AU J.T. 8(3): 146-152 (Jan. 2005)

Transient Temperature Variations in Stored Maize Bulk

B.A. Alabadan

Department of Agricultural Engineering
Federal University of Technology, Minna, Nigeria

Abstract

A two-dimensional transient heat conduction equation was solved by finite-difference method to predict temperature variations within the maize (Zea mays) bin. The mathematical model comprises the center, interior and exterior heat transfer equations. Variables used include bin diameter, bin-wall material, grain temperatures, grain thermal and air properties. Software was developed for the model in Visual Basic. Temperatures within the silo were predicted at radii 0.0m (silo center), 0.35m, and 0.7m (Silo Wall) and depths 0.0m (Silo Floor), 0.30m, 0.70m and 1.1m (Silo Top). To validate the model, a 1- ton capacity, 1.4m diameter and 1.1m height wooden silo was constructed to measure grain temperatures at the same radii and depths within the silo and ambient temperatures between July 1998 and March 1999 (9 months). Predicted and measured temperatures at the various radii and depths were in good agreement and not significantly different using F- test at 5% level of significance. Temperature gradient decreases from the wall towards the center and from the top to the floor. Wooden bin maintained lower temperatures than ambient temperatures at all seasons.

Keywords*: Storage, maize, temperature gradient, transient.*

Introduction

Farmers all over the world lose much of their grains due to influence/activities of insects, rats, birds, microorganisms and the interplay of some environmental conditions that could promote the activities of these agents of deterioration (Igbeka 1992). Ng (1994) identified the two most important factors affecting the storage conditions of grains as the storage temperature and relative humidity.

Abe and Basunia (1996) found that heat, moisture, and CO_2 are produced by respiration of living organisms during the deterioration of grain. It then became evident that grain temperature, moisture content, and increases in CO_2 concentration in the inter-granular air can be used as indicators of incipient grain spoilage.

Since temperature, moisture, carbon-dioxide (CO_2), oxygen (O_2), grain characteristics, microorganisms, insects, mites, rodents, birds, geographical location and granary structure are paramount to safe storage of grains, a prediction of their effects due to naturally occurring variations in weather is necessary. Monitoring temperature data at various points within the silo over along period is one way of finding temperature distributions. This approach is inefficient, requires a lot time, cost and labor. Mathematical models can potentially predict with accuracy temperature distributions with effects of several internal and external variables on the silo.

Various research workers have developed mathematical models to predict temperatures in stored grains (Yaciuk, *et al*. 1975; Longstaff and Banks 1986; White 1988; Alagusundaram, *et al*. 1990a, 1990b; Chang, *et al*. 1993; Jayas, *et al*. 1994; Basunia, *et al.* 1996 and Lucas and Alabadan 2002).

The objectives of this work are to:

(i) Develop a two-dimensional mathematical model to predict the temperature changes storage of maize; and

(ii) Measure the temperature distributions at the same locations of the storage bin to validate the model.

Simulation of Temperature

The following simplifying assumptions are made for deriving the governing equations of heat flow through the bulk maize:

(i) The bulk density, specific heat capacity and thermal conductivity of grain are constant and uniform throughout the bin.
(ii) Heat transfer by conduction in the circumferential direction is negligible.
(iii) Heat flow patterns are symmetrical around the vertical central axis of the hexagonal bin
(iv) Internal heat generation within the grain bin is negligible.
(v) Initial grain temperature is equilibrated with ambient temperature.
(vi) Temperature differences between the air within the grain bulk is negligible.

