Computer simulation of temperature changes in a wheat storage bin

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Abstract

A mathematical model describing the transient temperature distribution of grain in a cylindrical storage bin with mixed boundaries is presented and solved using the finite element method. Using the typical meteorological data of a region such as temperate China, temperature changes of wheat in a storage bin are simulated and analysed in detail. Simulated results indicate that high temperature accumulation areas of the grain are in the bin centre and near the bin bottom or at the top surface of the grain throughout the whole year and ventilation under appropriate weather conditions is necessary. This method can be used to develop and evaluate aeration control strategy and reduce the need for chemical treatments of grain during storage. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

After drying, grain is normally stored for a period of time. To maintain grain quality during storage, grain must be protected from the growth and reproduction of insects, mites and fungi (Sun and Woods, 1997a, b). Storage temperatures lower than 15°C can
prevent insect development (Sun and Woods, 1994a, b) and mite and fungi growth can be controlled by reducing the ERH (water activity) (Sun, 1998, 1999; Sun and Byrne, 1998; Sun and Woods, 1993, 1994c). Therefore, temperature in storage is one of the most important factors that determine grain storage quality (Muir, 1980; Brooker et al., 1992;

Nomenclature

\[ C \] specific heat of the grain (J/kg)

\[ F_b \] shape factor, 0.3 for bin roof and surface layer of grain

\[ h \] convective heat transfer coefficient (W/m² °C)

\[ I_H \] solar radiation on horizontal surface (W/m²)

\[ I_{HS} \] diffusion radiation on horizontal ground (W/m²)

\[ I_{ND} \] incident normal direct solar radiation (W/m²)

\[ I_P \] solar radiation on incline (W/m²)

\[ k \] thermal conductivity of grain (W/m °C)

\[ q_a \] radiation from bin wall to surrounding (W/m²)

\[ q_b \] radiation from bin roof to grain surface (W/m²)

\[ q_w \] net radiation on the wall (W/m²)

\[ t \] drying time (s)

\[ T \] grain temperature (°C)

\[ T_{aa} \] absolute temperature of ambient air (K)

\[ T_{ar} \] absolute temperature of bin roof (K)

\[ T_{as} \] absolute temperature of surface layer of grain (K)

\[ T_{aw} \] absolute temperature of bin wall (K)

Subscripts

0 initial

s element area

\( s_1, s_2, s_3 \) bin boundaries (indicated in Fig. 1)

\( v \) element volume

Greek symbols

\[ \theta \] solar incident angle (deg)

\[ \rho \] density of grain (kg/m³)

\[ \sigma \] Stefan–Boltzmann constant (=5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4)

\[ \varepsilon \] inclination angle of plate, 90° for bin wall; 0° for bin roof

\[ \lambda \] ground reflectance (0.1 for dry ground; 0.08 for wet ground; 0.7 for snow covered ground)

\[ \sigma_b \] surface absorptivity, 0.9 for grain

\[ \sigma_{wl} \] long wave emissivity of bin wall (0.23 for weathered galvanised steel; 0.70 for concrete)

\[ \sigma_{ws} \] short wave absorptivity of bin wall (0.66 for steel plate; 0.7 for cement)
Chang et al., 1993; Sun and Woods, 1997a, b). Because the thermal conductivity of grain is rather small and air flow among the grain within the storage bin is very feeble, the accumulation of heat in a localised area of the storage bin is one of the primary factors causing the acceleration of the growth and development of insects, mites and fungi. Furthermore, temperature differences between the grain bulk and the ambient air cause natural convection within the bulk (Abbouda, 1984), which results in moisture movement from high temperature to low temperature areas. This regular moisture movement in stored grain increases the chance of a wider distribution of insects, mites and fungi and can thus bring about the deterioration of grain quality (Converse et al., 1973; Muir et al., 1980; Brooker et al., 1992; Jia, 1995; Sun and Woods, 1997a, b).

