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Research Article

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Application of Heat Transfer Model for Prediction of Temperature Distribution in Stored Corn

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Abstract The combined convective and conductive heat transfer model previously developed by Abbouda *et al*. (1992) was applied in this study to simulate the temperatures of corn during storage using input data of initial grain temperatures, ambient air temperatures, wind speeds and thermal properties of grain, bin structure and soil. The local weather data used in the model were obtained from the meteorological station of King Faisal University at Al-Ahsa Province of Saudi Arabia. Experimental data showed that bin size and initial moisture content affected the grain temperature differences between the top surface and the bottom of the bin. The average grain temperature followed the trend of the ambient air temperature with a time delay. Predicted and measured grain temperatures were in close agreement for a test period of one year. Results indicated that the model and the parameter values used in the model are applicable for predicting temperature of stored corn under static storage conditions.

Keywords Heat Transfer Model, Temperature Distribution, Stored Corn

Introduction

To maintain the grain at a temperature and moisture below the level at which rapid deterioration occurs is one of the main objectives in the design and operation of grain storage system. But because of weather changes, both temperature and moisture are changing in both time and space within a storage bin. The criteria for safe storage are, therefore, dependent upon the local climatic conditions. Study of the effects due to naturally occurring variations in weather is necessary, in order to provide a rational basis for safe storage design [1].

Temperature of grain in storage is one of the three main abiotic factors, besides the intergranular gas composition and the grain moisture content, that determine the keeping quality and control measures used to protect grain from insects, mites and damaging micro flora [2-4]. Temperature changes in the stored grain are caused by both internal and external sources of heat. Internal sources are heat of respiration of grain, microorganisms, insects, and mites. External sources include the changes in the ambient air temperature, solar radiation, and wind velocity that varies with location of the storage structure [5]. Rates of respiration and multiplication of insects, mites and fungi, and respiration of the grain itself are largely dependent on grain temperature [2]. Grain-infesting insects multiply slowly or not at all at temperatures below 15°C, generally can not survive above 40°C, and thrive best at about 30 °C [6-8]. Difference between the center temperature of the grain bulk and the outside ambient air temperature causes convection currents in the grain accompanied by a movement of moisture from high temperature to low temperature areas [9], which further enhances the outbreak of mold growth. Knowledge of temperature distribution in the stored grain not only helps in identifying active deterioration, but also gives an indication of the potential for deterioration.

Collecting the temperature data at various points in grain storage bins of different sizes over a period of time is one way of finding the temperature distribution.

But this is an inefficient method, requiring a lot of time, cost, and labor. Mathematical models, based on physical principles can potentially predict with accuracy the temperature distribution in a grain storage bin. Further, using the mathematical models, the effect of bin size, bin wall material, location, etc., on the temperature distribution can be studied [10].

Numerical methods have served as useful tools for predicting temperature distribution in grain storage bins. Muir (1970), Yaciuk *et al.* (1975), and Lo *et al.* (1975) applied a finite-difference method to predict temperatures in the radial direction in the bin [1, 11-12]. Muir *et al*. (1980) [3] refined their model to simulate temperatures of stored grain in both the radial and axial directions in free-standing cylindrical bins under controlled atmosphere. Metzger and Muir (1983) [13] combined the force convection model [14] and the conduction model [13] into one model to predict temperatures, moisture contents, and deterioration of wheat in circular steel bins with and without ventilation. Alagusundaram *et al*. (1990) [10] developed a three-dimensional finite element model for predicting grain temperatures in storage of any shape and size. Chang *et al*. (1993) [15] developed a heat transfer model, which accounts for periodic aeration and daily variations in soil temperature, ambient weather, and solar radiation, for accurate prediction of grain temperatures. In another study, Abbouda *et al*. (1992) [16] employed the equivalent coefficient of thermal conductivity, which defined as the sum of the heat transfer coefficients for the conduction and natural convection, in the conduction equations to predict temperatures of grain sorghum in small cylindrical steel bins (0.76 and 1.42 m diameter). Their results showed an improved accuracy for temperature predictions with the inclusion of natural convection and internal heat generation.