With the above assumptions, the general differential equation of heat flow in two-dimension in a cylindrical coordinate systems which is adapted for the hexagonal bin can be written as:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial y^2}\right)$$

and $$\alpha = \frac{Kg}{\rho c_p} \qquad (1)$$

According to Carslaw and Jaeger (1959), the initial condition for equation (1) is

$$T(r, y, t) = T_i(r, y) \text{ for } t = 0, 0 \le r, y \le R \qquad (2)$$

Term T_i is the initial grain temperature. Considering that the boundary surface of the bin is subjected to a similar convective heat transfer in a medium of the ambient temperature the boundary conditions for equation (1) given by Carslaw and Jaeger (1959) are:

$$\pm K_g\left(\frac{\partial T}{\partial r} + \frac{\partial T}{\partial y}\right) + h_c(T - T_a) = 0 \quad \text{for } t > 0, r, y = R \quad (3)$$

$$T(r, y, t) = T(r) \text{ for } t > 0, r, y = R \qquad (4)$$

Since the varying ambient temperature determines the initial and boundary conditions, it is difficult to develop an analytical solution for equation (1). As an alternative to this, numerical methods of solution are adopted.

Finite-difference Method

In equation (1), temperature, T, is a function of the independent variables of radial length, r from the centre of the bin; axial distance y from the centre of the bin and storage time, t. In the r-y plane, any point of coordinate r and y is represented by $r = m\Delta r$ and $y = n\Delta y$, and $\Delta r = \partial r$ and $\Delta y = \partial y$ (Abe and Basunia 1996). The temperature at any point is denoted by $T_{m,n}$. In addition to being discretized in space, the problem must be discretized in time. The integer p is introduced for this purpose, where $t = p\Delta t$. The subscript p is used to denote the time dependence of T, and the time derivative is expressed in terms of the difference in temperatures associated with the (p + 1) and previous (p) times. Hence, calculations are performed at successive times separated by interval Δt.

The explicit form of finite-difference of equation (1) for the interior node, *m* of the storage bin is:

$$\frac{1}{\alpha}\left(\frac{T_{m,n}^{p+1} - T_{m,n}^{p}}{\Delta t}\right) = \frac{T_{m+1,n}^{p} + T_{m-1,n}^{p} - 2T_{m,n}^{p}}{(\Delta r)^2} + \frac{T_{m+1,n}^{p} - T_{m,n}^{p}}{m(\Delta r)^2} + \frac{T_{m,n+1}^{p} + T_{m,n-1}^{p} - 2T_{m,n}^{p}}{(\Delta y)^2} \qquad (5)$$

Solving for the nodal temperature at the new (p + 1) time and assuming that $\Delta r = \Delta y$, it follows that:

$$T_{m,n}^{p+1} - T_{m,n}^{p} = \frac{\alpha\Delta t}{(\Delta r)^2}\left[T_{m+1,n}^{p}\left(1 + \frac{1}{m}\right) + T_{m-1,n}^{p} + T_{m,n+1}^{p} + T_{m,n-1}^{p} - T_{m,n}^{p}\left(4 + \frac{1}{m}\right)\right] \qquad (6)$$

$$T_{m,n}^{p+1} - T_{m,n}^{p} = F_0\left[T_{m+1,n}^{p}\left(1 + \frac{1}{m}\right) + T_{m-1,n}^{p} + T_{m,n+1}^{p} + T_{m,n-1}^{p} - T_{m,n}^{p}\left(4 + \frac{1}{m}\right)\right] \qquad (7)$$

Equation (1) is invalid at the center of the bin where $\partial T/r\partial r$ becomes an indeterminate quantity.

However, using L'Hospital's rule, equation (1) can be transformed into the following form:

$$\lim_{r \to 0} \left(\frac{1}{r} \frac{\partial T}{\partial r} \right) = \frac{\partial^2 T}{\partial r^2} \qquad (8)$$

Now equation (1) for the centre of the bin can be written as:

$$\frac{\partial T}{\partial t} = \alpha \left(2 \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial y^2} \right) \qquad (9)$$

The finite-difference form of equation (9) for the centre of the bin where r = 0 (m = 0,n = 0) at new (p+1) is:

$$T_{0,0}^{p+1} = 2F_0 \left(T_{1,0}^{p} + T_{-1,0}^{p} \right) + F_0 \left(T_{0,1}^{p} + T_{0,-1}^{p} \right) + \left(1 - 6F_0 \right) T_{0,0}^{p} \qquad (10)$$

For a constant boundary temperature, the solution of equation (1) is simple and can be obtained by using equations (7) and (10). But in practice, the surface temperature changes with variation of the ambient or outside temperature. Frank and David (1990) and Abe and Basunia (1996) agreed that for points on such surfaces, which are exposed to convective conditions, the finite-difference equation must be obtained by applying the energy balance method to the control volume about that node.

