grade. The objective is then to determine which drying/storage practices will consistently limit dry matter losses to 0.5% or less for most years. Equations have been developed to estimate carbon dioxide production and dry matter loss based on temperature, moisture content, hybrid, and level of mechanical damage for various crops.

Wilcke et al (1998) investigated the effects of changing temperature on the amount of dry matter loss that occurred in shelled corn. They investigated the effects of constant temperature storage at 15, 20, and 25℃, a constant temperature of 15℃ and changed to 25℃ when the dry matter loss reached 0.25%, a constant temperature of 25℃ and changed to 15℃ when the dry matter loss reached 0.25%, and cycling temperatures on a 24 hour cycle, 12 hours at 15℃ and 12 hours at 25℃ It was concluded that the shapes of the dry matter loss vs. storage time curves were similar for predicted and measured values This indicated that current methods for predicting deterioration rates under changing conditions are probably adequate. For instance, corn with a moisture content of approximately 22% and held at a constant temperature of 20℃ had a measured AST of 225 hours, and a predicted AST of 290 hours (based on corn at a moisture content of 22%, 27% mechanical damage, and a temperature of 20℃ based on equations from Steele et al , 1969 and Thompson, 1972). If temperatures were cyclically changed at a period of 12 hours between 15 and 25℃ the measured AST of 22% moisture content corn was 270 hours compared to 280 hours for the predicted AST DML equations have also been developed for other crops such as rough rice (Sukabdi, 1979) and wheat (Fraser and Muir, 1980).

Insect reproduction and development

Insect models have been developed for numerous species of insects on a variety of crops. With these equations that describe insect reproduction and growth, and the simulated temperature and moisture content distribution within the bin, the estimated number of insects per element can be determined.

Estimated populations of insects and dry matter loss throughout the bin can be predicted based on the temperature and moisture content distribution A spatial distribution of the dry matter loss and insect populations can have an impact on which pesticide treatment will be most desirable. If insects are concentrated in the upper portions of the grain mass then a surface treatment may be more desirable instead of a complete fumigation of the bin.

Currently PHAST utilizes equations from Throne (1989) to simulate the response of the maize weevil, *Sitophilus zeamais* to the temperature and moisture content changes during storage. The model bases insect development on average temperature and moisture content for the bin. Flinn and Hagstrum (1998) investigated the effects of temperature gradients on the dispersal of the adult rusty grain beetle (*Cryptolestes ferrugineus*, Stephens). Temperature gradients were created in a 0.56m diameter cylinder filled with 19.9kg of hard red winter wheat to determine the dispersal of the rusty grain beetle to warmer areas of the bin. *C. ferrugineus* moved into the warmest area of the grain mass with temperature gradients of 21 – 20℃, 24 – 20℃, and 42 – 20℃. The beetles were able to locate the warmest area of the wheat even when the temperature gradient was 21 – 20℃. This has implications when insect populations and reproduction rates are modeled.

Weather conditions

Boundary conditions are evaluated after each time step. Hourly weather data (radiation, dry-bulb temperature, wind speed, relative humidity, and snow fall) is available for a number of US locations (Anon , 1993). From this data the heat and mass transfer into the bin can be estimated and the momentum, mass, and heat transfer equations solved. Hourly weather data can often be difficult to obtain for other locations in the world. However, with daily minimum, maximum, and average temperatures and relative humidity the daily fluctuations could be approximated by sinusoidal curves.

Other stored product quality prediction models

Thorpe (1995) included a model of pesticide decay from Desmarchelier and Bengston (1979) Thorpe modified the pseudo first order decay model of from Desmarchelier and Bengston to approximate the concentration of a pesticide during storage:

$$C^{p+1} = C^{p}\exp\left(\frac{-1.386r^{p}h_{1} \times 10^{B(T^{p}-30)}}{t^{*}_{1/2}}\right) \quad [13]$$

where the superscript p implies the previous timestep and $p+1$ is the current integration step, h_t is the integration step size (s), C is the concentration (kg/m^3), r is the decimal relative humidity, T is the temperature (K), B is a pesticide specific coefficient (1/℃), and $t^{*}_{1/2}$ is a pesticide specific coefficient (s).

Banks (1991) developed a model of phosphine release from aluminum phosphide formulations. The model included effects of water activity, temperature, and airflow rate on the decomposition of aluminum phosphide.

One alternative to traditional fumigation in stored grain is modified atmospheres (Anon, 1995) Mann et al (1997) worked with carbon-dioxide fumigation in welded steel hopper bins. The hopper bin was modified to improve its gas tightness, and the effect of CO_2 fumigation of wheat on the rusty grain beetle *Cryptolestes ferrugineus* (Stephens) in cages was investigated They observed that a CO_2 concentration of approximately 40% and wheat temperatures above 20℃ were adequate to get 100% mortality of *C. ferrugineus* after 10 days of exposure. If wheat temperatures were 13℃, a 99.7% mortality occurred after 10 days of exposure.

Alagusundaram et al (1996) developed a finite element model to predict the convective-diffusive transport of CO_2 in wheat filled (1.42m diameter × 1.37m tall) bins. The predicted concentrations adequately matched the experimental data after 12 hours. However, large errors (mean relative percent errors ranged from 30 to 60%) occurred during the initial 12 hours of sampling. It was theorized that the initial errors could have been caused by CO_2 sorption by the wheat at low concentrations, gravity effects, and a lack of information on CO_2 flow characteristics Some conferences have dealt with aspects associated with controlled atmosphere storage (Anon 1983).

Ozone was investigated by Strait (1998) as a possible fumigant of stored corn in 17.8 kg (0.7 bu) test bins Effects of concentration and time of exposure on mortality of adult confused flour beetle, *Tribolium confusum* (du Val), adult red flour beetles, *T. castaneum* (Herbst), adult maize weevils, *Sitophilus zeamais* (Motschulsky), and late instar Indian meal moths, *Plodia interpunctella* (Hubner) at two concentrations were investigated. Exposure to ozone at the low concentration resulted in 100% mortality of the adult confused flour beetle after 12 days, after 9 days for the adult red flour beetle and larval Indian meal moth, and after 4 days for the adult maize weevil. At a higher concentration 100% mortality occurred after 3 days for the adult confused flour beetle, red flour beetle, and maize weevil, and after 6 days for the Indian meal moth Delayed mortality effects in adult confused flour beetles, exposed for 1 day at the high concentration of ozone, exhibited a 63.3% mortality after four weeks Ozone at the concentration investigated was not effective at killing *Aspergillus flavus* conidia on the surface of corn.

A model of aflatoxin formation in stored grain was developed by Pitt (1995). The effects of oxygen and carbon dioxide concentration on the growth and toxigenesis were incorporated into the model, with toxigenesis being more sensitive to decreased oxygen and increased carbon dioxide than mold growth A statistical sensitivity analysis was performed for three of the model parameters that are not well defined; yield of aflatoxin per unit of cell growth, toxin degradation rate, and initial mold-cell mass

Effect of Boundary Conditions

Current numerical models do not accurately model the headspace and plenum conditions during storage. Most numerical models assume overly simplistic boundary conditions Khankari et al. (1995) assumed the plenum to be insulated with respect to temperature and moisture flow. The headspace and wall were assumed to be impermeable to moisture flow, and the temperature boundary condition was set equal to the ambient temperature. Solar radiation and wind effects were ignored, and the ambient temperature was based on averaging normal dry-bulb temperatures over 30 years for Minneapolis/St. Paul. Taking daily averages of the dry-bulb temperature and then averaging 30 years of weather data leads to a sinusoidal temperature change during the year Such a sinusoidal boundary condition essentially becomes fixed due to the slowly changing daily average temperature and practically all of the variation in the weather conditions is lost. Updating boundary conditions more frequently, such as every hour, is important when controlling aeration fans or deciding to implement other pest control strategies to minimize temperature, moisture migration, spoilage, and insect development.

