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Boundary Element Heat Transfer Model of Temperature Distribution in Grain storage Bins

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ABSTRACT

Boundary element method was used to solve heat conduction problem for predicting temperature distribution in grain storage bin. 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 and damaging microflora.

Collecting the temperature data at various points in the storage bins at different time of the day over a period of time is one way of finding the temperature distribution, this method requires a lot of time, cost and labour and less efficient. However data so collected serve useful purpose of being used to validate predicted temperature distribution using mathematical models. Mathematical models based on physical principles can potentially predict with accuracy the temperature distribution in a grain storage bin. Using the boundary element model the effect of bin wall material, ambient temperature, bin size etc. on temperature distribution can be studied.

A knowledge of temperature distribution in stored grain not only helps in identifying active deterioration, but also gives an indication of potential for deterioration.

Key Word: Grain storage, Temperature distribution, Boundary element method,

INTRODUCTION

Whenever the temperature in any quantity within a mass of grain differ from another part, moisture is carried from warm to cooler areas by convection and deposited. Grain next to the steel wall of a bin exposed to the sun may reach a temperature level close to the temperature of the bin walls during the day, as grain is an excellent insulator and changes its temperature very slowly, the temperature of the grain a few centimeter away remains unchanged. Whenever such temperature difference exists convection currents begin to move moisture from warm to cooler positions, moisture is absorbed by the grains located at the cooler regions. When this happens, molds grow profusely, some sprouting occurs, grain becomes caked, heating resulting from rapid growth of mold in the effected area may eventually spread throughout the entire bin.

As observed by Schmidt (1955) and discussed by Hall (1980) suggest that natural convection occur in grain stores. The resulting heat and mass transfer leads to a build up of moisture in some area of the store. From a study of only the heat transfer processes, Smith and Sokhansanj (1990) have shown that conduction is the main form of heat flow in grain store. Temperature changes in stored grains are caused by both internal and external sources of heat Converse et al. (1973). Internal sources are heat of respiration of grain, microorganism, insects and mites. External sources include the changes in ambient air temperature and solar radiation which varies with location of storage structure. The transfer of heat is also influenced by the local wind velocity. Rate of respiration and multiplication of insects, mites and fungi and respiration of the grain itself are largely dependent on the grain temperature. Oxley (1948). Babbit (1948) concluded that with a diurnal temperature variations in large mass of wheat were present only to a depth of about 15.24cm from the grain surface. He also stated that these temperature changes cause convection currents within the grain mass and are the major driving force behind the movement of gas within the grain mass.

Many attempts (Converse et al. (1973), Lo et al. (1975) Yacink et al. (1975), Muir et al. (1980), Metzger and Muir (1983), Manbeck and Britton (1988) Alagusundaram et al., (1990)) were made in developing mathematical models to predict the temperature distribution in grain storage bins. All previous researchers solved the heat conduction problem either analytically or using the finite difference method or the finite element method. The boundary element solution offer several important advantages over the finite element and the finite difference methods. These advantages are the possibility of defining only the surface of the body and the facility with which boundaries at infinity can be represented. One of the more interesting features of boundary element method is the simplicity of the input data required to run a problem. This contrasts with the large amount of data needed to run a finite element program.

The accuracy of boundary element solution is generally greater than that of the finite element techniques. These advantages are more marked in two and three dimensional problem. The boundary element method is well suited to solve problems with boundaries at infinity such as those occurring in soil mechanics, hydraulics and other engineering disciplines.

The objective of this study was to develop a mathematical model, solved using boundary element method for predicting grain temperature in a grain storage bin.

