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Measured and predicted temperature of maize grain (Zea mays L.) under hermetic storage conditions

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Abstract

The physical properties of grain, such as temperature and moisture content are two key factors in grain storage. Temperature and relative humidity are two crucial factors for stored grain. In this study, three different storage conditions (room temperature at , 25°C; cooling at , 4 °C; and freezing at , -20°C) were investigated. Yellow dent corn (Zea mays L.) maize(variety Blue River 571136) from Iowa, harvested in 2011 was used. Maize grain was stored in two hermetical sealed binsarrels (50-cm diameter x 76-cm height). Five logger sensors were installed inside the cylindrical bin to measure temperature and relative humidity of the maize graingrain. The sensors were located at the top, center, bottom, left and right at about 12 cm part. After placing each barrel into storage condition, temperature and relative humidity values were measured every minute for 9 days throughout the duration of the experiment. Model validation was carried out by comparing predicted with measured maize grain temperature data data in three differences points of plastic cylindrically bin the radial and vertical directions. arrel.The temperature in the hermetically sealed cylindrical bins varied, mostly in the radial direction and very little in the axial vertical directions. No noticeable change in temperature was observed in room condition. Moreover, the temperature in the grain changed more rapidly in the freezing conditions than in the room and cooling conditions. Furthermore, the lag time between the center temperature and the side (right, left, top, and bottom) was greater in the radial direction as compared to vertical temperature. Model validation was carried out by comparing predicted with measured maize temperature data in three differences points of plastic cylindrically barrel. Predicted data were closely followed measured data. The model can be used to predict the grain temperature changes in room, cooling and freezing under hermetic conditions.The maximum difference between predicted and measured temperature was ±1.5°C. The predicted and measured values of maize grain temperature at radial and vertical directions were found to be in good agreement. The model shows a good potential application to predict the temperature of maize grain stored at room, cooling and freezing conditions under hermetic storage.

Keywords

Maize, Mathematical model, Heat transfer, Grain temperature, Grain storage, Hermetic storage, Modeling

Disciplines

Agriculture | Bioresource and Agricultural Engineering

Comments

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Measured and predicted temperature of maize grain (*Zea mays* L.) under hermetic storage conditions

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The physical properties of grain, such as temperature and moisture content are two key factors in grain storage. In this study, three different storage conditions (room temperature at 25°C; cooling at 4°C; and freezing at -20°C) were investigated. Yellow dent corn (*Zea mays* L.) variety Blue River 571136 from Iowa, harvested in 2011 was used. Maize grain was stored in two hermetical sealed bins (50-cm diameter x 76-cm height). Five logger sensors were installed inside the bin to measure temperature and relative humidity of the maize grain. The sensors were located at the top, center, bottom, left and right at about 12 cm part. After placing each barrel in storage condition, temperature and relative humidity values were measured every minute for 9 days throughout the duration of the experiment. Model validation was carried out by comparing predicted with measured maize grain temperature data in the radial and vertical directions. The temperature in the hermetically sealed cylindrical bins varied, mostly in the radial direction and very little in the axial vertical directions. No noticeable change in temperature was observed in room condition. Moreover, the temperature in the grain changed more rapidly in the freezing conditions than in the room and cooling conditions. Furthermore, the lag time between the center temperature and the side (right, left, top and bottom) was greater in the radial direction *as* compared to vertical temperature. The maximum difference between predicted and measured temperature was ±1.5°C. The predicted and measured values of maize grain temperature at radial and vertical directions were found to be in good agreement. The model shows a good potential application to predict the temperature of maize grain stored at room, cooling and freezing conditions under hermetic storage.

Key words: Maize, grain temperature, grain storage, hermetic storage, modeling.