Casada and Young (1994) used realistic boundary conditions in their work on modeling heat and mass transfer in peanuts during transport in rail cars. A heat and mass balance was applied to the headspace of the rail cars to estimate condensation and moisture transfer from the peanut bulk. However, rail cars are essentially sealed in the headspace and no mass transfer from the ambient air into the headspace occurs, which is a realistic assumption.

Thorpe (1995) applied constant boundary conditions in his model. However, he states that modeling of the interaction between the grain bulk and headspace needs to be incorporated. Especially when fumigation is done in the headspace, where turbulent buoyancy driven air currents exist that affect the rate of fumigant liberation and distribution within the grain bulk. Also, the headspace effect on moisture migration has not been investigated. However, the generic problem of heat transfer and buoyancy driven fluid flows between a porous material and a fluid has been investigated in the heat and mass transfer literature extensively.

Modeling of bin boundary conditions

Modeling of bin side-wall

The side-wall temperature is influenced by the ambient temperature, wind speed, and the solar radiation. Muir et al. (1980) developed a procedure for calculating the solar flux on the bin sidewall. The net radiant heat flow, consists of the radiative heat exchange between the ground and the bin, the sky and the bin, the bin and the surroundings, and direct (beam), and diffuse, solar radiation (Muir et al., 1980; Maier, 1992).

Modeling of the headspace

Muir et al. (1980) set the headspace temperature as the ambient temperature plus 5℃. Maier (1992) during experimental chilling tests found that the headspace temperature was actually much greater than the ambient temperature plus 5℃. Maier (1992) used a heat balance for the plenum and headspace in grain bins that included solar radiation and heat transfer from the ambient air that was similar to the method ASHRAE (1981) uses for estimating the attic and basement temperatures of buildings. The steady-state heat flow in the headspace can be expressed as the heat flow from the grain, heat transfer from the roof, and the heat exchange due to infiltration (Maier, 1992).

Modeling of the plenum

Maier (1992) modeled the plenum of a bin similar to the procedure used by ASHRAE (1981) to evaluate the temperature in a crawlspace. The plenum temperature can be expressed as a function of the heat flow from the floor, the perforated bin floor, the perimeter of the bin surrounding the plenum, and the heat exchange due to air infiltration (Maier, 1992).

Effect of bin size

It is believed that the difference in temperature between the north and south side of a bin can be significant. Alagusundaram et al. (1990a) investigated the effects of the north versus south side temperatures during non-aerated storage. Simulated temperature distributions for a 3m deep bin filled with rapeseed in Winnipeg at an initial temperature of 20℃ on January 1, 1974 were determined. Based on different diameter to height ratios the temperature at half the radius and midway between the top and bottoms showed a significant difference. For instance, at a diameter to height ratio of 0.33 the average absolute temperature difference between the north and south location was 15℃. However at a diameter to height ratio of 4.0 the temperature difference between the north and south was 5℃.

The ratio of the bin surface area, which included the circular side-wall and the roof surface area, to the bin volume, which included the grain volume and the volume of the headspace above the pile, maybe a more suitable predictor of the effect of the boundary conditions than the diameter to height ratio (Maier, 1992). Simulated temperatures in corn during non-aerated storage for Lansing, MI from October 1988 to July 1991 in bins with different surface to volume ratios were performed. At a surface to volume ratio of 1:3 (which has a diameter to height ratio of 2:1) showed a small variation in the average bulk temperature between the minimum and maximum temperature during storage. A minimum temperature average bulk temperature of 3℃ occurred early February, 1989 and a maximum temperature of 13℃ occurred early September 1990. If the surface to volume ratio increased to 2:3 (diameter to height ratio of 2:1) the minimum temperature was 2℃ and the maximum temperature was 17℃.

Effect of wall temperature

Thermocouples were attached to the inside wall and roof of food corn storage bins with automatic ambient aeration, automatic chilled aeration, and a non-aerated bin. On going research in these pilot bins at the Post-Harvest Education and Research Center (PHERC) at the Purdue University Agronomy Farm illustrates the temperature difference between the north and south wall and the ambient temperature (Figure 1). A grain chiller was running intermittently to minimize insect activity. The north wall was consistently cooler than the south wall, which was largely due to solar radiation. On July 29 at 2:30 PM the south wall temperature reached a maximum of 46.7℃ and the north wall reached a temperature of 31.8℃, however the ambient air temperature was 29.8℃. During the nighttime hours the north and south wall approach the same temperature. However the walls did not cool to the ambient temperature at night. Over the period the south wall temperature was on average 2.1℃ warmer than the north wall, and 5.7℃ warmer than the ambient temperature. The north wall, which during the summer received some solar radiation, was on average 3.6℃ warmer than the ambient temperature. A silicon pyranometer was used to estimate the amount of solar radiation striking the grain bins. For instance, on July 30 there was essentially no temperature difference between the north and south wall and the amount of solar radiation measured was relatively small due to cloud cover. However, on July 28 there was intermittent cloud cover that resulted in a fluctuating level of solar radiation that produced nearly a 6℃ temperature difference between the north and south wall. On July 29 there was minimal cloud cover and a consistent level of solar radiation was measured, which resulted in a temperature difference of approximately 15℃ difference between the north and south walls.

Figure 2 shows the temperature difference between the north and south wall and ambient temperature in a non-aerated bin. The trends in Figure 1 and Figure 2 are approximately the same. However, the difference between the north versus south wall temperature was even greater. For instance a maximum south wall temperature of 49.6℃ occurred on July 29 at 2:30 PM, while the north wall temperature was 32.7℃ at an ambient temperature of 29.8℃. On average, in the non-aerated bin the south wall temperature was 2.3℃ warmer than the north wall, and 7.0℃ warmer than the ambient temperature. This experimental data proves the significant effects of solar radiation and its influence on the boundary condition along the walls, which must be considered in a realistic ecosystem model.

Effect of headspace conditions

Another important boundary condition when modeling insect and mold development is the headspace temperature and relative humidity. Heat transfer through the roof will dramatically increase the headspace temperature, and decrease the headspace relative humidity. Figure 3 shows the north and south roof temperature and the ambient temperature in a PHERC pilot bin with ambient aeration. A maximum roof temperature of 64.0℃ occurred on August 1 at 12:35 PM, while the ambient temperature was only 30.1℃. This high roof temperature caused the headspace to warm-up to a significantly higher temperature than the ambient temperature.

The effect of solar heating on the roof and the headspace temperatures of a non-aerated PHERC pilot bin and a bin with automatic ambient aeration can be seen in Figure 4. Five thermistors were located approximately at the grain surface and the temperatures were averaged to an estimated average temperature at the top of the bin. The non-aerated bin was consistently warmer (1.7℃) than the bin with ambient aeration, and on average was 2.6℃ warmer than the ambient temperature. The solar heating of the roof changed the relative humidity within the headspace. The relative humidity in the headspace above the grain and the ambient air are shown in Figure 5. On average the ambient relative humidity was 23.4% higher than the headspace relative humidity. This could have an impact on the mass transfer and moisture migration in the top layers of the grain bin.