MATERIALS AND METHODS

Model Development

The partial differential equation governing the transient heat transfer in an anisotropic solid body in the cartesian (x and y) coordinate system is given as:

$$\frac{\delta}{\delta x}(k_x\frac{\delta T}{\delta x})+\frac{\delta}{\delta y}(k_y\frac{\delta T}{\delta y})+q=\rho c\frac{\delta T}{\delta r} \qquad \text{Eq. (1)}$$

Eqn. (1) can be written in the form of Poisson's equation.

$$k_x(\frac{\delta^2 T}{\delta x^2})+ k_y(\frac{\delta^2 T}{\delta y^2}) = p \qquad \text{Eq. (2)}$$

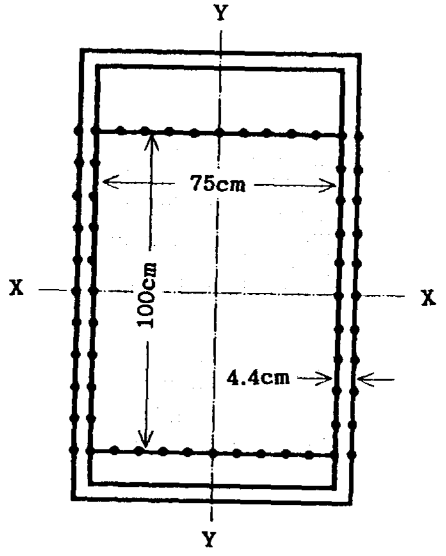

Fig. 1a, Bin configuration and discretigation for boundary element formulation.

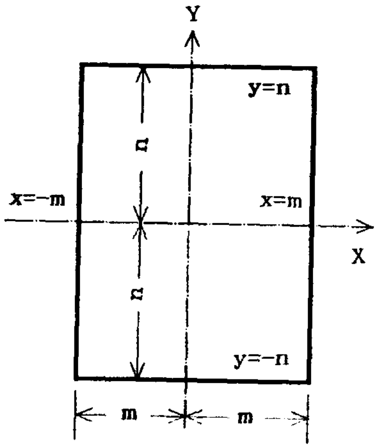

Fig. 1b, Two dimensional domain for Poisson's equation.

Using Galerkin's method and considering the Poisson's equation above, with T=0 at x=±m and y=±n Fig. 1b.

As a first approximation one can take,

$$T = \alpha(x^2+m^2)(y^2+n^2) \qquad \text{Eq. (3)}$$

The corresponding Galerkin's statement can be written as follows,

$$\int_{-m}^{m}\int_{-n}^{n}(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2}-p)\delta T\delta x\delta y = \int_{-m}^{m}\int_{-n}^{n}\epsilon\delta T\delta x\delta y = 0 \qquad \text{Eq. (4)}$$

Eqn. (4) is the starting point for boundary element method, Where

$$\delta T = 2\alpha(x^2-m^2)(y^2-n^2) \qquad \text{Eq. (5)}$$

The error function is given as:

$$\epsilon = 2\alpha(y^2-n^2) + 2\alpha(x^2-m^2) - p \qquad \text{Eq. (6)}$$

Hence Eqn. (4) become:

$$\int_{-m}^{m}\int_{-n}^{n}(2\alpha((y^2-n^2) + (x^2-m^2)) - p)(x^2-m^2)(y^2-n^2)\delta x\delta y = 0 \qquad \text{Eq. (7)}$$

Which after integration give:

$$\frac{128}{45}\alpha(m^3n^3(m^2+n^2)) - \frac{16}{9}p\,m^3n^3 = 0 \qquad \alpha = \frac{5}{8}\,\frac{p}{(m^2+n^2)} \qquad \text{Eq. (8)}$$

The value of T at (x=0, y=0)

$$T_0 = \frac{5}{8}\,p\frac{m^2n^2}{(m^2+n^2)}$$

Details of this method is given by (C. A. Brebbia; (1978) in Boundary element method for engineers.

Simulation of Grain Temperature Distribution.

The boundary element heat transfer model was coded in fortran to predict the temperature distribution in store grain. Input data required for the program are, node and element data the thermal properties of grain, temperature of the bin wall and the ambient temperature.