The objectives of this study were to: (1) test the applicability of the mathematical model developed by Abbouda *et al*. (1992) [16] under the weather conditions of the Eastern Province of Saudi Arabia; and (2) observe the temperature changes of corn stored in cylindrical steel bins as the ambient air temperature, initial moisture content, and bin size varied.

Mathematical Model

The combined convective and conductive heat transfer model previously developed by Abbouda *et al*. (1992) [16] was applied in this study. The finite-difference model developed by muir *et al.* (1980) [3] was used by Abbouda *et al.* (1992) [16] as a basis in their study. The original model was capable of simulating conductive heat transfer in both the radial and axial directions. The free convection was incorporated by Abbouda *et al*. (1992) [16] into the original model by using an equivalent thermal conductivity coefficient (k_{eq}) which was defined by Lykov (1966) [17] as:

$$k_{eq} = k + hL$$

Where

k = thermal conductivity (W/m.K)

h = convective heat transfer coefficient (W/m^2.K)

L = characteristic dimension (m)

The combined convective and conductive heat transfer model was run on a digital computer to simulate the temperatures of corn during storage using input data of initial grain temperatures, ambient air temperatures, wind speeds and thermal properties of the grain, bin structure and soil. The local weather data were obtained from the meteorological station of King Faisal University at Al-Ahsa-Eastern Province of Saudi Arabia. The thermal conductivity and specific heat of corn were estimated at 0.1591 W/m.K and 2.026 kj/kg.K , respectively. The average bulk density of stored corn was estimated to be 754 kg/m^3.

Materials and Methods

Four cylindrical, leak-proof steel bins of the same height (128 cm), but of two different diameters, were constructed and placed outdoors on concrete floor from 6th of March 2001 to 7th of March 2002in the Research Station at King Faisal University, Eastern Province, Saudi Arabia. The diameters of the two bins were 142 cm and 76 cm, respectively.

Corn from the local market was divided into two lots. Lot 1 was originally with 12.00% moisture content and 46°C temperature. Lot 2 was conditioned to 10.00% moisture content and 46°C temperature. Two bins (a large one and a small one) were loaded with corn from lot 1. The other two bins were filled with grains from lot 2. All bins were filled to 112 cm high.

Temperature measurements were taken hourly at three cross-section of the cylindrical bins. They were 8, 61 and 112 cm above the bottom of the bin, respectively. As shown in Fig. 1, five points were selected for the large bins along each axis beginning at 8 cm from the wall and 31.5 cm apart. For the smaller bins, four points were selected along each axis beginning at 8 cm from the wall and 20 cm apart. Thus, temperatures were measured at a grid of 39 points (13 × 3) for the large bins and 36 points (12 × 3) for the small bins. In each bin, thermocouple sensors were installed in the specified points to measure the temperatures of grain at different depths and different radial distances from the bin center. The sensors (accuracy ± 0.2 °C) were connected to a data-logger system to test, display and record the data throughout the experimental work.

