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# A Heat Transfer Model to Predict Temperature Distribution in Stored Wheat

**A.M.S. Al-Amri*** **and S.K. Abbouda**

*Department of Agricultural Engineering, Faculty of Agriculture and Food Sciences King Faisal University, P. O. Box 4421, Al-Ahsa 31982, Saudi Arabia*

**تطبيق نموذج انتقال الحرارة لحساب توزيع درجات حرارة القمح المخزن**

علي العمري و سرالختم عبوده

**خلاصة:** في هذه الدراسة تم تطبيق النموذج الرياضي المزدوج لإنتقال الحرارة بالتوصل و الحمل الذي أستنبط بواسطة عبوده و آخرون (١٩٩٢م) لحساب توزيع درجات حرارة القمح أثناء التخزين و ذلك بإستخدام المعلومات الأولية لدرجة حرارة القمح الإبتدائية و درجة حرارة الهواء الخارجي و سرعة الرياح و الخصائص الحرارية للقمح و مادة تشييد الصوامع و التربة. و لقد تم الحصول علي معلومات الأرصاد الجوية التي استخدمت في النموذج الرياضي من محطة الأرصاد الجوية التابعة لجامعة الملك فيصل بالأحساء – المملكة العربية السعودية. أوضحت نتائج التجربة أن حجم الصومعة و المحتوى الرطوبي للقمح قد أثر على الفرق بين درجات حرارة القمح على السطح العلوي للصومعة و قاع الصومعة. كما وجد أن متوسط درجات حرارة القمح داخل الصوامع الأربع (محل التجربة) تتبع متوسط درجات حرارة الهواء الخارجي مع فارق في الزمن. وقد وجد أيضا أن هناك تقارب شديد بين درجات حرارة القمح المقاسة و المحسوبة بالنموذج الرياضي للتجربة لمدة عام. النتائج أثبتت النموذج الرياضي و قيم المعلومات التي أستخدمت فيه يمكن تطبيقها لحساب درجات حرارة القمح المخزن تحت ظروف التخزين الثابت.

ABSTRACT. The combined convective and conductive heat transfer model which previously developed by Abbouda *et al.* (1992) was applied in this study to simulate the temperatures of wheat grain during storage process 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 wheat under static storage conditions.

**Keywords:** wheat, storage, temperature distribution, heat transfer, model.

To maintain grain at a temperature and moisture level below which rapid deterioration occurs, represents one of the main objectives in the design and operation of grain storage systems. Due to weather changes, ambient air temperature and moisture content are continuously variable in both time and space withih a storage bin. The criteria for safe storage are, therefore, dependent upon local climatic conditions. Study of the effects of naturally occurring variations in weather is necessary, in order to provide a rational basis for safe storage design (Lo *et al.*, 1975).

Temperature of grain in storage is one of the three main biotic factors, besides the intergranular gas composition and the grain moisture content, that determines the keeping quality and control measures used to protect grain from insects, mites and damaging microflora (Muir, 1980; Longstaff and Banks, 1987). Temperature changes in stored grain are caused by both internal and external sources of heat. Internal sources include heat of respiration of grain, microorganisms, insects, and mites. External sources include changes in ambient air temperature, solar radiation, and wind speed which varies with location of the storage structure (Converse *et al*, 1973). Rates of respiration and multiplication of insects, mites and fungi, and respiration of the grain itself are strongly dependent on

*Corresponding author.

grain temperature (Hunt, 1974). 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 (Christensen, 1974; McKenzie *et al.,* 1980; Noyes *et al.*, 1987). Differences between the center temperature of grain bulk and outside ambient air temperature cause convection currents in the grain accompanied by a movement of moisture from high temperature to low temperature areas (Sinha and Wallace, 1977), which further enhances the outbreak of mold growth. A knowledge of temperature distribution in stored grain not only helps in identifying active deterioration, but also gives an indication of the potential for deterioration.