The effect of convective heat transfer in the bin storage space was calculated using the procedure of Yagi and Kunii (1957)

$\lambda_{ez} = \lambda_0 + \beta * C_g * d_g * G$ (Concurrent flow)

$\lambda_{er} = \lambda_0 + \alpha * C_g * d_g * G$ (crossflow)

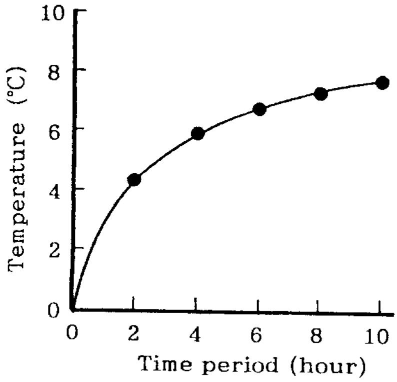

Fig. 2, Predicted wall inside temperature(made from polyurethane foam)

Where: $\lambda_{er}, \lambda_{ez}$ = Effective thermal conductivity of grain packed bed with airflow

λ_0 = Effective thermal conductivity of packed bed without airflow

α = Effective thermal diffusivity of grain packed bed

C_g = Specific heat of grain packed bed

G= Mass flow rate in the bin

d_g=Grain diameter

The change in temperature of the grain stored in the bin was calculated for every 10℃ rise in temperature of the bin wall. The base nodal temperature of the bin wall was set at 0℃, the program computes temperature change in the internal points, starting from the boundary element nearest to the bin wall to the one at the center of the bin.

Model Validation

Temperature data collected from the four rectangular bins length 2.9m, width 1.69m and 1.55m high filled with rough rice at 15% moisture content (w.b.), the height of the rough rice bulk was 1m and the thickness of the bulk 75cm was used to validate the model.

To monitor the temperature of the grain, copper constantan thermocouple probes were inserted at 2.5cm interval from the bin wall at 50cm height of the grain bulk to a distance of 9cm and then at 5.5cm and there after at an interval 7.5cm until the center of the grain bulk. The bin wall temperature was measured by placing thermocouple on the outer and inner walls of the bin, ambient air temperature was also measured. The thermocouple probes were connected to an interface analog digital converter (Green kit 77A model) then to personal computer for data collection. The temperature readings from the thermocouple probes were recorded every 20min. through out the duration of the experiment.

Simulation Procedure

The temperature of rough rice was simulated using 40 boundary element and 7 internal points where function is calculated. Thermal and physical properties used for rough rice were as follows, specific heat, 2.03*103J/kg.k. Bulk density 651kg/m^2. The effective thermal diffusivity and the effective thermal conductivity of packed bed of rough rice differ under different air flow rate, and relative direction of air movement through the bin. Many researchers , Matsuoka (1986), Ohshita (1988), Kobe University(1993) reported different values of thermal diffusivity for rough rice measured under differing conditions. Selection of both thermal conductivity and thermal diffusivity for simulation of the temperature distribution in a grain storage bin with aeration unit, requires the air flow rate data, and air flow pattern. Using Yagi and Kunii equation, the effective thermal conductivity and the effective thermal diffusivity for rough under the experimental storage condition were computed and used for the simulation run. The bin wall has coefficient of overall heat transmission of 0.403Kcal/m^2/℃

RESULT AND DISCUSSION

Predicted Temperature

The temperature predicted by the boundary element model closely followed the observed values at several location in the rough rice storage bin. Temperature simulated using the physical properties of rough rice as reported by Matsuoka, Kobe U and Oshita and modified using Yagi and Kunii equation for cross and concurrent air flow were compared with the measured temperature to determine which of the reported rough rice effective thermal conductivity is most appropriate for computing grain temperature under the experimental storage condition.