INTRODUCTION

The knowledge of physical and thermal properties of grain is essential to the food engineers, processors and grains ecologists for the effective designing of machine, storage structures, heat transfer optimization and bulk storage (Amin et al., 2004; Mohamed, 2009). The physical properties of grain such as moisture content and

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temperature are two key factors in grain storage. Temperature and moisture content are the main causes of grain spoilage in stored grain ecosystems (Manickavasagan et al., 2006). As reported by many researchers, moisture content and temperature are the two key factors in maintaining grain quality during handling, storage and are the major sources of grain deterioration, because they encourage the growth of mold and infestation of insects (Parry, 1985; Jin, 1996; Flinn et al., 1997). Likewise, as mentioned by Hong et al., (1997) and Ng (1994), temperature, moisture content and relative humidity are three major factors influence storage conditions of grain. Furthermore Jayas and White (2003) revealed that temperature and moisture content are the two physical factors that control deterioration and quality of grain in storage. In addition White (1995) reported that the growth and multiplication of biological agents such as insect and mold in grains are highly dependent on the presence of temperature and moisture content.

Moreover, temperature and moisture content can be used to predict grain drying and deterioration potential (Iguaz et al., 2000). Temperature is regarded as a physical variable in grain storage, the variability is from from two main sources: internal and external. Internal are those from grain respiration (Equation 1), insects, mites, rodents and other microorganisms. While external sources are mainly from the solar radiation and surrounding area around the storage bin (Jia et al., 2000; Andrade et al., 2002).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2834\ \mathrm{kJ} \quad (1)$$

In addition, grain kernels like other living substances continue to respire after harvest, releasing CO_2, water vapor and heat (Iguaz et al., 2004). Consequently, increased temperature of grain and moisture migration creates favorable conditions for insects and mold to flourish (Suleiman et al., 2013; Iguaz et al., 2004). Carbon dioxide released by grain and other organisms is used as a parameter for grain deterioration and directly related to dry matter loss of grain (Sharp, 1982). Temperature is a single most important non-biological factor controlling the rate of deterioration of grain in storage (Muir and Viravanichai, 1972) and can be easily measured and simulated mathematically (Yaciuk et al., 1975). Moreover, temperature and moisture content can be modeled mathematically to optimize storage conditions and efficient control measured at any point in a storage bin (Lawrence et al., 2013; Iguaz et al., 2000). Further, Sutherland et al. (1971) showed mathematical models based upon physical and thermal properties of grain as a useful tool to predict grain conditions in a storage bin.

Furthermore, mathematical models have been used as initial tools for predicting physical factors like temperature and moisture content in grain storage (Jin, 1996; Yaciuk et al., 1975). In addition, mathematical simulation can be used to predict the temperature distribution in grain storage structure with different shape and sizes, grain varieties and locations (Jia et al., 2000). The main advantages of the mathematical model outline by Andrade et al. (2002) and others include lower cost and it takes less time than is needed in the experimental investigations. It allows analyzing systems that are impossible to accomplish by experimental investigations and it allows the complementation of experimental investigations with more detailed information (Andrade et al., 2002; Jian et al., 2005; Franca and Haghighi, 1995). Several three-dimensional heat transfer models have been developed for simulating grain storage temperature in the cylindrical bin (Andrade et al., 2002; Jian et al., 2005; Lawrence et al., 2013; Jayas et al, 1995). Thus, the consequences of variations in the dimensions, geometry, properties of the materials and external conditions can be easily studied by using computer simulation (Franca and Haghighi, 1995). Although, several 3D heat transfer models have been established, 3 D heat transfer model in grain storage under hermetic conditions has not yet been developed. Therefore, the aim of this study was to develop a mathematical model to optimize storage condition of maize in a cylindrical bin in the room, freezing and cold temperature under hermetic condition.

MATERIALS AND METHODS

Experimental set up and procedure

A temperature equilibrium experiment was conducted at a water quality, laboratory, Iowa State University; the laboratory was fitted to Norlake Scientific RSF5 compartments chamber (cold room at 4°C and freezer at -20°C). Maize of commercial hybrid Blue River 57436 with initial temperature and moisture content of 21°C and 14.5±0.5% (wet basis) respectively, was used, two cylindrical plastic barrels, 50 cm diameter by 76 cm by height, were filled with maize to a height of 45 cm and airtight (hermetic) to maintain uniform conditions, each were fitted with five sensors from omega engineering, Inc. models OM-EL-USB-2-LCD and OM-EL-USB-2-LCD-PLUS placed about 12 cm apart (top, center, bottom, right, and left) as shown in Figure 1 to measure internal temperature, dew point and relative humidity of maize.