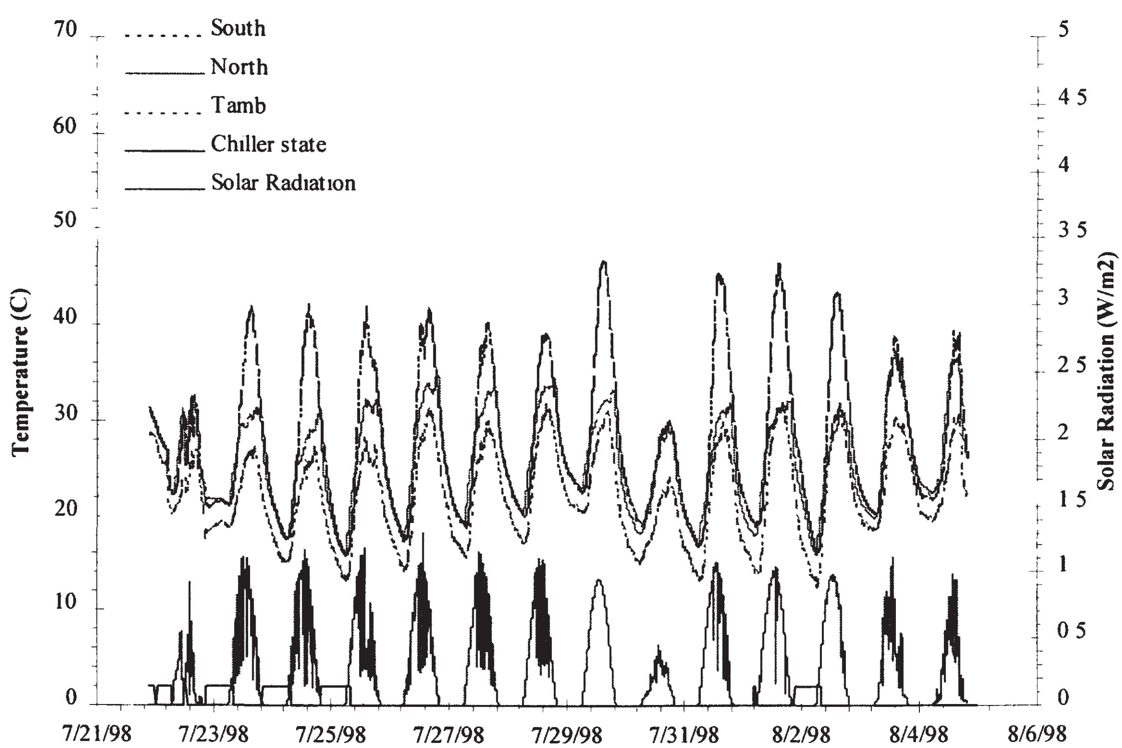

Fig. 1. North versus south wall temperature difference, ambient temperature, chiller state, and solar radiation during summer storage in a PHERC bin with chilled aeration

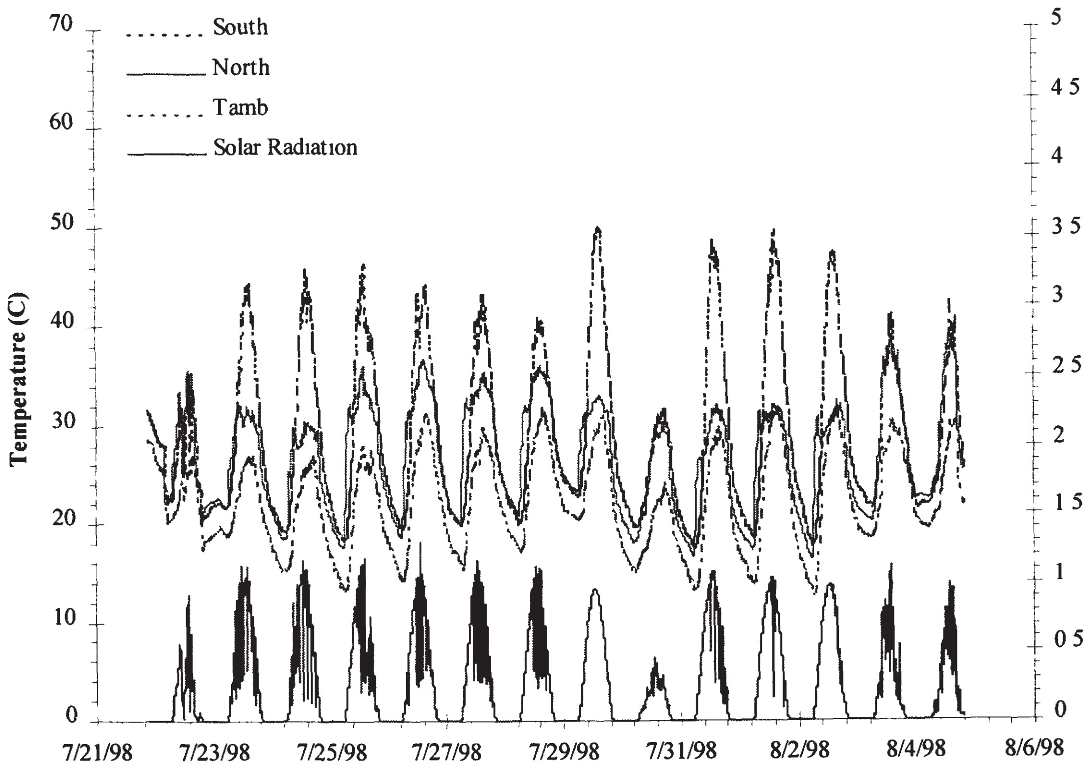

Fig.2. North versus south wall temperature difference, ambient temperature, and solar radiation during summer storage in a non-aerated PHERC bin

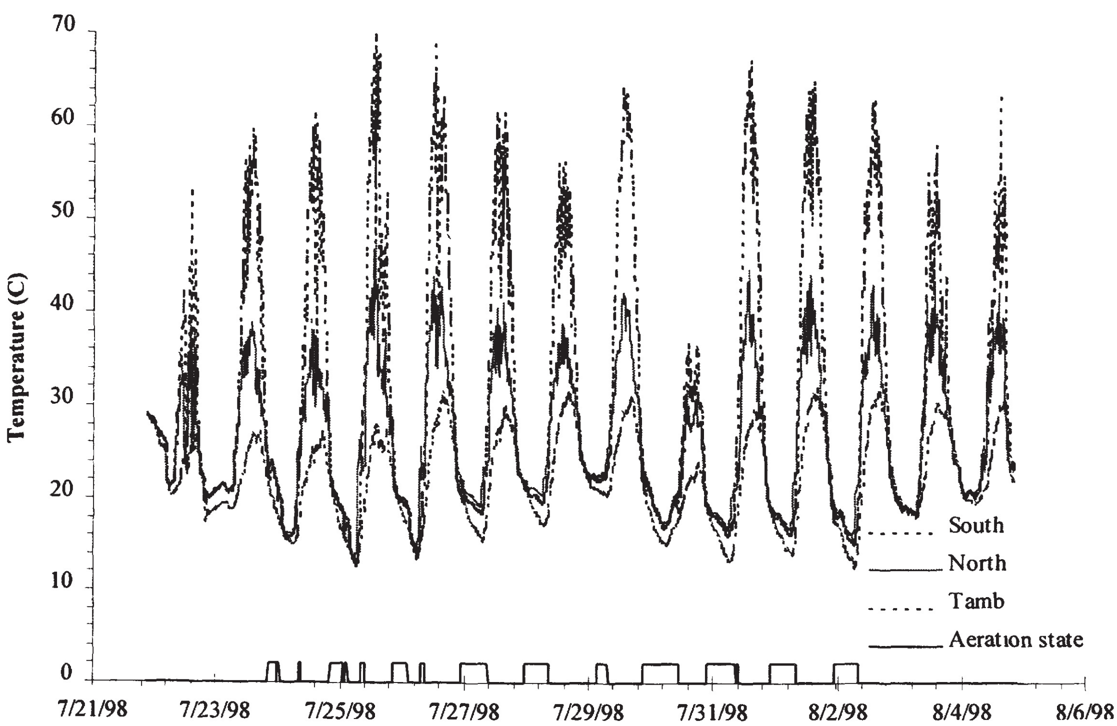

Fig.3. North versus south roof temperature, ambient temperature and fan state in a PHERC bin with automatic ambient aeration control.