Fig 4. show the predicted temperature distribution at given locations using the various reported effective thermal conductivity (α). Comparison with the measured temperature showed that temperature predicted using α = 7.9*10-4m^2/h had the least average standard

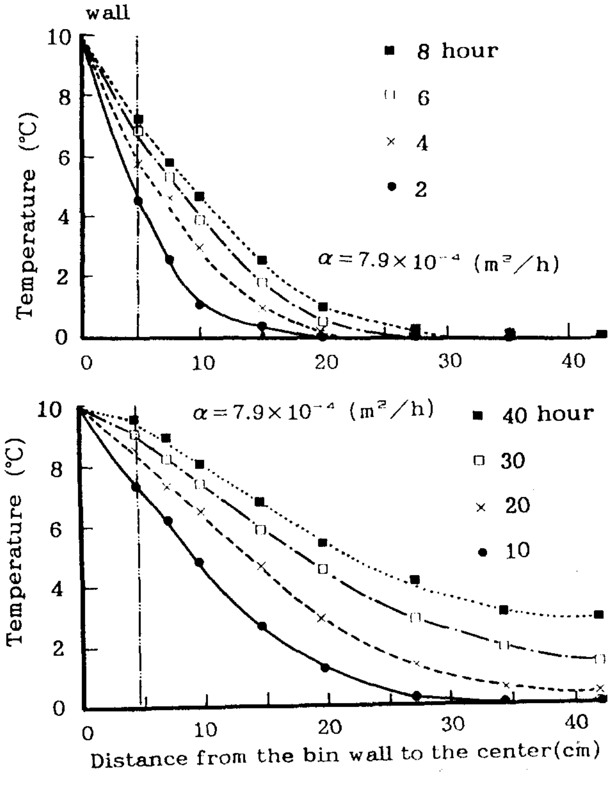

Fig. 3, Predicted temperature distribution in the rough rice storage bins

error of estimate of 1.8℃ . The model was under predicting the grain temperature, however the error of estimate is acceptable for analyzing stored grain ecosystems because grain temperatures are also influenced by several other factors including internal heat generation due to insect and microorganism respiration, variations in thermal properties of the grain due to moisture content and foreign material. The thermal properties of the grains in space and time were assumed constant, and the internal heatgeneration was assumed to be zero. The accuracy of prediction might be improved by taking these factors into consideration