The barrels were stored at room temperature for 72 h, then moved to the cooler for 72 h, move back to the room for another 72 h. The same procedures were repeated for freezer condition. Censors were set to record the data after every 5 min for 9 days for each condition. Then censors were carefully removed and the data were downloaded in the computer and analyzed. The following assumptions were made while developing this model:

1. Maize was assumed to be free of arthropod populations and mold growth.
2. Conduction where the only heat transfer was between the grain bulk (in the horizontal and vertical direction) and the sides of the bin.
3. Properties of maize grain remain constant.
4. Initial maize temperature (T_o) is at a specified temperature.
5. The maize temperature at the center of the bin (r = 0) is a finite.

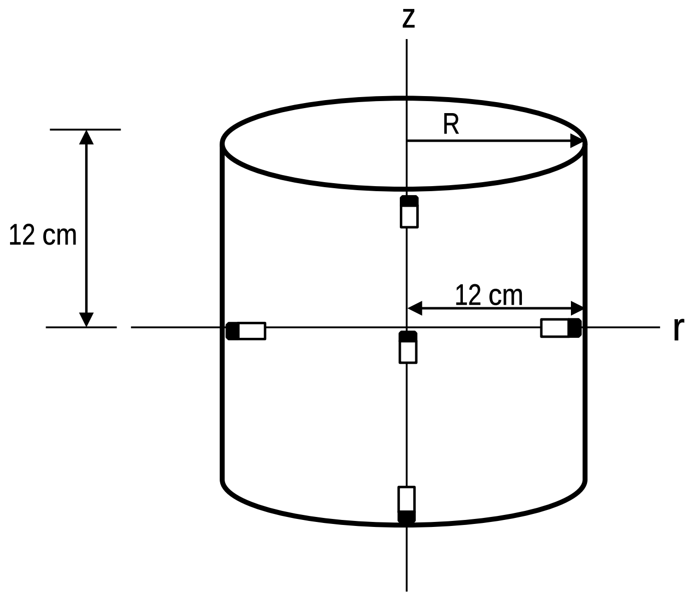

Figure 1. The cylindrical geometry shows temperature/relative humidity sensor arrangement.

6. Ambient temperature (T_a) or grain temperature at the wall (r = R)

Model development

The partial differential equation describes the heat transport inside the grain storage bin under cylindrical coordinate system (Figure 1) following Fourier's law (Incropera and De Witt, 1996; Andrade et al., 2002; Mills, 1995). The heat conduction equations are:

$$q_r = -k\frac{\delta T}{\delta r}; \qquad q_\phi = -\frac{k}{r}\frac{\delta T}{\delta \phi}; \qquad q_z = -k\frac{\delta T}{\delta z} \tag{2}$$

Where q_r is the component of the heat flux in the r direction, $\frac{\delta T}{\delta r}$ is the partial derivative of T(r, ϕ, z and t) with respect to r, same for ϕ and z directions.

$$q = k\nabla^2 T \tag{3}$$

$$\frac{1}{r}\frac{\delta}{\delta r}\left(kr\frac{\delta T}{\delta r}\right) + \frac{1}{r^2}\frac{\delta}{\delta \phi}\left(k\frac{\delta T}{\delta \phi}\right) + \frac{\delta}{\delta z}\left(k\frac{\delta T}{\delta z}\right) + \frac{\dot{q}}{\rho c_p} = \frac{\delta T}{\delta t} + vr\frac{\delta T}{\delta r} + v\phi\frac{\delta T}{\delta \phi} + vz\frac{\delta T}{\delta z} \tag{4}$$

For stationary materials like maize grain ($v_r = v_\phi = v_z = 0$), Equation 4 will be simplified to:

$$\frac{1}{r}\frac{\delta}{\delta r}\left(kr\frac{\delta T}{\delta r}\right) + \frac{1}{r^2}\frac{\delta}{\delta \phi}\left(k\frac{\delta T}{\delta \phi}\right) + \frac{\delta}{\delta z}\left(k\frac{\delta T}{\delta z}\right) + \dot{q} = \rho c_p\frac{\delta T}{\delta t} \tag{5}$$

Where r, ϕ and z are the cylindrical coordinates, k is the thermal conductivity of maize (W/m*°C), ρ is the specific mass or density of maize (kg/m^3), C_p denotes the specific heat of maize in (kJ/kg*°C), t is the time in s, T is the temperature of the maize kernel (°C), and $\dot{q}$ is the rate of generation of heat as function of (r, φ, z, and t) in W.