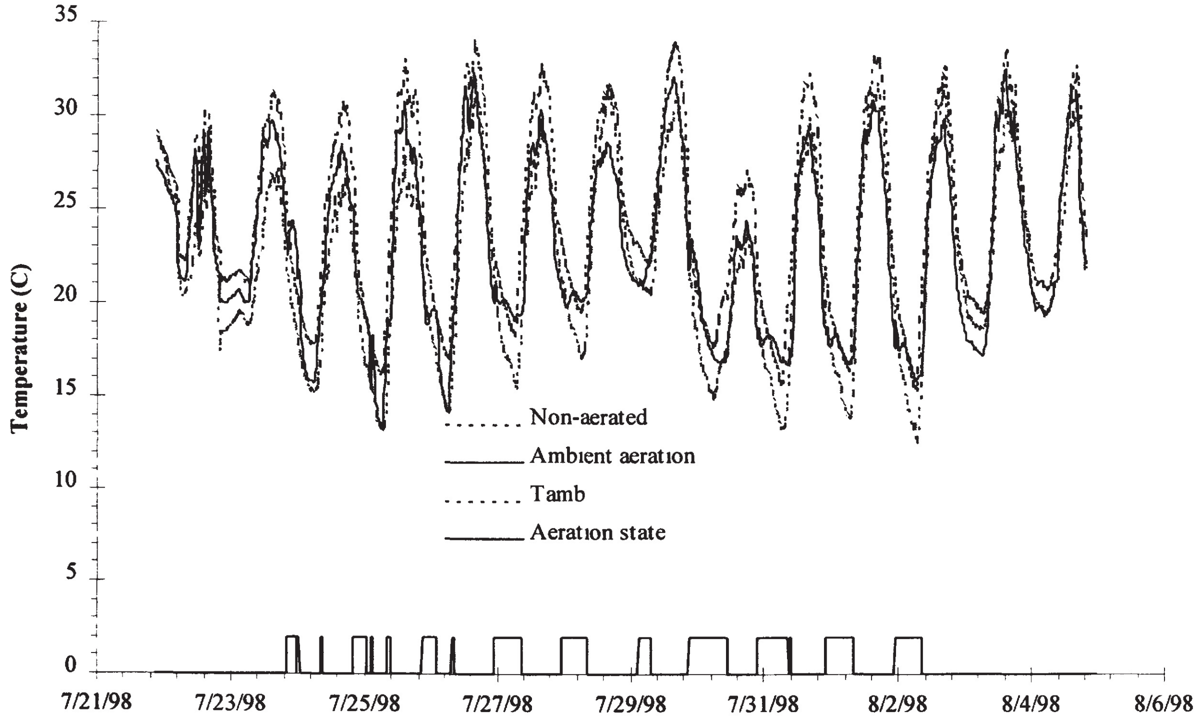

Fig.4. Differences in headspace temperatures of a non-aerated bin and a bin with automatic aeration at the PHERC facility relative to the ambient temperature.

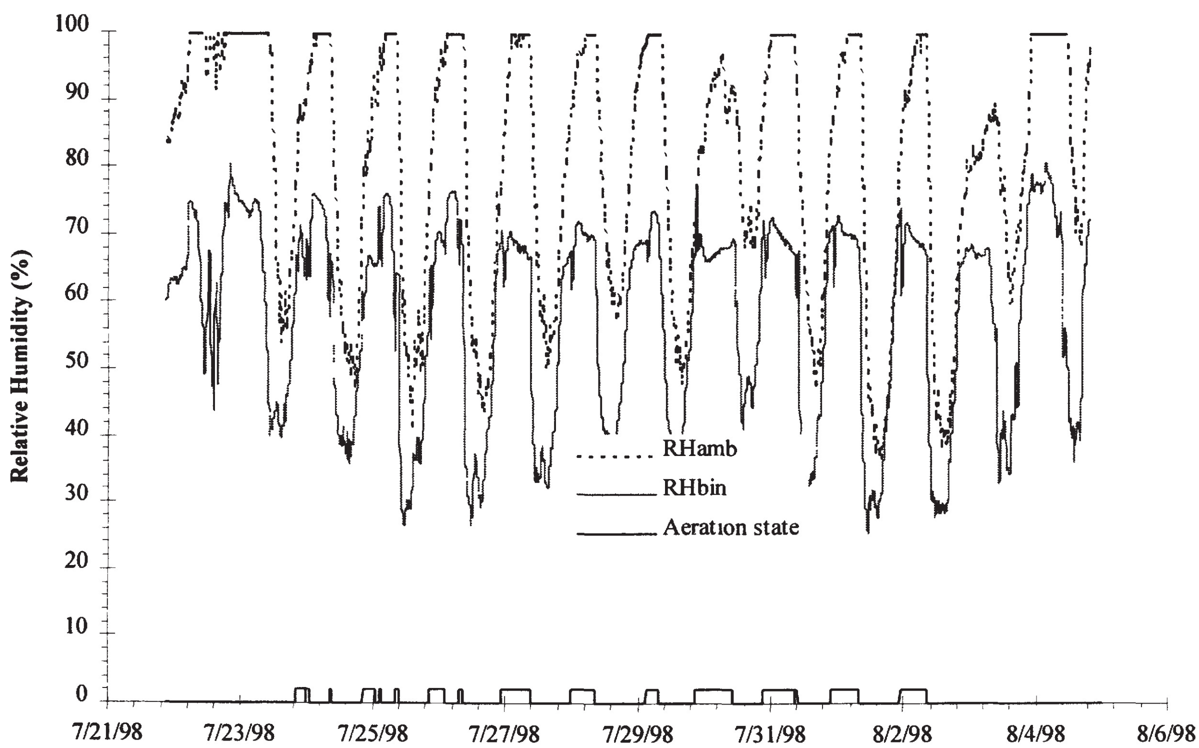

Fig.5. Relative humidity difference in the headspace of a PHERC bin with automatic ambient aeration and the ambient relative humidity.

Possible condensation periods on the underside of the roof are shown in Figure 6 A relative humidity sensor and a thermocouple were mounted in the headspace of a PHERC bin The dew point temperature was calculated to estimate the potential for condensation on the underside of the north roof of a PHERC bin. It can be seen that there were extended periods of time from 3/25/98 to 3/27/98, and 4/8/98 to 4/10/98 where condensation on the underside of the roof was predicted Additionally, during the nighttime hours of 3/19 to 3/21, 3/23 to 3/24, 3/28 to 3/31, and 4/8 periods of condensation were predicted.