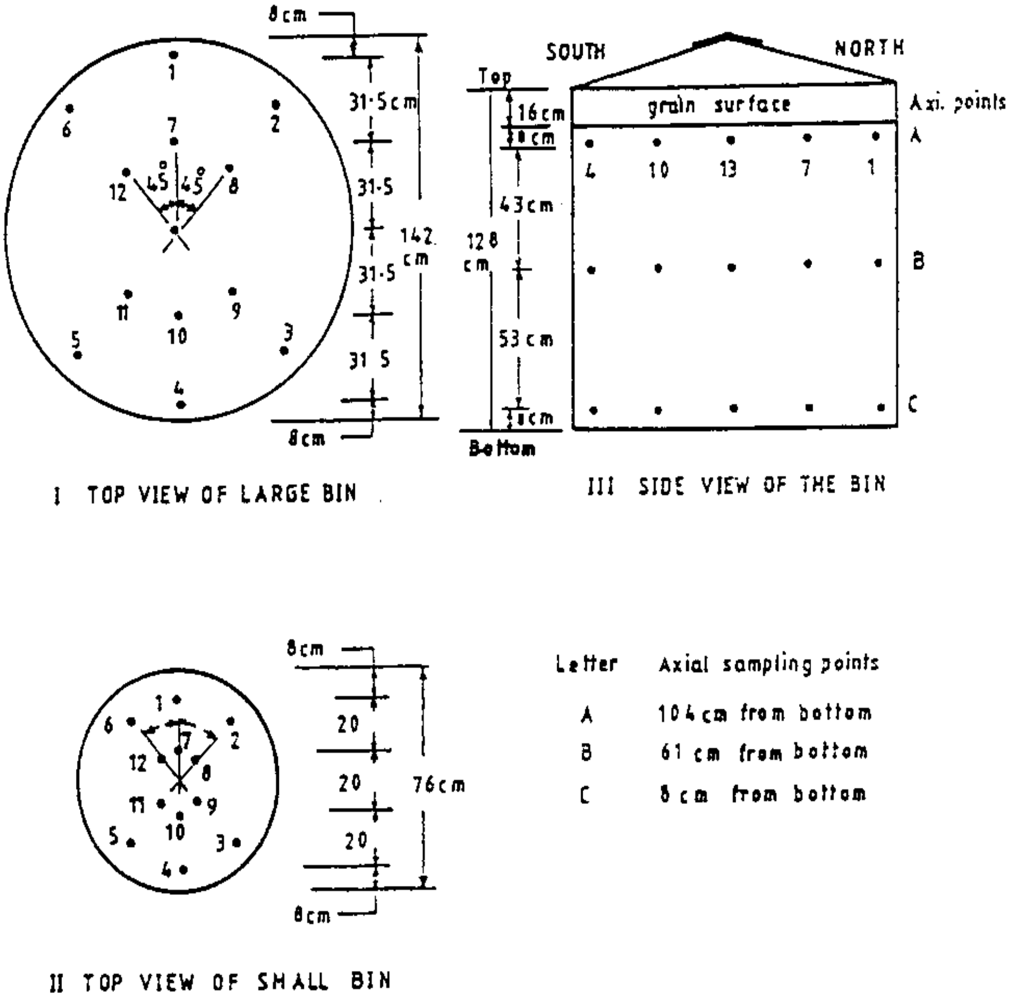

Figure 1: Location of measurement points in the experimental bins

Results and Discussion

Measured Temperatures in Experimental Bins

Figure 2 shows the variation of measured temperatures as ambient temperature changes. The data shown are the average of 13 radial temperatures over time at different vertical depths in one of the large bins.

Figure 3 shows the changes of average axial grain temperature at different radius as the ambient temperature changes. Each point on Fig. 3 is an average of 18 points (6 radial x 3 axial ones). The data for the center position are the average of 3 axial points.

In general, the temperature of the stored grain followed the trend of changes in air temperature. It reached 21.42°C during the winter and 42.62°C during the hot summer, whereas the lowest air temperature was 10.6°C and the highest was 38.2°C. It took 8 weeks for the grain temperature to respond to the cold temperatures and approximately two weeks to respond to the hot temperatures. This time lag was observed to be the same for all measuring points considered as shown by the parallelism of the temperature graphs in Figures 2 and 3.

As expected the grain at the surface and near the bin wall had higher temperatures than that in other parts during prolonged heating period from 17 to 43 weeks storage. The average grain temperature at the top surface was about 0.44 - 4.80°C higher than that at the bottom bin. The average temperature near the bin wall was approximately 0.65 - 4.80°C higher than that at the center. An opposite trend existed during the cooling period from 0 – 17 weeks; the grain at the center was generally 2.13°C to 7.53°C higher than that near the wall.

The average temperature at each layer in the small bin is shown in Fig. 4. A similar trend found in Fig. 2 is observed here. The highest grain temperature in the hot summer was not as high as that observed in the large bin. The difference between the top and the bottom surface during the prolonged heating period (between 17 to 43 weeks storage) was between 0.16 to 3.92 as compared to 0.44 to 4.80°C occurred for the large bin.