Accurate predictions of grain temperature can be used to develop and evaluate aeration control strategies to maintain grain most effectively and reduce the need for chemical treatments to control insects, mites and fungi. However, collecting temperature data at any location and any time in grain storage bins of different sizes is a difficult, time-consuming and costly job. Therefore predicting grain temperature changes using experimental or statistical methods only is not practical. Mathematical simulation is a more rapid, less expensive and efficient method to predict accurately the temperature distribution in stored grain bins. Many investigators have studied grain temperature changes in various types of storage bins, especially round bins. Most of the researchers solved the heat conduction problem using the finite difference method for predicting the temperature distribution in stored grain bins (Lo and Chen, 1975; Yaciuk et al., 1975; Muir et al., 1980; Metzger and Muir, 1983; Obaldo et al., 1990; Chang et al., 1993; Sun and Woods, 1997a, b). For example, Chang et al. (1993) obtained excellent agreement between measured and predicted grain temperature over a 32 month period using a finite difference based simulation. However the finite difference method is inconvenient and difficult-to-solve irregular geometry with mixed boundary problems including solar radiation and air convection. The finite element method provides the flexibility and versatility necessary for the analysis of such complicated boundary problems and therefore has been widely applied in simulating temperature changes of grain during storage (Shufen and Jofreit, 1987; Alagusundaram et al., 1990; Mao, 1991; Jia and Cao, 1998).

Temperature distribution of grain in a storage bin is affected by many factors such as ambient air temperature, air convection, local wind velocity, solar radiation, and bin structure and size. The following are some limitations in the past work: (1) mixed boundaries were simplified as only convection; (2) air convection on the top surface or the bottom layer of the bin was neglected when the temperature changes of the grain were analysed; or (3) solar radiation from bin roof to the top layer surface of the grain was not considered.

The objective of this study is to develop a mathematical model describing the heat transfer during wheat storage and to solve it using the finite element method (FEM). In this model, the mixed boundary conditions including solar radiation, ambient air temperature and air convection on the surface layer of wheat are considered. The temperature distributions of the wheat during storage are then described and analysed.
2. Mathematical model and solution

2.1. Model and boundary conditions

The model describing the transient heat transfer with no internal heat in a cylindrical coordinate system is given by the theory of heat transfer. The effect of internal heating on temperature distribution during wheat storage is reported elsewhere (Jia et al., 2000).

\[
\rho C \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial z^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \right).
\]

(1)

The boundary conditions of a cylindrical grain bin are shown in Fig. 1. The fans and pipelines are used to ventilate the grains under variable weather conditions. Hence, for boundary \(s_1\),

\[-k \frac{\partial T}{\partial n} = h_{s_1}(T - T_s) \quad (t > 0).
\]

(2)

On boundary \(s_2\), there exist solar radiation and ambient air convection, therefore,
The temperature change of the surface layer is dependent upon solar radiation on the bin roof and air convection between the grain surface and the bin roof. Therefore, at boundary \(s_3\):

\[-k \frac{\partial T}{\partial n} = h_{s_3}(T - T_{s_3}) - q_w \quad (t > 0)\]  

(3)

The net solar radiation on the bin wall in Eq. (3) can be calculated as (Jia, 1995; Shufen and Jofreit, 1987; Chang et al., 1993):

\[q_w = \sigma_{ws}I_P|_{\theta=90^\circ} + q_a = \sigma_{ws}\left(I_{ND}\cos \theta + \frac{I_{HS}}{2} + \frac{I_H}{2}\right) + q_a\]  

(5)

where:

\[I_P = I_{ND}\cos \theta + (1 + \cos \epsilon)I_{HS}/2 + \lambda(1 - \cos \epsilon)I_H/2\]

and

\[q_a = \sigma_{swl}(T_{as}^4 - T_{aw}^4)\]

The solar radiation from the bin roof to the surface layer of grain \(q_b\) can be given by (Jia, 1995; Shufen and Jofreit, 1987; Chang et al., 1993):

\[q_b = \sigma_{sb}F_b(T_{ar}^4 - T_{as}^4)\]  

(6)

The relevant formula used to calculate the convective heat transfer coefficients can be found elsewhere (Holman, 1992).

2.2. Finite element formulation

Eq. (1) is a two dimensional non-linear partial differential equation. Using the variation calculus method, the function of Eq. (1) can be written as (Jia and Cao, 1998):

\[J = \int \frac{1}{2} \left[ k \left( \frac{\partial T}{\partial r} \right)^2 + k \left( \frac{\partial T}{\partial z} \right)^2 + 2 \rho C \frac{\partial T}{\partial t} \right] d\nu + \frac{1}{2} \int_{s_1} h_{s_1}(T - T_{s_1})^2 ds_1 + \int_{s_2} q_w T dS_2 + \frac{1}{2} \int_{S_3} q_b(T - T_s)^2 ds_3.\]  

(7)

With the finite element method, the grain bin section can be divided into \(n\) triangular elements and by solving the minimum values, Eq. (7) can be rewritten as:

\[\frac{\partial J}{\partial \{T\}} = \frac{\partial}{\partial \{T\}} \sum_{e=1}^{n} J^{(e)} = \sum_{e=1}^{n} \frac{\partial J^{(e)}}{\partial \{T\}} = 0.\]  