The boundary and initial conditions for the Equation 5 are:

$$at\ t = 0, \quad 0 \le r \le R{:}\, T = T_{in} \tag{6}$$

$$0 \le r \le L{:} = T_{in} \tag{7}$$

Where, T_{in}= initial temperature, T= temperature at time (t) and point (x), F_o = Fourier number = ($\alpha t/L^2$), with δ_n being roots of the Bessel function Jo(R δn) = 0. The validation of the simulated model was done by comparing the simulated temperatures with measured temperatures.

Physical properties of maize grains

The value of the thermal and physical properties of the maize grains and plastic cylindrical bins used in the simulation is presented in Table 1. Thermal properties of maize grain (the thermal conductivity and the diffusivity) were determined by a thermal properties meter (KD2, Decagon Devices, Pullman, Wash).

RESULTS

The measured and predicted maize grain temperatures at five different positions (top, center, right, left and bottom) in the cylindrical bin filled with maize grains were determined. Temperatures were monitored at three different conditions (room, cooler and freezer) in vertical

Table 1. Thermal and physical properties for corn and plastic barrel bin.

Property	Maize	Plastic barrel (bin)*
Specific heat (J/kg/C)	1851.5	16700
Thermal conductivity (W/m/K)	0.1618	0.50
Thermal diffusivity (m^2/s)	1.21×10^{-7}	---
Density (kg/m^3)	1247	---
Initial moisture content (% w. b.)	12.7	---

Source (ASAE, 2000; http://www.engineeringtoolbox.com/).

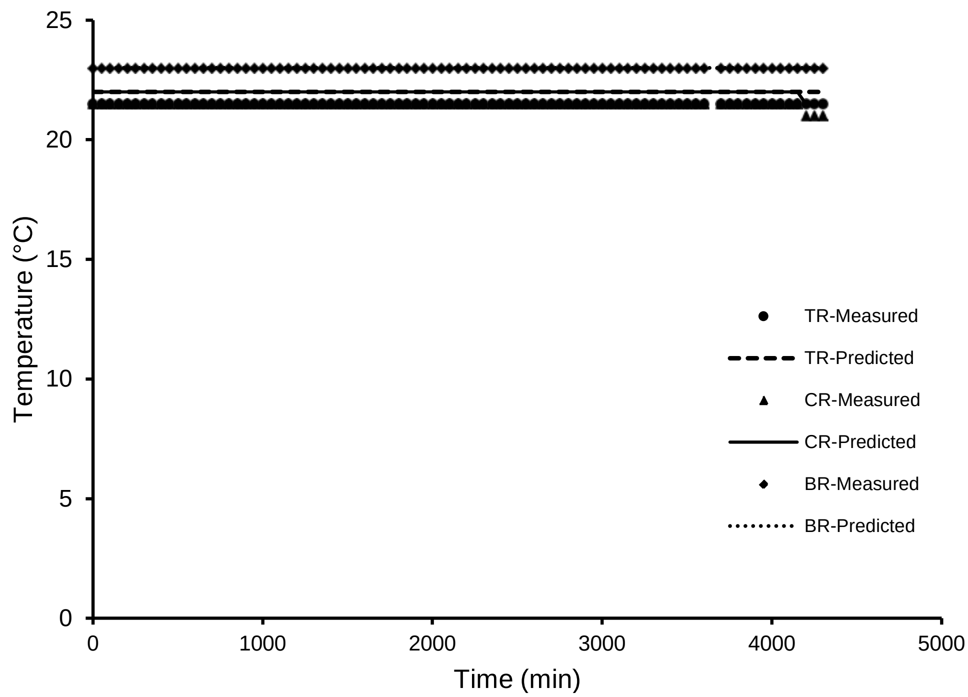

Figure 2. Measured and predicted maize grain temperature over time at room temperature in the vertical direction (before the cooling experiments). TR = Top room, CR = center room, BR = bottom room.

and radial directions.