Thus the finite-difference form of the equation (1) for the exterior points with specified convective boundary condition at the new time (p+1) from equation (7) is given by:

$$T_{m,n}^{p+1} = F_{_0} \left[2T_{m-1,n}^{p} + T_{m,n+1}^{p} + T_{m,n-1}^{p} + \frac{2B_i T_a^{p}}{1 + \frac{h_c L_w}{K_w}} \right] + \left[1 - 4F_{_0} - \frac{2F_{_0} B_i}{1 + \frac{h_c L_w}{K_w}} \right] T_{m,n}^{p} \qquad (11)$$

Where the finite-difference form of the Biot No. is $B_i = h_c \Delta r / k_g$ and the Biot No. of the bin-wall material, is $B_W = h_c L_W / k_W$.

The modified equation, Equation 11, was adopted for the surface elements. Equations (7), (10) and (11) were applied to each interior node, the centre node and the surface node of the bin respectively to determine and obtain the temperature distribution by successive increment in t by Δt. The three equations are solved together simultaneously using the Gauss-Seidal iteration method.

Since Bi > 0, the stability criterion determined from equation 11 to ensure stability for all nodes is

$$F_{_0} \left(2 + \frac{B_i}{1 + h_c L_w / K_w} \right) \le \frac{1}{2} \qquad (12)$$

Methodology

Description of the Silo

For the verification of the model, a one ton capacity model of the wooden silo (Fig. 1) was constructed and erected in Minna, Nigeria. The walls, roof and floor were made from plywood while the frames were made from 2 x 2-solid Iroko (*Melicia excelsa*) timber. Plywood of exterior grade was used. The plywood is 3 plies (9 mm) thick, 1,440 x 2,880 mm in area and bonded together using phenol-formaldehyde resin adhesive. The silo has three openings; a triangular shaped one at the top for loading, and two squares shaped ones at the sides that serve as door and discharge chute. All the openings are normally kept closed so that the bin is practically airtight. The silo is raised 0.5m above the ground level with the timber columns fitted with rodent guards.

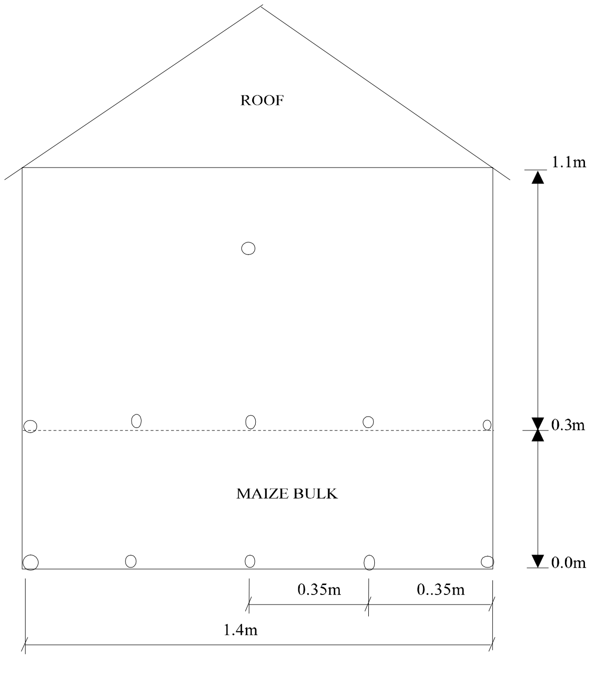

Fig. 1: A Cross-section of the Silo with Layers and Points of Temperature Measurement.

Measurement of Temperature

The positions of the temperature probes are shown in Fig. 1. The silo is filled with shelled corn of height 0.3m and 300 Kg weight at initial moisture content of 13.8 % wet basis. Temperature were measured at depths 0.0m (silo floor), 0.3m and 0.7m (grain surface) and radii 0.0m (silo center), 0.35m and 0.7m (wall/grain inter-phase) with both the dry-bulb and wet-bulb ambient temperature of the silo. Measurements were taken three times daily at 900, 1200 and 1500 hours for morning, afternoon and evening, respectively. Daily average of the temperature values was used.