Collecting temperature data at various points in grain storage bins of different sizes over a period of storage time is one way of finding temperature distribution. But this is an inefficient method, requiring a lot of time, cost, and labor. Mathematical models, based on physical principles may potentially predict with satisfactory accuracy, temperature distribution in a grain storage bin. Further, using mathematical models, the effect of bin size, bin wall material, location, etc., on temperature distribution can be studied (Alagusundaram *et al.*, 1990).

Numerical methods have served as useful approaches 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 of bins. Muir *et al.* (1980) refined their model to simulate temperatures of stored grain in both radial and axial directions in free-standing cylindrical bins under controlled atmosphere. Metzger and Muir (1983) combined a force convection model (Thompson, 1972) and a conduction model (Muir *et al.*, 1980) into one model to predict temperatures, moisture content, and deterioration of wheat in circular steel bins with and without ventilation. Alagusundaram *et al.* (1990) developed a three-dimensional finite element model for predicting grain temperatures in storage systems of any shape and size. Chang *et al.* (1993) developed a heat transfer model that accounted 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) incorporated equivalent coefficient of thermal conductivity, defined as the sum of the heat transfer coefficients for conduction and natural convection, in 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 the present study were to: (1) test the applicability of the mathematical model developed by Abbouda *et al.* (1992) under the climatic conditions of the Eastern Province of Saudi Arabia; and (2) observe temperature changes of wheat stored in cylindrical steel bins as 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) was applied in this study. The finite-difference model developed by Muir *et al.* (1980) formed the basis of Abbouda *et al.*'s (1992) model. The original model was capable of simulating conductive heat transfer in both radial and axial directions. Free convection was incorporated by Abbouda *et al.* (1992) into the original model by using an equivalent thermal conductivity coefficient ($k_{eq}$) which was defined by Lykov (1966) as :

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

Where k was the thermal conductivity (W/m.K), h the convective heat transfer coefficient ($W/m^2.K$), and L the characteristic dimension (m).

The combined convective and conductive heat transfer model was run on a digital computer to simulate wheat temperatures during storage using input data of initial grain temperatures, ambient air temperatures, wind speeds and thermal properties of the grain, bin structure and soil. Local weather data were obtained from the meteorological station of King Faisal University (100 m distant from storage bins) at Al-Ahsa, Eastern Province of Saudi Arabia. The thermal conductivity and specific heat of wheat were estimated at 0.19 W/m.K and 2 kJ/kg.K, respectively (Chang, 1986). The average bulk density of stored wheat was estimated to be 790 $kg/m^3$ (Chang *et al.*, 1993).

## Materials and Methods

Four experimental cylindrical, leak-proof steel bins of the same height (128 cm), but of two different diameters, were constructed and placed outdoors on concrete floors between 10 October 1997 to 30 October 1998 in the Research Station of King Faisal University, Eastern Province, Saudi Arabia. The diameters of the two bins were 142 cm and 76 cm, respectively.

Newly harvested wheat supplied by Saudi Siloe Cooperation was divided into two lots. Lot 1 was originally with 7% moisture content and 35°C temperature. Lot 2 was conditioned to 8% moisture and 35°C temperature. Two bins (large and small) were loaded with wheat from lot 1. The other two bins were filled with grains from lot 2. All bins were filled to 112 cm height.