Type of weather data

Four simulations were run using Indianapolis, Indiana weather data from 1990 to demonstrate the effect of the type of weather data and solar radiation effects on simulated temperatures using PHAST. Most researchers have used daily average temperature values as inputs to their storage models and many have neglected solar radiation and wind speed Changes during storage of a bin with a diameter of 9 m and filled to a depth of 6 m with corn at an initial temperature of 15℃ and an average moisture content of 15 % w b in Indianapolis, Indiana was investigated Aeration was performed whenever the ambient temperature was less than 15℃, starting on May 1, 1990 and ending on September 1, 1990. Two simulations were run using hourly weather data; one simulation included the effects of solar radiation and windspeed and the other simulation did not. Two additional simulations were run using daily averaged weather data; one simulation included the effects of solar radiation and windspeed and the other simulation did not.

Figure 7 presents the estimated average bin temperature during the year if (a) hourly temperature, solar radiation, and windspeed data was employed, (b) if hourly temperature data was used and solar radiation and windspeed were neglected, (c) if daily averaged temperature, solar radiation, and windspeed values were generated from the hourly data, (d) and if daily averaged temperature data was used and solar radiation and windspeed were neglected During the storage period the average simulated corn temperature was 17.7℃, with a maximum temperature of 22.3℃, if hourly temperature data was used and solar radiation was included However, if solar radiation was neglected and hourly temperature data was used the simulated average corn temperature was 14.9℃ with a maximum of 17.4℃. If the temperature data was converted to daily average temperatures, the average corn temperature was 14.9℃ with a maximum of 17.0℃. If daily average temperatures, solar radiation, and wind speed were included, the average corn temperature was 15.3℃ with a maximum temperature of 17.6℃.

The effect of weather data, timestep, and the influence of solar radiation were even greater when the perimeter temperatures were considered (Figure 8) The perimeter temperatures were defined as the 10 percent of the grain mass along the wall and headspace. If hourly temperature, solar radiation, and wind speed data were included, the simulated perimeter temperature was on average 23.6℃ with a maximum temperature of 33.6℃. However, if hourly temperature data was used and solar radiation and wind effects were neglected the average perimeter corn temperature was 16.6℃ with a maximum of 20.9℃. If daily averaged weather data was used the average corn temperature was 17.3℃ with a maximum of 22.1℃ if solar radiation and windspeed were included The average corn temperature was 16.4℃, with a maximum of 21.0℃ if solar radiation and windspeed was neglected. These temperature differences are important if insect activity or fungal growth needs to be estimated. If dry matter loss is estimated using the four different weather conditions then large differences are predicted (Figure 9) If hourly temperature, solar radiation, and windspeed data were included the average dry matter loss at the end of the storage season for the entire bin based on the Thompson model was 0.238%. However, if daily averaged temperatures were used and solar radiation and windspeed was neglected the dry matter loss was only 0.197%, or 17% smaller.

To minimize temperature gradients within the bin during the summer an automatic aeration controller can be employed. With daily averaged temperatures the amount of runtime available decreased significantly (Figure 10). During the early and late summer the choice of weather data and therefore the timestep made very little difference. However, during the warmest portion of the summer (June 1 to September 1), very little runtime was predicted when daily averaged weather data was used. When hourly weather data was used the fan runtime was nearly 176 hours (or 35%) greater than when daily averaged weather data was used

Effect of convection currents

Simulations were made to predict the temperature changes and free convection currents in two dimensions that occur when a bin is filled with corn at an initial uniform moisture content of 15% and a uniform temperature of 25℃. Material properties for corn were taken from Brooker et al. (1992). The boundary conditions were simplified by assuming that all boundaries were impermeable to airflow. Temperatures in the headspace and plenum were estimated according to Maier (1992) assuming free convection transferred heat from the headspace, plenum, and wall to the grain without moisture exchange.

By late winter the outer portion of the unaerated grain cooled, while the center remained unchanged (Figure 11). According to past theory, natural convection currents develop in a downward fashion along the colder outer wall, and rise in the center of the bin where the grain is warmer.

Figure 11 shows the downward air currents that developed in the grain mass as the outer wall became colder. As air cools it becomes denser, and theoretically sinks due to gravity. At the center of the bin the grain is warmer than the air, and as the air warms it rises. By early summer the temperature distribution within the bin is fairly uniform and cold (Figure 12) The convection currents begin to reverse because the outer wall is now consistently warmer. The air will rise due to buoyancy along the walls, and the air in the center of the bin will sink because of its higher density. By mid-summer the outer portions of the grain have warmed (Figure 13), and the convection currents become fully established. The reversal of the convection currents causes the core of the bin to rewarm faster in the summertime It is believed that if this reversal of the free convection currents was delayed through controlled aeration, then problems associated with moisture migration could be limited. Realistically, however, the plenum and headspace boundaries in a grain storage structure are not impermeable Additionally, warming of the sidewalls and grain mass is not uniform due to solar radiation and shading effects. Thus, the development of convection currents and their pattern of wall versus core effect appear questionable. It would seem more realistic that convection currents are driven by differences between sun exposed versus shaded sides, and that they may dissipate in the plenum and headspace instead of recirculating. Additionally, the effect of air exchanges due to unsealed fans (chimney effect) may be more significant than previously thought

Effect of permeability

Loading and storage practices such as coring bins, using a grain spreader, or pre-cleaning grain before storage influences the air distribution and airflow rates through the bin Loading practices will change the permeability of the grain bulk and therefore the grain will have varying degrees of resistance to airflow depending on the location within the bin and the loading practice. Directly under the point where a bin is loaded, a concentration of fines and broken kernels develops that will create more resistance to air movement. This influences the airflow distribution during periods of aeration and should have an influence on the amount of moisture movement that could possibly occur during storage. Numerous researchers have developed numerical models for airflow distribution (Franca and Haghighi, 1995; Sinicio et al., 1992; Smith, 1982), but in general they have not been applied to investigate the influence of loading and unloading practices on airflow distribution.

A FE model that includes free convection and diffusion would allow for the analysis of a particular bin to predict trouble spots that may result from changes in temperature and moisture content during storage. With a reliable ecosystem model areas that have an increased probability of insect and mold development within a grain mass could be predicted, and the best possible storage management technique recommended to limit potential problems.

Modeling Aeration Practices

Using historic weather data for US locations it has been shown that proper aeration using automatic fan controllers will often be enough to limit insect and mold development (Zink, 1998; Adams, 1994; Wilson and Desmarchelier, 1994; Flinn and Hagstrum, 1990) By keeping the grain sufficiently cool insect and mold growth will be limited However, in some years ambient aeration will not be effective in controlling insect and mold development in all portions of the bin. In these regions and years it is expected that large numbers of insects and mold could develop and alternative techniques need to be applied.

Insect growth is a function of moisture content and seed temperature, and the seed wet-bulb temperature (SWBT) has been shown to be related to the intrinsic rate of increase for a number of stored-product pests (Desmarchelier, 1988). As an alternative to cooling grain based on the dry-bulb temperature, an aeration controller was developed to cool grain according to the wet-bulb temperature (Wilson and Desmarchelier, 1994). It was found that dry seed does not need to be cooled to as low a dry-bulb temperature as wet seed to achieve an acceptable level of insect control. For example, at a SWBT of 14℃ the dry-bulb temperature of wheat is 24℃ at a moisture content of 10% However, if the moisture content is 14% the corresponding dry-bulb temperature is 17℃. Aerating according to the SWBT in warm temperate climates has been shown to be effective. Zink (1998) investigated the feasibility of using aeration based on the SWBT for locations in Kansas and Indiana for popcorn storage. However, the warmer and more humid climate in the Midwestern United States did not lend itself as well to aeration based on the SWBT.