Results and Discussion

Geographical Location

The average monthly temperature in Minna, Nigeria ranged between 28.50^{o}C in the wet season of August (wet season) to 38.90^{o}C in February and March (dry season) giving a range of 10.40^{o}C. The corresponding average monthly rainfall was usually about 409.0mm in August and none in February and March.

Temperature Variations at the Centre, interior and Wall of the Wooden Silo

From Figs. 2 to 7, it can be observed that simulated temperatures in the stored grain changed slowly except for the layers next to the bin wall and or near the grain surface in agreement with the report of Lo, *et al.* (1975) on bins made from plywood and concrete. The temperature lag between the ambient and the silo temperatures range between about 2^{o}C at the wall and 10^{o}C at the center.

The range of temperatures at the centre (radius 0.0m and depth 0.3m) is between 24.00 - 36.00^{0}C and 27.33 - 31.86^{o}C for measured and predicted respectively as shown in Fig. 2. There is a close agreement between the measured and predicted temperatures. The relationship is not significant at 5% level of significance using F-test and the standard error of estimate of 0.85^{o}C. This is in agreement with the findings by Lo, *et al.* (1975).

At the interior (radius 0.35m and depth 0.3m) as shown in Fig. 3, temperatures ranged between 24.42 - 37.50^{o}C for measured and 27.09 - 31.86^{o}C for predicted. The relationship is not significantly different with the standard error of estimate of 0.97^{o}C.

The measured and predicted temperatures at the internal wall (radius 0.7m and depth 0.3m) ranged between 24.30 - 39.00^{o}C and 26.16 - 31.98^{o}C respectively as shown in Fig. 4. The standard error of estimate is 0.97^{o}C and also not significant.

There are close agreement between the measured and predicted temperatures at radii 0.0, 0.35 and 0.7m at depth 0.0m (Silo floor) as shown in Figs. 5, 6 and 7, respectively, for center, interior, and internal wall of the wooden silo. The standard error of estimate was 0.78, 0.90 and 0.90^{o}C, respectively for the different radii. These temperatures followed the same pattern like those at depth 0.3m but were generally lower with about 3-4^{o}C. This is in agreement with the findings of Chang, *et al.* (1993) in the United States that reported a range of 9-10^{o}C between bin top surface and bin floor in 6.6m diameter wooden silo.

At depth of 0.7m and above, the bin temperatures were about 8^{o}C higher than those at the depth of 0.3m. A comparative assessment of the surface temperatures and the ambient temperatures show that the standard error of estimate was 1.67^{o}C with F-test value of 1.504E-06. The grain surface temperatures were about 1-5^{o}C higher than the ambient temperatures during the wet period between July to November (150 days of storage). The dry period between December to March recorded a difference of up to 8^{o}C probably due to accumulated heat during the days and the long hours of sunshine. This phenomenon is a potential source of danger to the grain bulk in storage. The consequences is the exposure of the grain surface to invasion by insect pests while the boundary between the grain bulk and the head space of the storage bin are subjected to the extensive heat, gas and vapor transfer processes occurring between these two systems as reported by Longstaff and Banks (1987).

From the patterns above, temperature variation increases from the bin floor to the bin top but increases from the center towards to the wall.

Also, the measured data have more peaks and valleys than the simulated results. This could be due to the fact that the measured temperatures were taken at three times daily and the usage of the average values for the plot.

Conclusion

Based on the results of this study, the following conclusions are drawn:

(i) A two dimensional finite-difference mathematical heat transfer model to predict a temperature variation in wooden silo was developed.

(ii) Temperatures were highest at the top of the silo and decreases through the grain bulk towards the floor.

(iii) The measured and predicted temperatures of the silo were not significantly different at 5 and 1% levels of significance on statistical analysis using F-test.