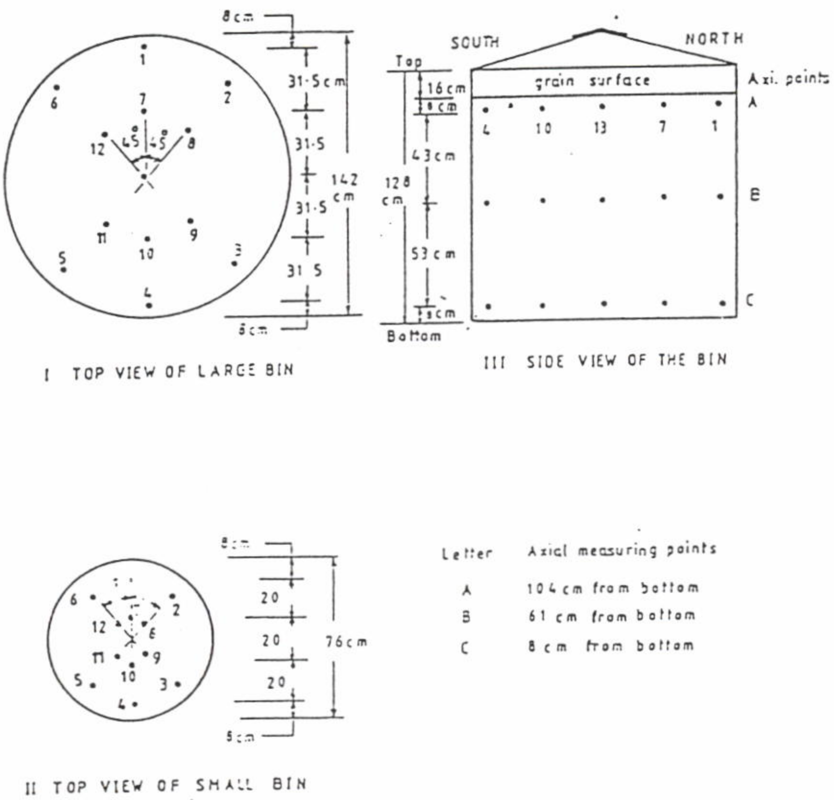


**Figure 1.** Diagrammatic representation of experimental bins and location of measurement points.

Temperature measurements were taken hourly at three cross-sections of the cylindrical bins. They were 8, 61 and 104 cm above the bottom of the bin, respectively. As shown in Figure 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 commencing at 8 cm from the wall and 20 cm apart. Thus, temperatures were measured at a grid of 39 points (13x3) for the large bins and 36 points (12x3) for the small bins. Thermocouple sensors (type K) were installed in the specified points inside the four bins 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.

## Results and Discussion

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

Figure 3 illustrates changes in average axial grain temperature at different radii as ambient temperature changed. Each point on Figure 3 is an average of 18 (6 radial x 3 axial). The data for the center position represent the average of 3 axial points.

In general, temperature of the stored grain followed the trend of changes in internal ambient air temperature, reaching 19.42°C during the winter and 40.62°C during summer. The lowest external air temperature was 13.6°C, while the highest was 38.2 °C. It took 10 days for grain temperature to respond to the colder, and approximately five days to respond to the hotter temperatures. This time lag was observed to be the same for all measurement points 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 the prolonged heating period between 120-300 days storage. The average grain temperature at the surface was between 0.44-4.80°C higher than that at the

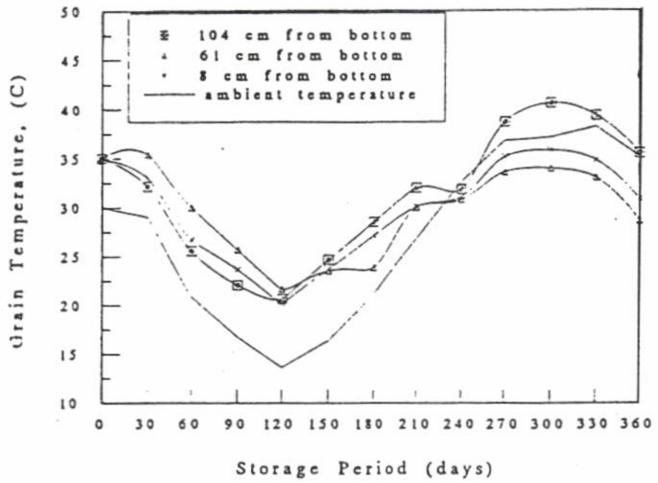


Figure 2. Average daily grain temperature at different depths inside a 142 cm diameter bin containing wheat at 8.0% IMC.