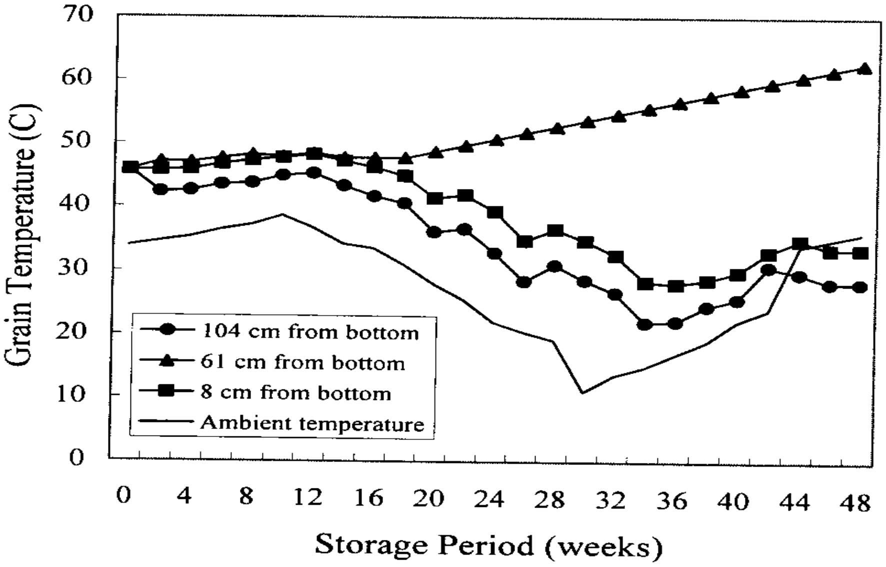

Figure 2: Measured weekly grain temperature variation at different depths inside the 142 cm Diameter bin containing corn grains at 12.0% IMC

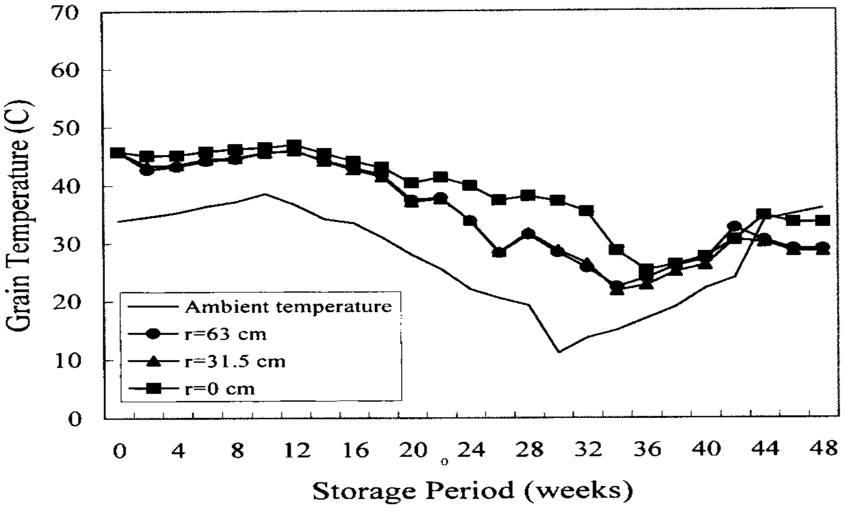

Figure 3: Measured weekly grain temperature variation at different radii inside the 142 cm diameter Bin containing corn grains at 12.0% IMC

Figure 5 is presented to show the effect of initial moisture content (IMC) on storage temperature. The data in Fig. 5 were from a small size bin. The bin was filled with corn at 10.0% IMC as compared with 12% in Fig. 4. Examining the heating period between 17 to 43 weeks storage, one will notice that the highest grain temperature in Fig. 5 (10.0%) was lower than that in Fig. 4 (12.0%). The temperature difference between top surface and bottom bin was approximately 0.01 to 2.30 °C for 10.0% IMC, as compared with 0.16 to 3.92 for 12.0% IMC.

It is known that the amount of dry matter loss is a function of grain moisture content. Lower moisture content results in a smaller amount of dry matter loss. As a result, the heat generated from respiration will be small. Comparing Fig. 5 and Fig. 4, it is reasonable to say that lower initial moisture content results in less heating of grain.