Room and cooling condition in the vertical and radial directions

The predicted and measured grain temperature in a vertical direction at room temperature is shown in Figure 2. The grain temperature at the bottom of the bin was the first to change followed by top grain temperature and the center grain temperature was last to change. One possible explanation is the fact that at the bottom of the grain temperatures was too close in contact with the ground concrete floor, thus that was why it was the first to change. The predicted temperatures were closely matched to the measured temperature. Furthermore, Figure 3 shows the grain temperature at the cooler condition in vertical directions. The grain temperature at the bottom decreases faster at the first 500 min and slowly afterward. For the center, grain temperature was lagging and it took approximately 600 min before it started to drop. Similarly, the top grain temperature was between bottom and center as shown in Figure 3. The predicted temperatures are in excellent agreement with the measured temperature. Moreover, Figure 3 indicates warm temperature condition when grain bins were taken out of the cooler. Like in cooler conditions, bottom temperature was the first to change following a smooth curve as shown in Figure 3. For the top temperature, it took approximately 300 min to change and then it the

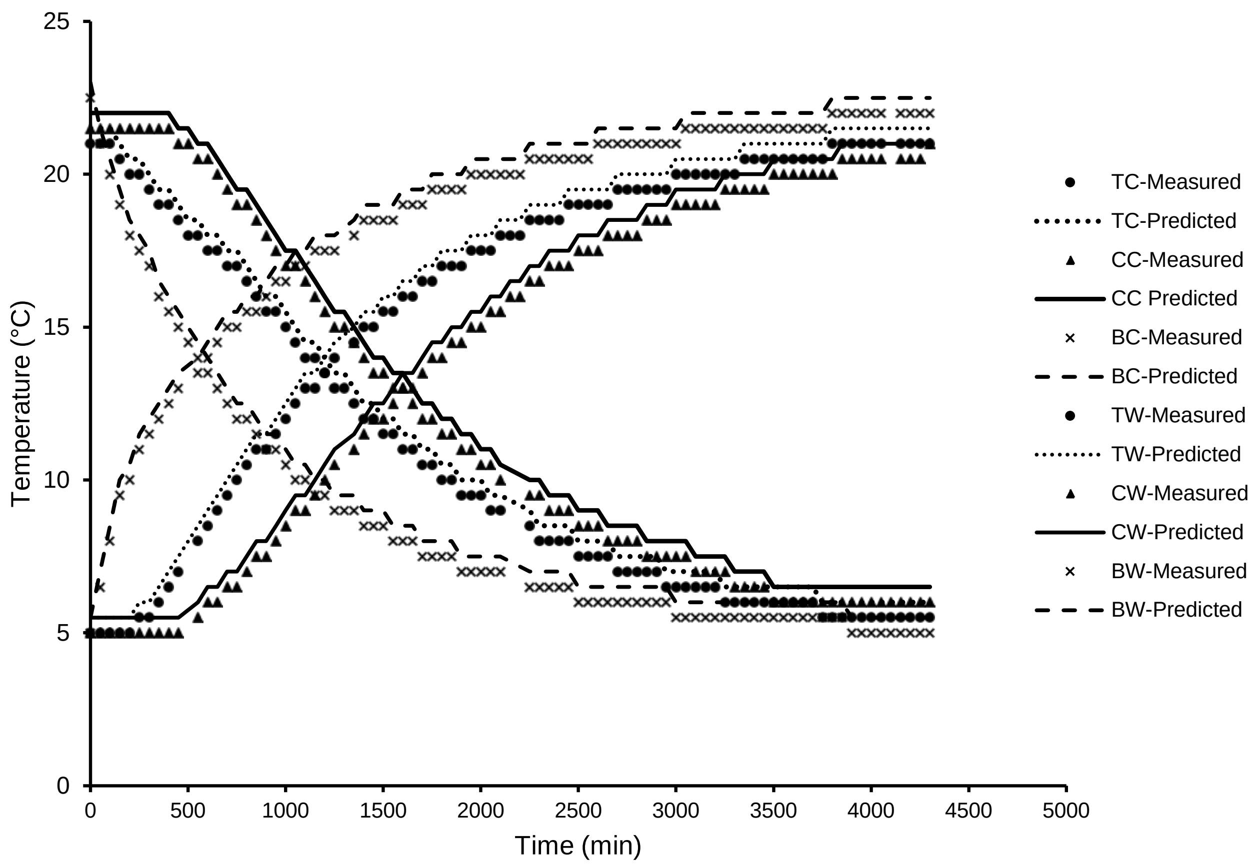

Figure 3. Measured and predicted maize grain temperature over time from the room to cooler and from cooler to back room temperature in the vertical direction. TC = Top cooling, CC= center cooling, BC= bottom cooling, TW = top warming, CW= CENTER warming, BW= bottom warming.