(8)

Or in a simplified form:
\[ [C] \frac{\partial \{T\}}{\partial t} + [K]\{T\} - \{F\} = 0 \]  \hspace{1cm} (9)

where \([C]\) is the element capacity matrix, \([K]\) is the element conductivity matrix, and \(\{F\}\) is the element flux vector. If the forward difference method is used to approximate \(\{T\}\) in the \(L\) time step, Eq. (9) becomes

\[ [C]\{T\}_{L+1} = \left([C] - \Delta t[K]\right)\{T\}_{L} + \Delta t\{F\}. \]  \hspace{1cm} (10)

The finite element computer program was developed to solve the above model. The input data required are the codes of node and element data, the boundary condition types, the thermal properties of grain, air and bin material, the initial temperature of every node in the domain, and weather data. For every time step \(\Delta t\), a set of new nodal values in the next time step can be calculated using the given node values. By repeating this procedure, the temperature distribution within a grain bin can be obtained.

2.3. Simulation procedure

During the simulation, it was assumed that temperature distributions in the grain bin are symmetric about the vertical central axis, i.e. heat flow in the circumferential direction is negligible.

A 4890-mm-diameter corrugated cylindrical steel bin storing wheat, which is shown in Fig. 1, with an eave height of 5335 mm and an apex height of 6475 mm, was used in the simulation. The thickness of bin wall (galvanised steel plate) was 1.5 mm. The average level height of the surface layer of the stored wheat was 4500 mm. The centrifugal fans and perforated steel aeration ducts were installed on the bin bottom. The bin was fitted with two vents on the roof.

The simulation date used was from 1 June 1992 to 1 January 1994. The fans on the bin bottom were switched off during the simulation. The initial average moisture content and temperature of the stored wheat were 0.135 (w.b.) and 22°C, respectively. The density, specific heat and thermal conductivity of wheat were taken as 863 kg/m³, 1757 J/kgK and 0.159 W/mK, respectively, and the density, specific heat and thermal conductivity of the corrugated galvanised steel were 7790 kg/m³, 470 J/kgK and 45.8 W/mK, respectively. The weather data were supplied by Beijing Meteorological Observatory, China. Fig. 2 shows the two-dimensional finite element grid used to calculate the semi-section of the bin.

3. Results and discussion

The predicted wheat temperatures at two radial distances of 0.82 m (i.e. Node 18) and 2.45 m (i.e. Node 16) from the bin wall are given in Fig. 3. The wheat temperature variation in the radial direction was in line with the change in the ambient temperature and the values of the wheat temperature change decreased as the distance from the bin wall increased. The maximum difference of wheat temperature at 0.82 m location was about 18 and 13°C at the bin centre (2.45 m location). During the first summer (i.e. 1 June–1 September 1992), the peak temperature of the wheat at 0.82 m location was about 3°C higher than that at the bin centre.
However, the peak temperature at 0.82 m location became about 3°C lower than that at the bin centre during the first winter (1 November 1992–1 February 1993). The time lag between the peak temperatures of the ambient air and the wheat at the bin centre was about 4 months and this time delay decreased as the distance from the bin wall decreased.

Fig. 4 shows the predicted wheat temperature at two different depths of 0.64 m (i.e. Node 31) and 3.81 m (i.e. Node 6) from the surface layer of the wheat. The comparison indicates that the wheat temperature variation in the vertical direction is also following the change in the ambient temperature and the wheat temperature decreased with increasing depth from the surface layer, which is very similar to that at the radial direction. However, the peak difference of wheat temperature between the top layer and the bottom layer was slightly larger than that in the radial direction. The time delay between the ambient peak temperature and wheat peak temperature in the vertical direction was a little more than that in the radial direction.

The authors only recorded some wheat temperature values between June and July 1992 because the wheat temperature inside the bin rose very quickly and aeration had to be carried out after 20 July 1992. The simulation results (Nodes 18 and 31) in Figs. 3 and 4 also indicate the rapid rise of temperature during this period, indicating the necessity for aeration. Although the long-term change of temperature with the seasons may be harmless depending on the ambient temperature variation, it was assumed that the simulation should proceed without the aeration in order to explain the changing wheat temperature during storage. Table 1 shows the comparison of the measured and predicted temperatures.
at Nodes 31 and 18. It can be seen from Table 1 that the simulation values agree well with the measured data. This also indicates the accuracy of the model developed in predicting temperature distributions in the storage bin.