(iv) Temperatures at the grain headspace (surface) were 1-8^{o}C higher than the ambient temperatures. The higher temperatures make the space most conducive for insect pests and also extensive heat.

(v) The temperatures at various points within the wooden silo were generally lower than those from other silo materials such as steel. This shows a great potential of the wood product in reducing the effect of the ambient temperatures and hence would perform better in the tropics than steel.

References

Abe, T.; and Basunia, M.A. 1996. Simulation of temperature and Moisture changes during storage of rough weather variability. J. of Agric. Engineering Research 65: 223-333.

Alagusundaram, K.; Jayas, D.S.; White, N.D.G.; and Muir, W.E. 1990a. Finite difference model of three-dimensional heat transfer in grain bins. Trans. of the ASAE 32: 315-321.

Alagusundaram, K.; Jayas, D.S.; White, N.D.G.; and Muir, W.E. 1990b. Three-dimensional, finite element, heat transfer model of temperature distribution in grain storage bins. Trans. of the ASAE 33: 577-584.

Basunia, M.A.; Abe, T.; and Bala, B.K. 1996. Application of finite element method for the simulation of temperature distribution during storage of rough rice in cylindrical bin. Agric. Mechaniz. in Asia, Africa and Latin America (AMA) 27(2): 33-40.

Carslaw, H.S.; and Jaeger, J.C. 1959. Conduction of Heat in Solids. 2nd Ed. Oxford University Press, London.

Chang, C.S.; Converse, H.H.; and Steele, J.L. 1993. Modeling of temperature of grain during storage with aeration. Trans. of the ASAE 36(2): 500-519.

Frank, P.I.; and David, P.D. 1990. Fundamentals of Heat and Mass Transfer. John Wiley,

Igbeka, J.C. 1992. Interrelations of Variable and Factors of Deterioration in Stored Grains. Lecture delivered at the Induction Course for Engineers and Pest Control Officers of Strategic Grain Reserve complexes held at Crop Storage Unit, Ibadan. Nigeria.

Jayas, D.S.; Alagusundaram, K.; Shunmugam, G.; Muir, W.E.; and White, N.D.G. 1994. Simulated temperatures of stored grain bulks. Canadian Agricultural Engineering 36 (4): 239-245

Lo, K.M.; Chen, C.S.; Clayton, J.T.; and Adrian. D.D. 1975. Simulation of temperature and moisture changes in wheat storage due to weather variability. J. of Agric. Engineering Research 20: 47-53.

Longstaff, R.A.; and Banks, H.J. 1987. Simulation of temperature fluctuations near the surface of grain bulks. J. of Stored Product Research 23: 21-30.

Lucas, E.B.; and Alabadan, B.A. 2002. Simulation of temperature changes during storage.e of maize in hexagonal wooden bin due to weather variability. J. of Applied Science and Technology 2(1): 16-32.

Ng, N.Q. 1994. Preservation of Genetic Resources by Seed Storage. IITA Research Guide 52. Training Program, IITA, Ibadan, Nigeria.

White, G.G. 1988. Temperature changes in bulk stored wheat in sub-tropical Australia. J. of Stored Product Research 24 (1): 5-11.

Yaciuk, G.; Muir, W.E.; and Sinha, R.N. 1975. A simulation model of temperatures in stored grain. J. of Agric. Engineering Research 20: 245-258.

Notations

α	thermal diffusivity of stored grain,(m^2/h)
ρ_a	density of air, (Kg/m^3)
ρ	bulk density of the stored grains, (Kg/m^3)
Δr	space interval or finite increment in radial direction, (m)
Δt	time interval or increment, (s)
B_i	Biot number
B_w	Biot number for silo-wall material
c_p	specific heat of shelled maize, (J/ Kg K)
D	diameter of silo or bin, (m)
F_0	Fourier number
h_c	convective heat transfer coefficient on silo wall, (W/m^2K)
K_a	thermal conductivity of air, (W/mK)
K_g	thermal conductivity of the stored grain, (W/mK)
K_w	thermal conductivity of silo wall material, (W/mK)
L_w	silo wall thickness, (m)
m ,p,n	integer
R, r	radial coordinate of the hexagonal storage silo, (m)
y	vertical coordinate of the hexagonal storage silo, (m)
t	time, (s)
T	Temperature of grain, (^0C)
$T_a{}^p$	Ambient temperature of the wooden silo at any time p (^oC)
$T_a{}^{p+1}$	Ambient temperature of the wooden silo at any time p+1 (^oC)
$T_{m,n}{}^{p+1}$	Ambient temperature of the wooden silo at any time p+1 (^oC)
$T_{m,n}{}^p$ silo	Ambient temperature of the wooden at any time p (^oC)