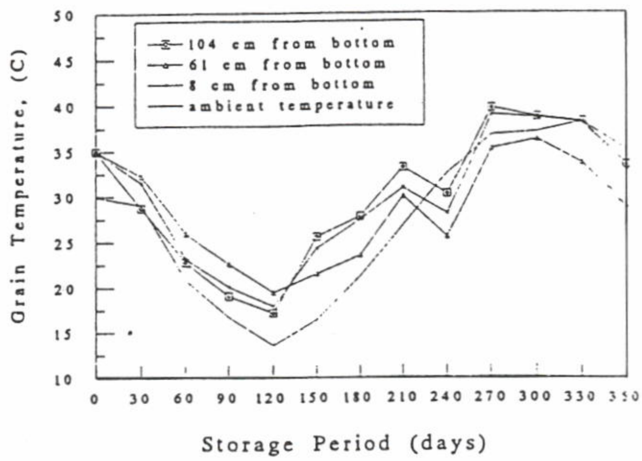


Figure 5. Average daily grain temperature at different depths inside a 76 cm diameter bin containing wheat at 7.0% IMC.

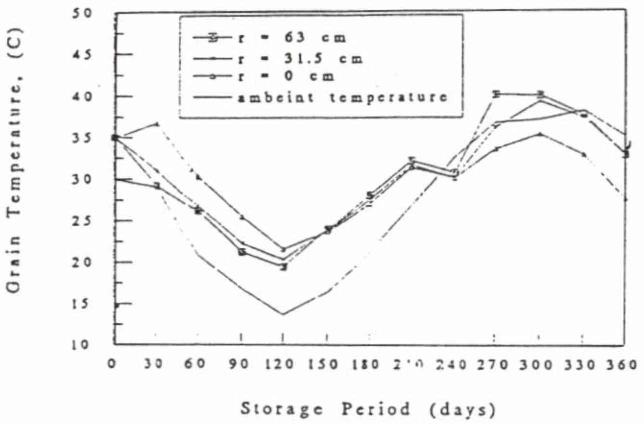


Figure 3. Average daily grain temperature at different radii inside a 142 cm diameter bin containing wheat at 8.0% IMC.

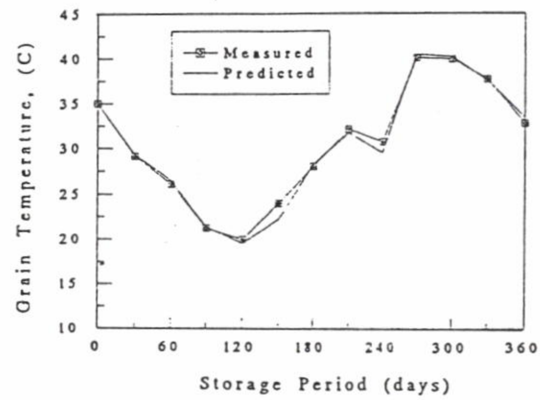


Figure 6. Comparison between measured and predicted temperatures 104 cm from the base of a 142 cm diameter bin.

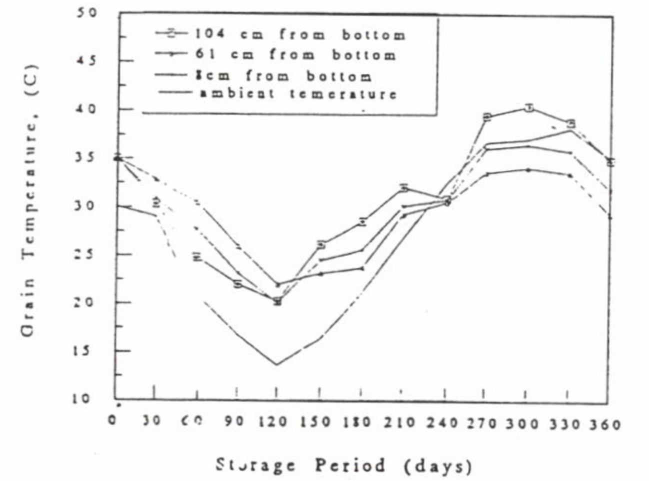


Figure 4. Average daily grain temperature at different depths inside a 76 cm diameter bin containing wheat at 8.0% IMC.