Figs. 3 and 4 also illustrate that the predicted temperature in the stored wheat changed

Table 1
Comparison of the predicted and measured wheat temperatures at Nodes 31 and 18 inside the bin between June 1992 and July 1992

<table>
<thead>
<tr>
<th>Date</th>
<th>8 June</th>
<th>15 June</th>
<th>22 June</th>
<th>29 June</th>
<th>6 July</th>
<th>13 July</th>
<th>20 July</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured values (°C)</td>
<td>Node 31</td>
<td>22.4</td>
<td>22.8</td>
<td>23.5</td>
<td>24.5</td>
<td>25.3</td>
<td>26.2</td>
</tr>
<tr>
<td></td>
<td>Node 18</td>
<td>22.4</td>
<td>22.8</td>
<td>23.3</td>
<td>23.8</td>
<td>24.3</td>
<td>24.8</td>
</tr>
<tr>
<td>Predicted values (°C)</td>
<td>Node 31</td>
<td>22.5</td>
<td>23.1</td>
<td>23.9</td>
<td>25.0</td>
<td>25.6</td>
<td>26.4</td>
</tr>
<tr>
<td></td>
<td>Node 18</td>
<td>22.4</td>
<td>22.9</td>
<td>23.5</td>
<td>24.2</td>
<td>24.6</td>
<td>25.0</td>
</tr>
</tbody>
</table>
slowly except for the layers near the bin wall and at or near the surface layer of the wheat. In
the winter, a sharp decrease in the stored wheat temperature took place because the ambient
temperature dropped rapidly to below 0°C, and the wheat temperature then increased
gradually in the spring. Throughout the whole year, the wheat temperature was above 7°C.
This means that after harvesting or drying, the aeration facilities should be used to lower the
grain temperature in the initial stage of storage, otherwise the possibility of grain spoilage
would occur during storage. This phenomenon has been observed by other investigators
(Converse et al., 1973; Lo and Chen, 1975; Chang et al., 1993).

The predicted distributions of the wheat temperature after storage for 80 and 220 days are
shown in Figs. 5 and 6. The wheat temperatures near the bin wall and at the top layer were
mainly influenced by the solar radiation and air convection between the bin roof and surface
layer of the wheat. Fig. 5 indicates that wheat temperature near the bin wall and at the top
layer was still higher than that in the bin centre and near the bin bottom when the ambient
temperature began to drop in the late summer. The high temperature accumulation area of

![Graph showing wheat temperature distributions](image-url)

**Fig. 4.** Predicted wheat temperature at vertical locations from top surface during storage (Beijing, from 1 June 1992
to 1 January 1994).
wheat was at the top surface in this period. Fig. 6 shows that the wheat temperature near the bin wall and at the top layer was lower than that in the bin centre and near the bin bottom when ambient temperature fell to the lowest values in winter. The high temperature accumulation area of wheat was in the bin centre and near the bin bottom. Therefore, grain spoilage is most likely to occur in these high temperature areas if temperatures are not lowered quickly at the beginning of the storage or if sufficient ventilation is not performed during the storage period, as widely stated in the literature (Lo and Chen, 1975; Muir et al., 1980;

Fig. 5. Simulated temperature distribution of wheat within the grain bin (1/2 section) after storage for 80 days from 1 June 1992 (Beijing, China).
Due to the ambient air temperature and solar radiation changing regularly, temperatures of materials in contact with the structure of a bin are severely affected by the ambient conditions. Therefore, it is advisable to apply reflective paints or insulation materials to reduce the heat flow from the bin wall or bin roof into the stored grain in the summer.

Fig. 6. Simulated temperature distribution of wheat within the grain bin (1/2 section) after storage for 220 days from 1 June 1992 (Beijing, China).
4. Conclusions

A mathematical model describing the transient temperature distribution in a cylindrical grain bin is presented and solved using the finite element method. The model incorporates mixed boundary conditions including solar radiation, air convection and heat conduction.

The simulation results indicate that the wheat temperature changes decrease as the distance from the bin wall and from the top surface of the wheat increase. The time delay between the ambient peak temperature and the wheat peak temperature in the bin centre was about 3 to 4 months and this delay decreases towards the sides. The high temperature accumulation areas of the grain are identified to be in the bin centre and near the bin bottom in the winter or at the top surface of the grain in the summer. The regular changes of ambient air temperature and solar radiation throughout the year will greatly influence the grain quality near the bin wall and the surface layer of the grain.

The work demonstrates the potential of the finite element method for predicting complex and slow changes of temperature in stored grain under varying environmental conditions. This method can be used to develop and evaluate aeration control strategies and thus to reduce the need for chemical treatments during grain storage.

References