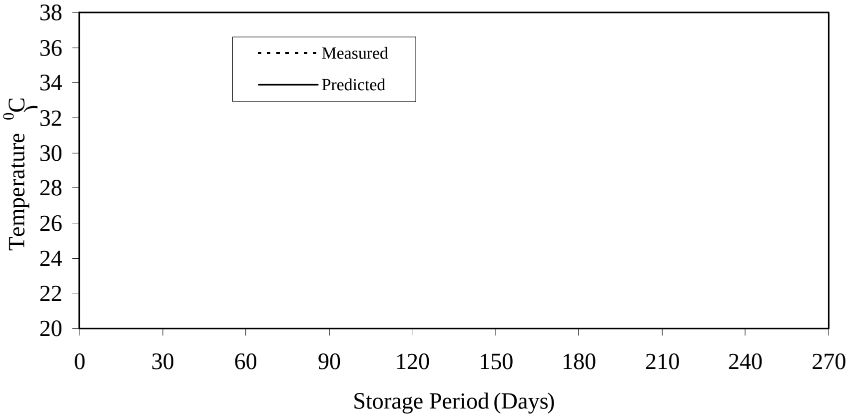

Fig. 2: Grain Temperatures at radius 0.0m and Depth 0.3m

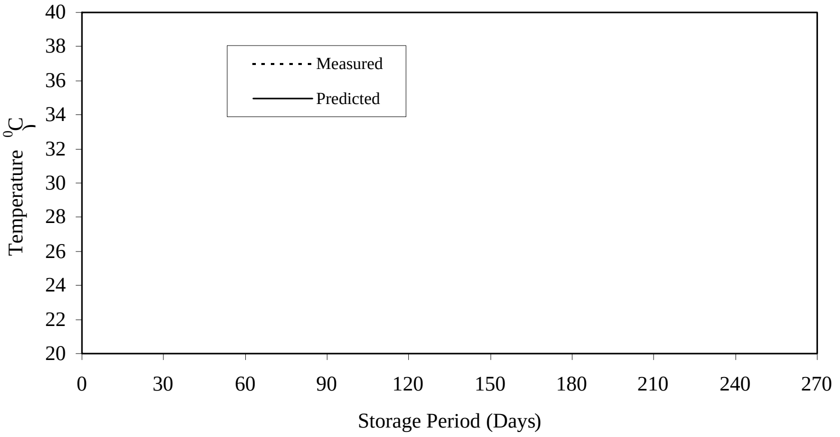

Fig. 3: Grain Temperatures at radius 0.35m and Depth 0.3m

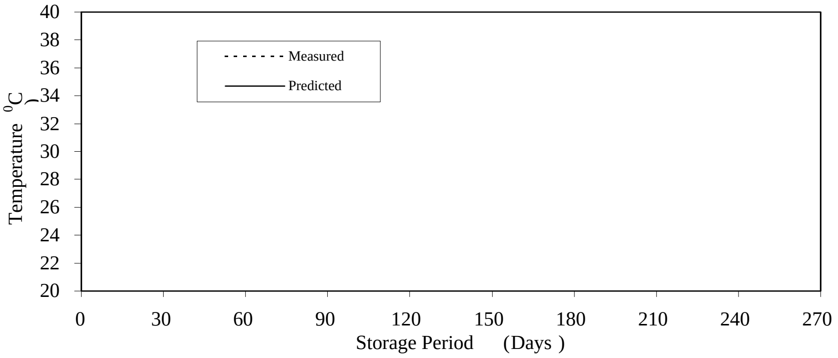

Fig . 4: Grain Temperatures at radius 0.7m and Depth 0.3m