One non-chemical control technique to prevent or limit infestation that can be economically used is grain chilling. Maier et al. (1997) and Mason et al. (1997) investigated the effects of grain chilling on the temperature and pest management within four 121.5 tonne corrugated steel bins of popcorn Two bins used a chiller that was set to operate whenever the popcorn periphery temperature was greater than 20℃, the other two bins were cooled using ambient air The chiller operated at an average temperature of 10.1℃ and a relative humidity of 70%, and kept popcorn temperatures below 17℃ While the control bins with ambient aeration never decreased to below 23℃, and on average were between 6 – 18℃ higher than the chilled bins Probe traps and Indian meal moth pheromone traps were placed in the headspaces of the four bins It was found that chilled aeration significantly lowered pest populations compared to the traditional ambient aeration and fumigation. These experiments were repeated in the PHERC pilot bins during the summer of 1998, and the findings validated in replicated bin experiments using yellow food corn

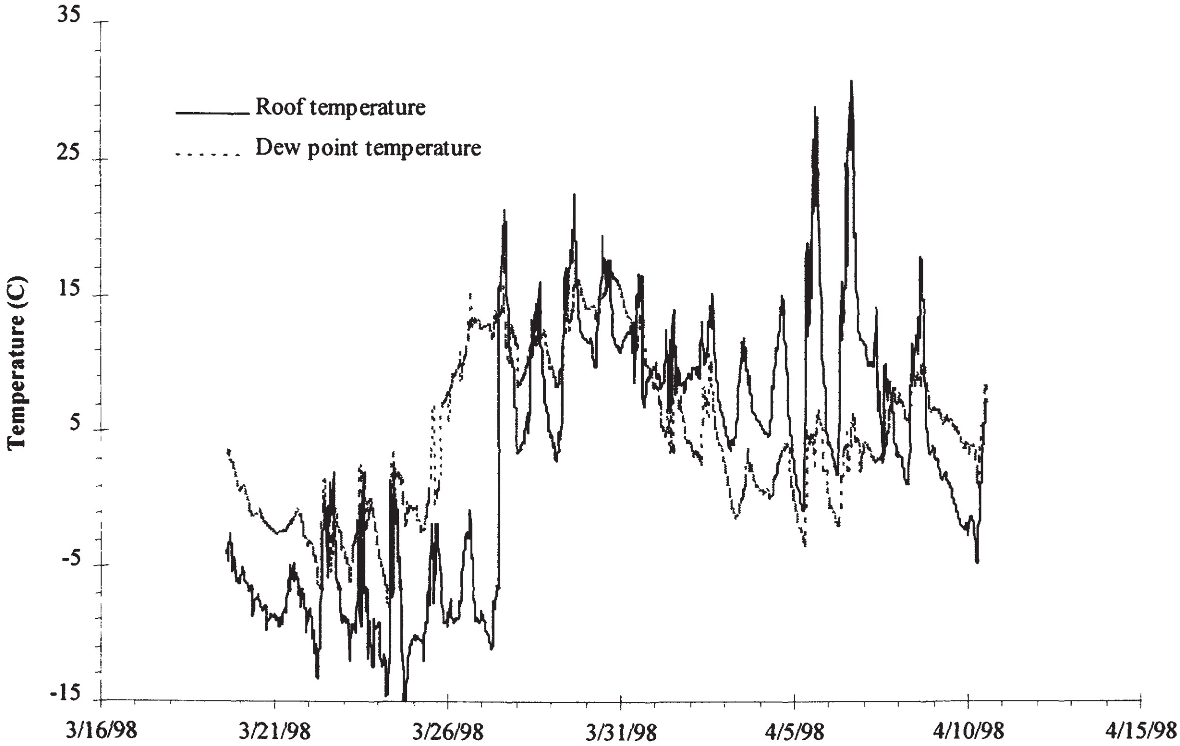

Fig.6. Dew point temperature during winter storage when condensation occurred on the underside of the roof on a PHERC bin

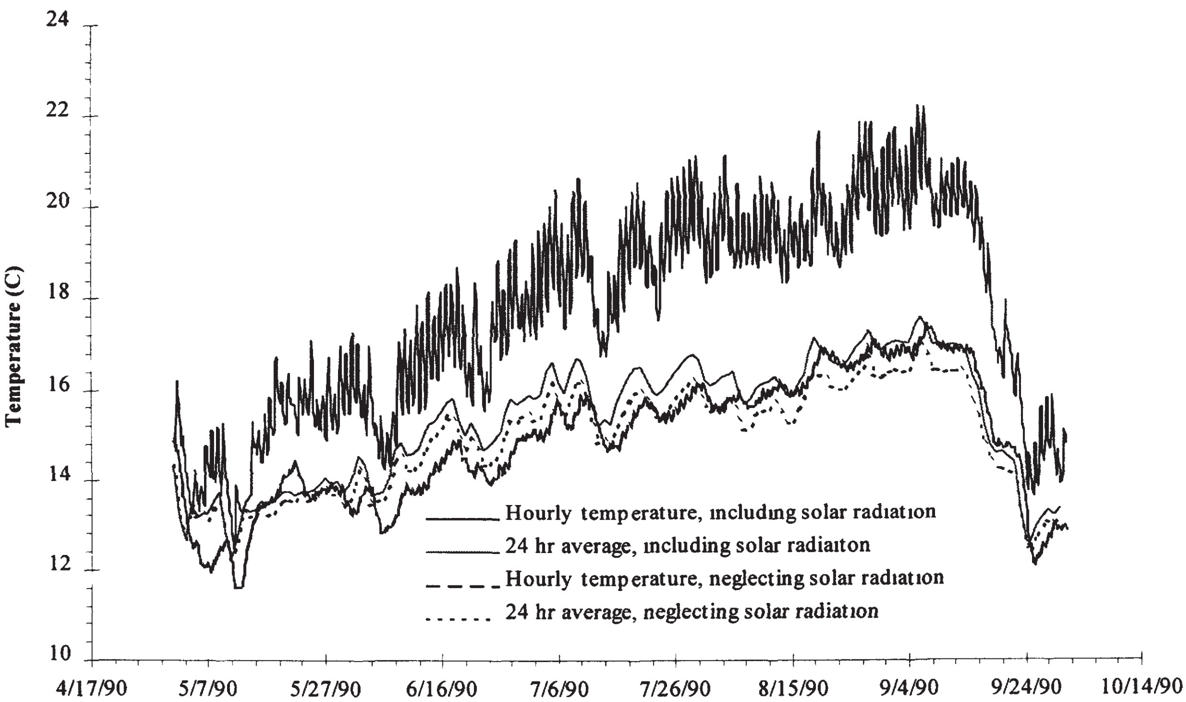

Fig.7. Simulated average bin temperatures if hourly temperature and solar radiation is included, hourly temperature and neglecting solar radiation and average daily temperature and neglecting solar radiation