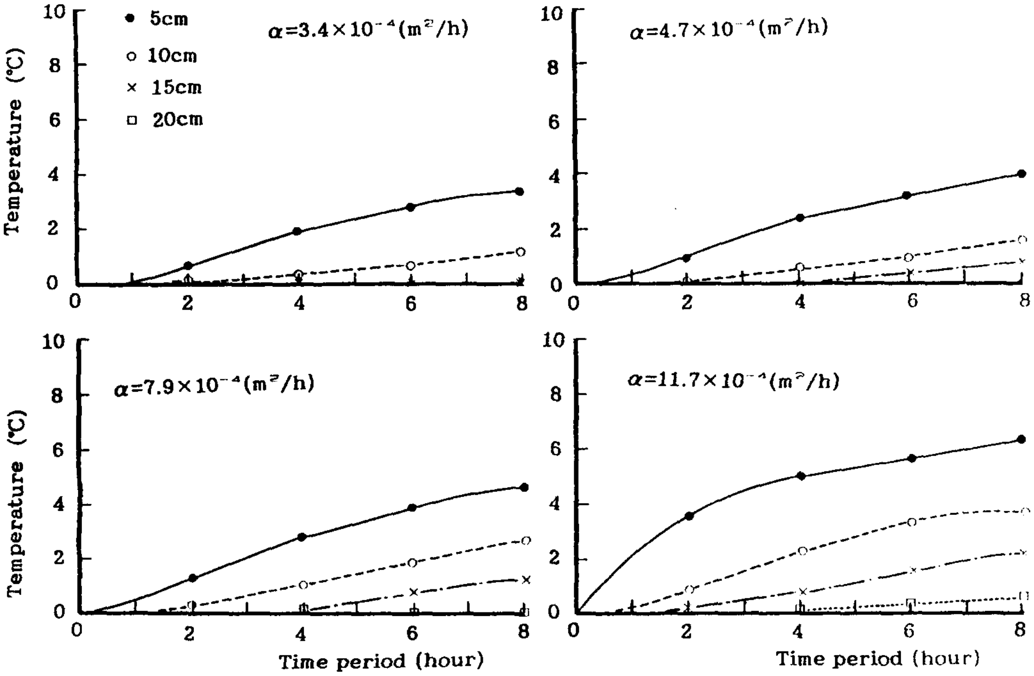

Fig. 4, Predicted temperature distribution in the rough rice storage bins using various author's rough rice effective thermal conductivity

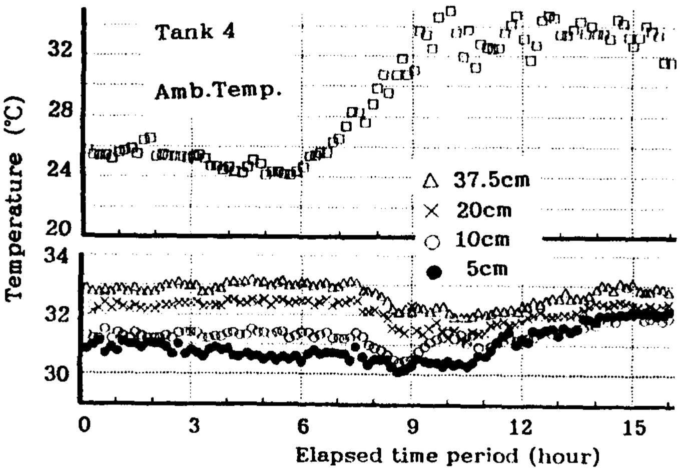

Fig. 5, Daily temperature distribution for 15th of August

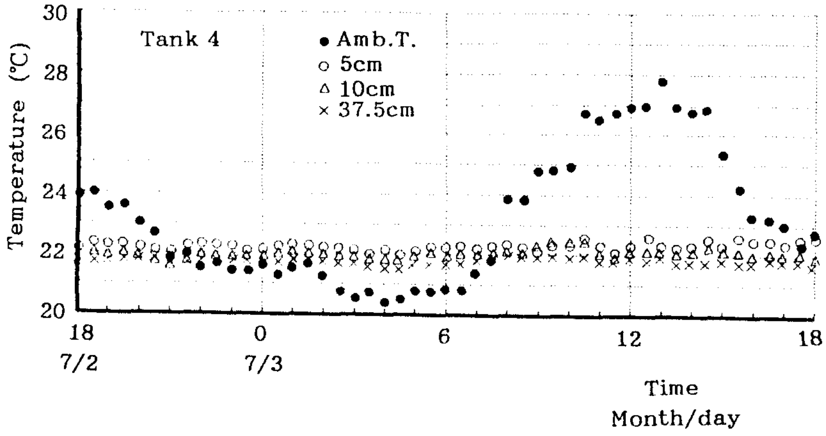

Fig. 6, Observed grain and ambient temperature changes during the 2-3rd July 1992

The diurnal variation of observed air, grain and bin wall temperatures for the 14th to 19th August 1992 are plotted in Fig. 7. The trends in temperature responses during the day time were similar to those of the predicted temperatures. Both the bin wall and the grain near to the bin wall were within 2 to 3℃ of the ambient temperature during the night time hours. Between sunrise and sunset the outer bin wall exceeded ambient temperature. The observed and predicted diurnal grain temperature 37.5cm from the bin wall varied very little over the 120hr period. The observed and predicted diurnal range of temperature 5cm from the bin wall 3.5℃ and 2.3℃ respectively. The diurnal range of ambient air temperature was 10℃. The maximum daily air bin wall and grain temperature changes during the entire observation period 14th to 19th August as shown in Fig. 7 are for the period starting from midnight each day.