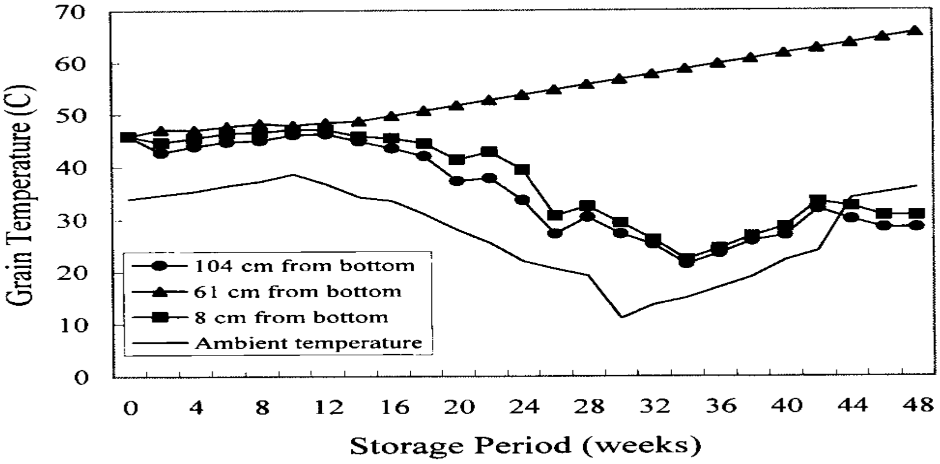

Figure 4: Measured weekly grain temperature variation at different depths inside the 76 cm diameter Bin containing corn grains at 12.0% IMC

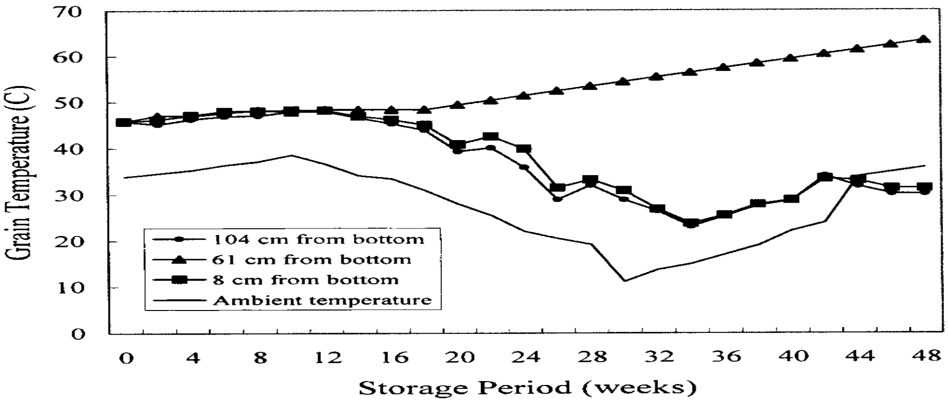

Figure 5: Measured weekly grain temperature variation at different depths inside the 76 cm diameter Bin containing corn grains at 10.0% IMC

Comparison of Measured and Predicted Temperature

Predicted and measured grain temperatures at 104 cm from the bottom and at the center of bin are plotted in Figs. 6 and 7 for a large size bin containing corn at 10.0% IMC. The predicted temperatures were from the combined convective and conductive heat transfer model developed by Abbouda *et al*. (1992). The standard error of estimate was 0.32 for grain at 104 cm from the bottom and 0.28 for the grain at the center of the bin. Close agreement between measured and predicted grain temperatures indicated that the model and the parameter values used in the model are applicable for predicting temperature of stored grain under the local climatic conditions of Al-Ahsa Province of Saudi Arabia.