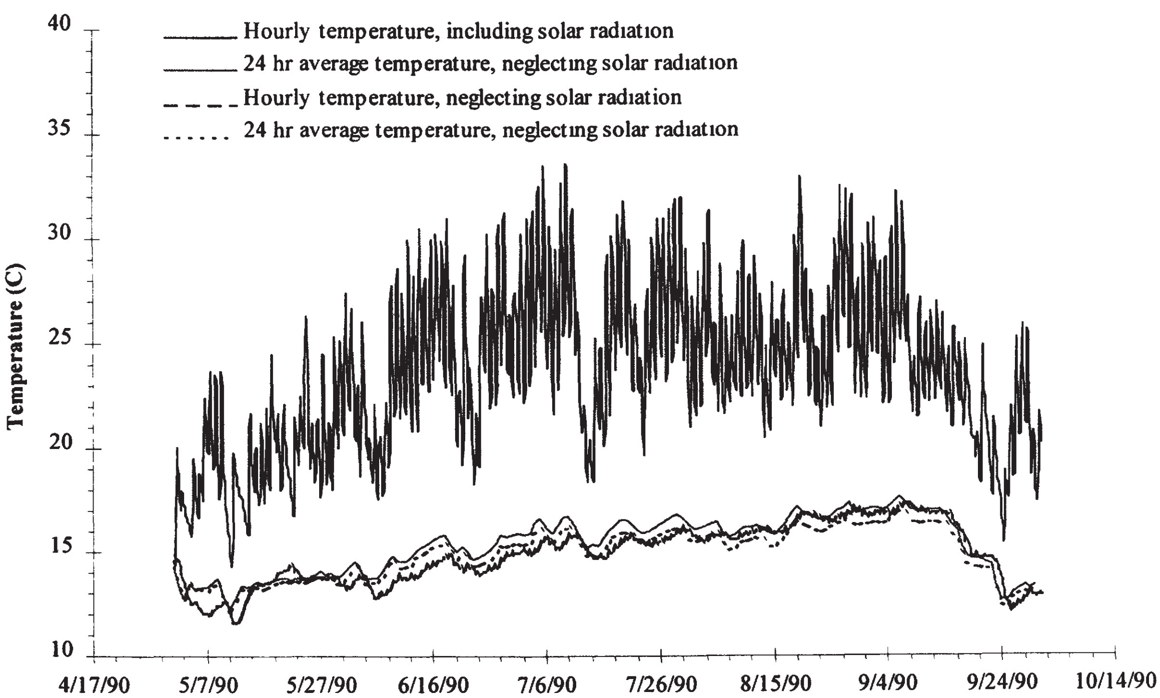

Fig.8. Simulated perimeter temperatures if hourly temperature and solar radiation is included, hourly temperature and neglecting solar radiation and average daily temperature and neglecting solar radiation.

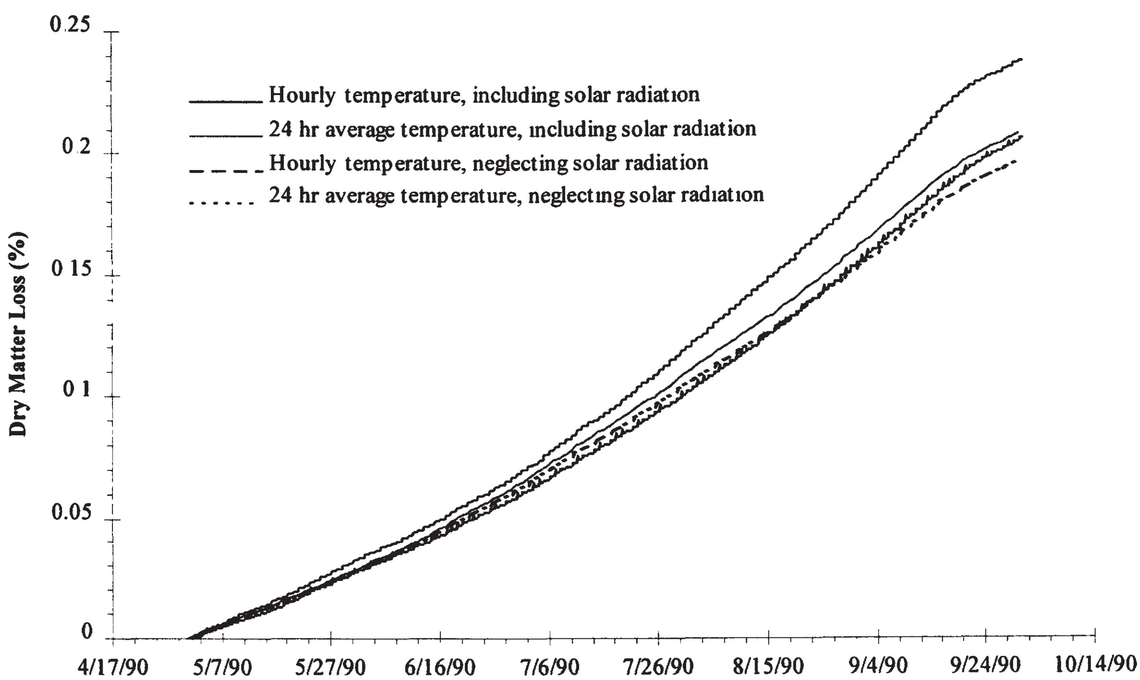

Fig.9. Simulated average bin dry matter loss if hourly temperature and solar radiation was included, hourly temperature data and neglecting solar radiation, and average daily temperatures and neglecting solar radiation.

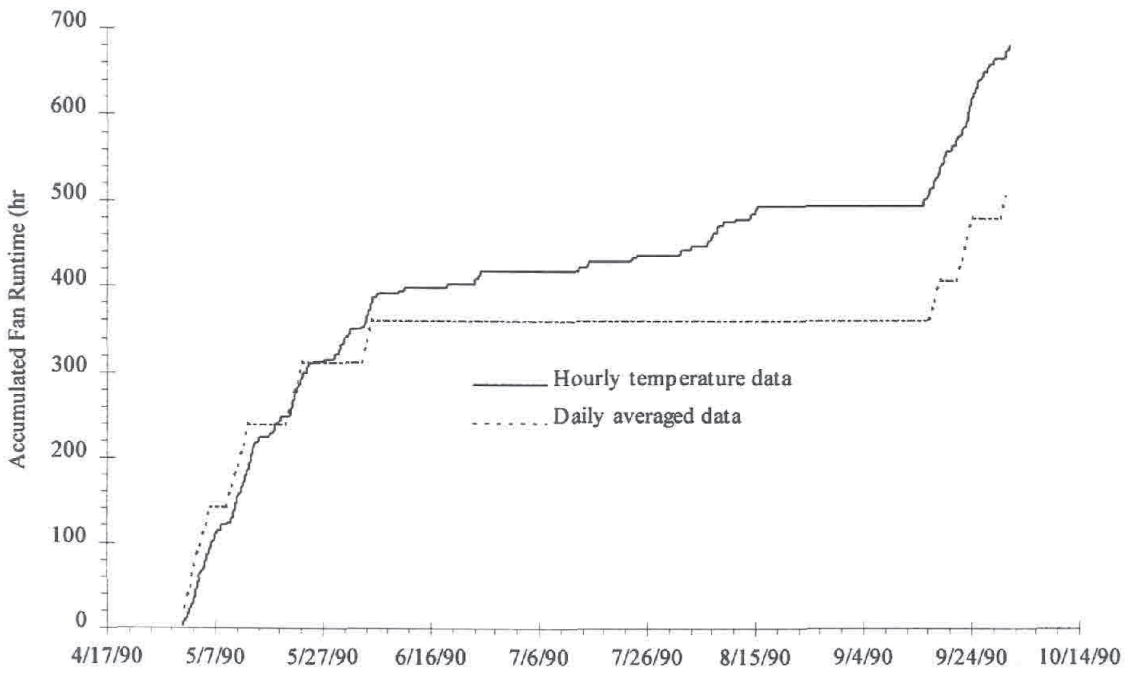

Fig.10. Accumulated fan runtime if hourly weather data or 24 hour averaged temperatures are used during aeration.