Fig. 3 Show the predicted temperature distribution for a 10℃ rise in the temperature of the ambient air in the rough rice storage bin. The predicted temperature in all locations within the bin storage space were slightly lower than the observed temperature. The temperature of the grain located at the center of the bin can be observed from the temperature distribution curve Fig. 3 to have increased by less than 1 ℃ for the simulation period of 40hr. This is lower than the observed value. The error is attributed to the neglect of the internal heat generation of the grain in computing the change in the grain temperature.

Fig 5. show the daily temperature distribution for the 15th of August. It can be observed that during the month of August the temperature of the grain at the center of the storage bin was higher than the grain near to the bin wall, this particular phenomenon is as a result of

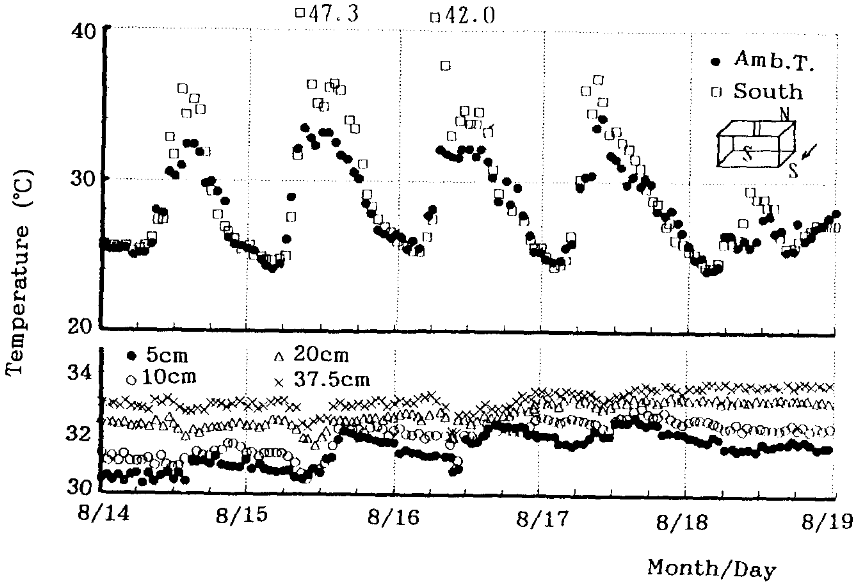

Fig. 7 Observed air and grain temperature during the hottest period of the year (14 to 19 August 1992)

accumulated heat during the hot summer months, since the storage bin was not fitted with aeration facility, heat dissipation from the bulk grain located in the center of the bin to the outside was hampered.

Fig 6. Show the observed grain and ambient temperature changes for the 2nd and 3rd of July. The diurnal changes in ambient temperature is reflected on the temperature distribution of the stored grain. The grain at the center of the bin remain cooler than those near to the bin wall, however as the summer heat mellow down, the grain near the bin wall cool down at a higher rate than the grain located in the center of the bin, this can be observed from the temperature distribution curve for the month of August. The effect of diurnal changes in temperature was not reflected in the predicted grain temperature because the model was programmed to compute the increase in the grain temperature for an increase in the ambient temperature.

CONCLUSIONS

A two dimensional boundary element model was developed to predict the temperature distribution in a rectangular grain storage. The boundary element model predicted temperatures in the storage bin filled with rough rice with an average standard error of estimate of 1.8°C. The temperature predicted by the the boundary element model closely follow the observed values at several location in the storage bin. The predicted temperatures were for all location slightly lower than the observed temperature.

The accuracy of prediction would be improved by taking into account the internal heat generation and variation in the thermal properties of grain due to moisture content.

The model provided the basis for predicting the grain and bin temperatures, thus enabling the study of stored product ecosystem.

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