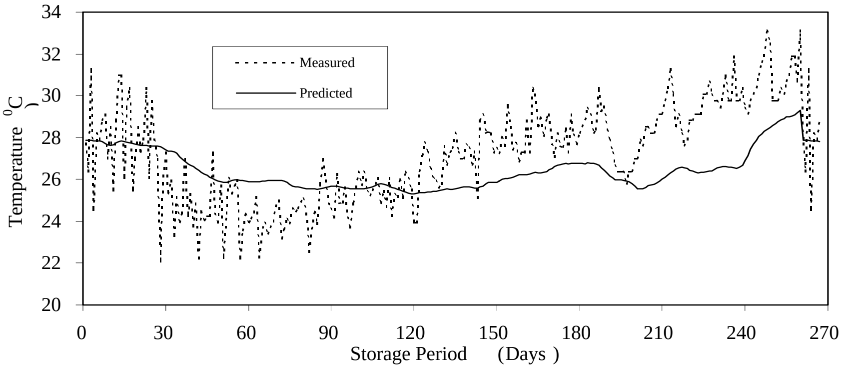

Fig . 5: Grain Temperatures at radius 0.0m and Depth 0.0m

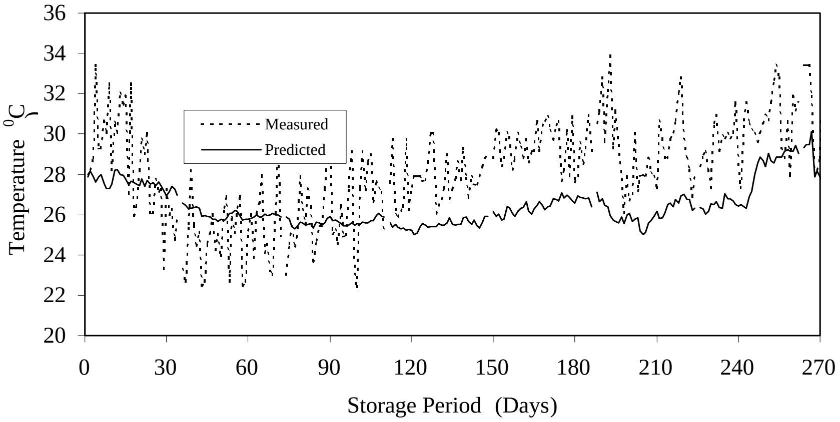

Fig. 6: Grain Temperatures at radius 0.35m and Depth 0.0m

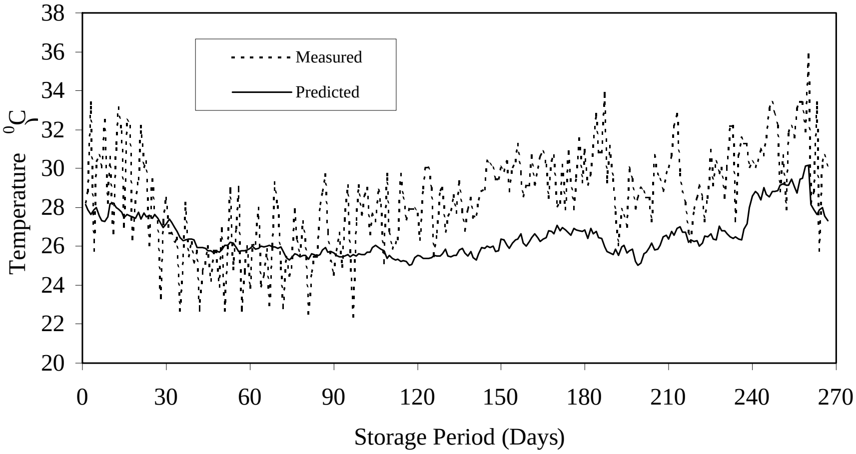

Fig. 7: Grain Temperatures at radius 0.7m and Depth 0.0m