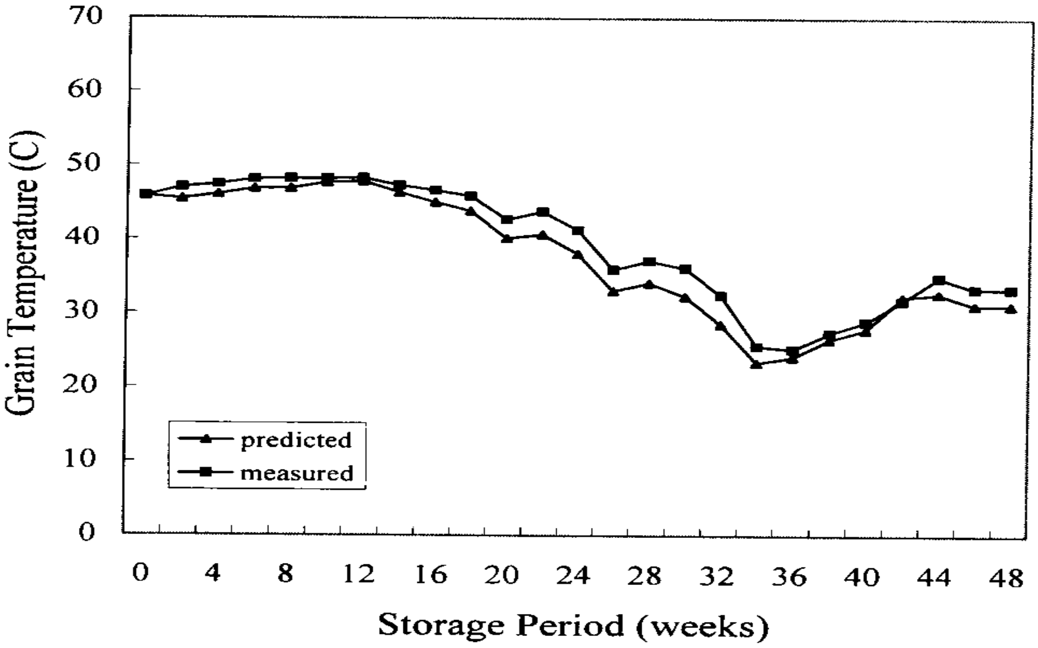

Figure 6: Comparison between measured temperature and temperature predicted by the model at 104 cm from bottom of a 142 cm diameter bin

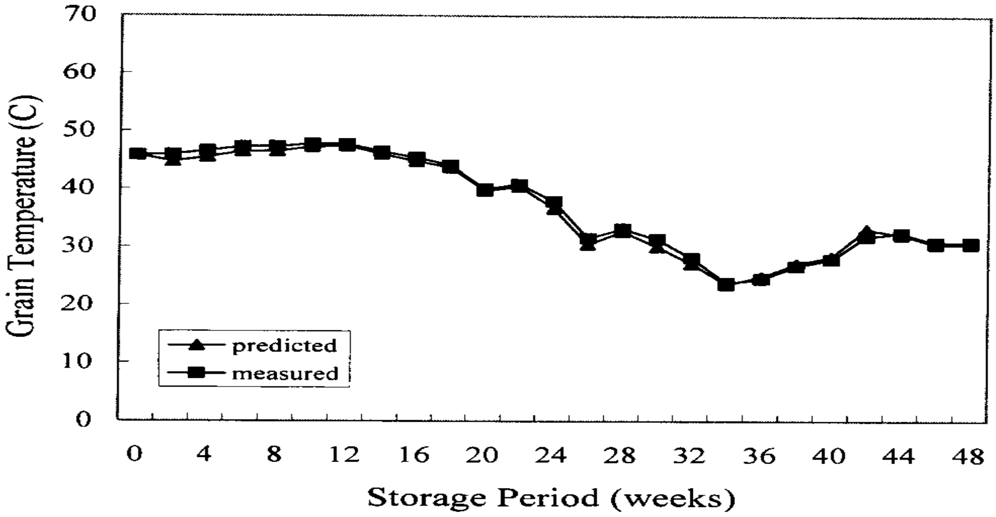

Figure 7: Comparison between measured temperature and temperature predicted by the model at the center of 142 cm diameter bin

Conclusions

The average grain temperature followed the trend of ambient air temperature after 8 days of storage. The time lag between a change in ambient air temperature and a change in grain temperature was approximately 2 to 8 weeks.

The bin size and the initial moisture content of wheat had some influence in grain temperature during storage. In general, lower initial moisture content resulted in lower storage temperature. The temperature difference in small bins is smaller than that in large bins.

The grain temperature predicted by the combined model including conduction and free convection agreed very well with measured temperature in the experimental bin. Thus, the model developed by Abbouda *et al*. (1992) [16] and the parameter values used in the model are applicable for predicting temperature of stored grain.

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