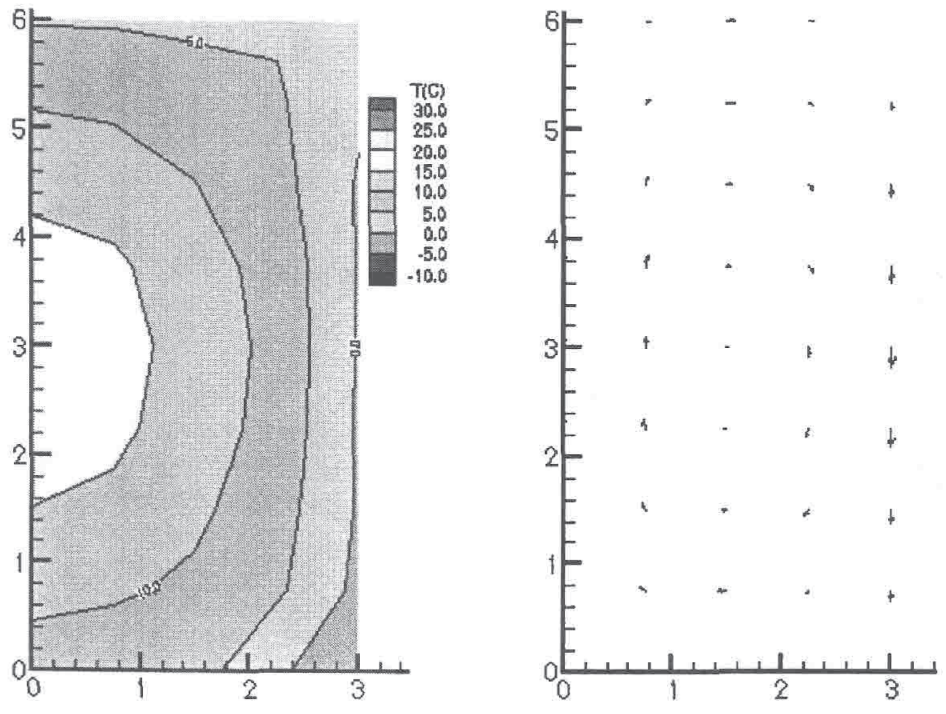

Fig.11. Predicted temperature changes and free convection currents in stored corn in Indianapolis, IN on March 30, 1990.

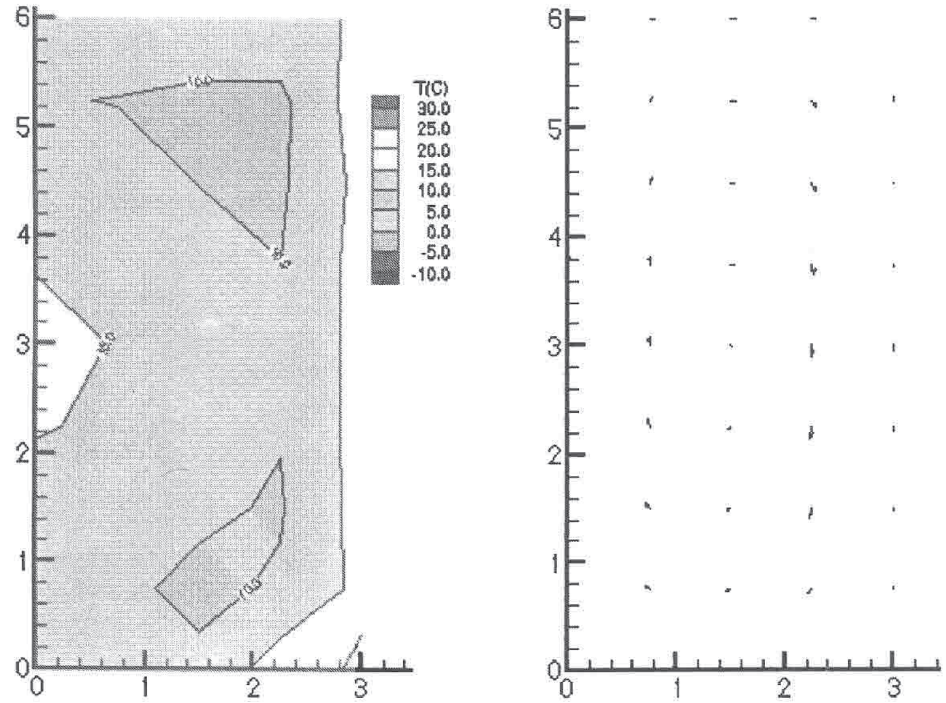

Fig. 12. Predicted temperature changes and free convection currents in stored corn in Indianapolis, IN on April 29, 1990.

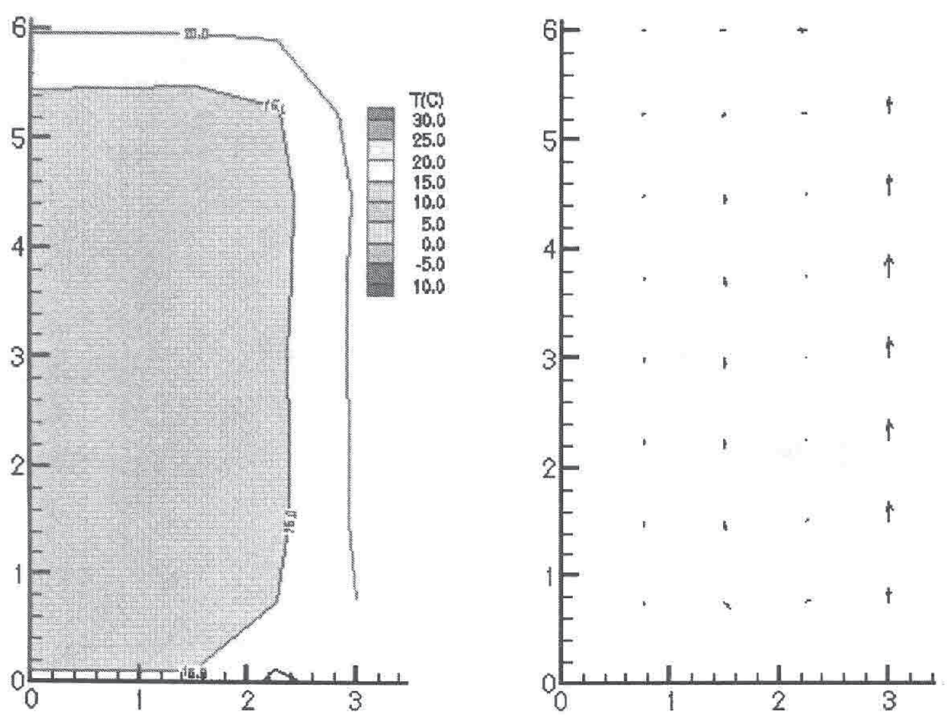

Fig. 13. Predicted temperature changes and free convection currents in stored corn in Indianapolis, IN on May 29, 1990.

Future Approach to Modeling the Stored Grain Ecosystem

Once a comprehensive three-dimensional finite element ecosystem model has been developed and validated, storage structures of any size or shape and located anywhere in the world can be accurately simulated Predicting the heat and mass transfer in the storage bins accurately is required before biological and quality factors can be used to make management decisions. Other end use quality models predicting the effect of storage on head rice yield, popping volume of popcorn, milling yield of wheat and oats, extractable starch yield in corn, oil yield in soybean crushing are needed in the future to optimize stored product protection further.

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