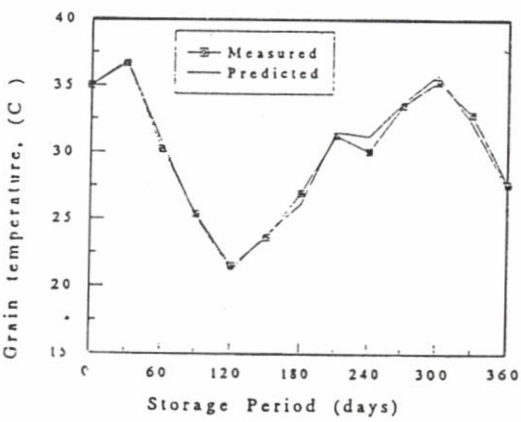


Figure 7. Comparison between measured and predicted temperatures at the center of a 104 cm diameter bin.

bottom bin. While the average temperature near the bin wall was approximately 0.34-6.51°C higher than that at the center. An opposite trend existed during the cooling period from 0-120 days; the grain at the center was generally 2.13-7.53°C higher than that near the wall.

The average temperatures recorded for each layer in the smaller bins is depicted in Figure 4. A similar trend to that presented for large bins (Figure 2) was observed. However, the highest grain temperature achieved in the smaller bins during the hot summer were not as high as those observed in the larger containers. The difference between the top and the bottom surface during the prolonged heating period (120 to 300 days storage) was between 0.16-3.92°C.

Figure 5 reveals the effect of initial moisture content (IMC) on storage temperature in a larger bin, whereas Figure 6 illustrates the same effect observed for a small sized bin. The bin was filled with wheat at 7.0% IMC as compared with 8.0% in Figure 4. Examining the heating profiles between 120-300 days storage, temperature differences between top surface and bin bottom were approximately 0.01-2.30°C for 7.0% IMC, compared to 0.16-3.92°C for grain at 8.0% IMC.

Since the amount of dry matter loss is a function of grain moisture content, lower levels of moisture leads to a reduction in the amount of dry matter loss. As a result, the heat generated from respiration will be smaller. Comparing Figure 5 and Figure 4, it is evident that lower initial grain moisture content leads to lower grain heating.

COMPARISON OF MEASURED AND PREDICTED TEMPERATURES. Predicted and measured grain temperatures at 104 cm from the bottom and at the center of bin are plotted in Figures 6 and 7 for a large size bin containing wheat at 7.0% IMC. The predicted temperatures were from the combined convective and conductive heat transfer model developed by Abbouda *et al.* (1992). The standard error of estimation was 0.32 for grain at 104 cm from the bottom and 0.28 for the grain at the center of the bin. Good agreement between measured and predicted grain temperatures was obtained and indicated that the model and the parameter values employed herein, are applicable for predicting temperature of stored grain under the local climatic conditions of Al-Ahsa Province of Saudi Arabia.

## Conclusion

Average grain temperature followed the trend in ambient air temperatures after 10 days of storage. The time lag between a change in ambient air temperature and that of grain was approximately 5-10 days.

Bin size and initial wheat moisture content influenced grain temperature during storage, with lower initial moisture content resulting in lower storage temperature. The temperature difference in small bins was smaller than that observed for large bins.

Grain temperature predicted by the combined model, including conduction and free convection, agreed well with measured temperature in the experimental bins. Thus, the model developed by Abbouda *et al.* (1992) and the parameter values employed herein proved useful in predicting temperature of stored grain.

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