take same path as the bottom temperature. Likewise, the center temperature was lagging and it took almost 500 min before the center temperature could respond as seen in Figure 3. All the predicted temperatures were in agreement with the measured temperature.

In addition, the predicted and measured temperatures in a radial direction (left, center and right) at room temperature are illustrated in Figure 4. The result shows that the measured temperature in the right side was the first to change followed by left, while the center temperature was between right and left temperature. The predicted temperatures were in the same path as the measured temperatures. Furthermore, Figure 5 shows the combined results of the temperature changes from room to cooler and from the cooler back to the room. The result indicates that the right temperature was first to change followed by right and center (Figure 5). The predicted temperatures were similar to the measured temperature as shown in Figure 5.

Furthermore, for the cooler condition, the result shows the temperatures in the boundaries (left and right) dropped at the same time and reached a steady state after about 4000 min. While, the temperature at the center was lagging for about 500 min and dropped sharply afterward and relatively constant at a lower temperature (Figure 5). In warming conditions, the same trend was observed for the right, left and center temperature as shown in Figure 5. These results also show that the predicted temperatures were similar to the measured temperature.

Room and freezing condition in the vertical and radial directions

The temperature change for freezing conditions in the vertical direction at room temperature is shown in Figure 6. Slight variation between the top, bottom and center temperature was observed. Bottom temperature was first to respond and the center was last to change. Moreover, the predicted temperature had a close tie with the measured temperature (Figure 6). The temperature

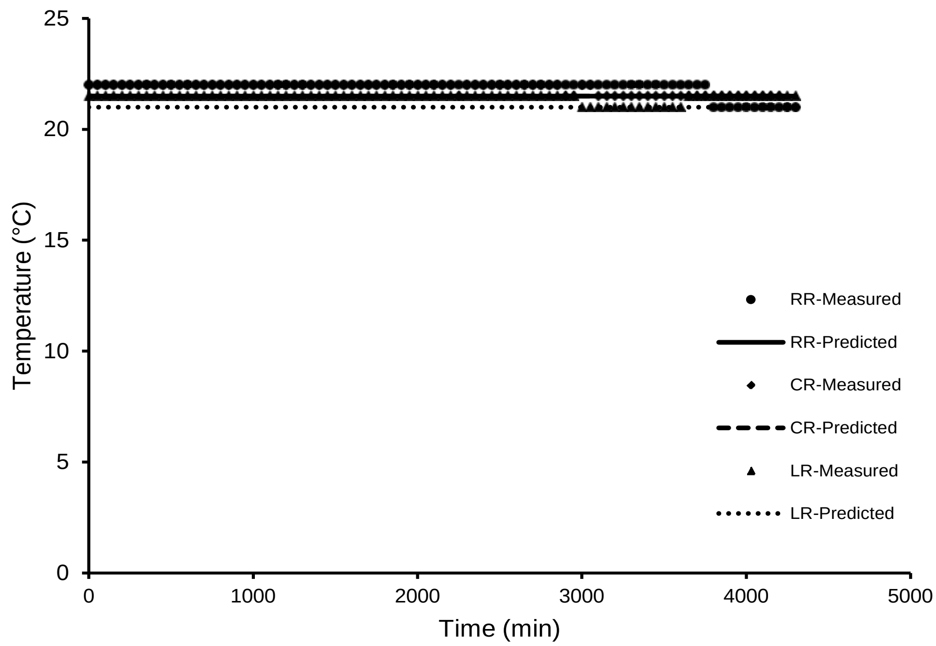

Figure 4. Measured and predicted maize grain temperature over time at room temperature in the radial direction (before the cooling experiments). RR = Right room, CR = center room, LR = left room.

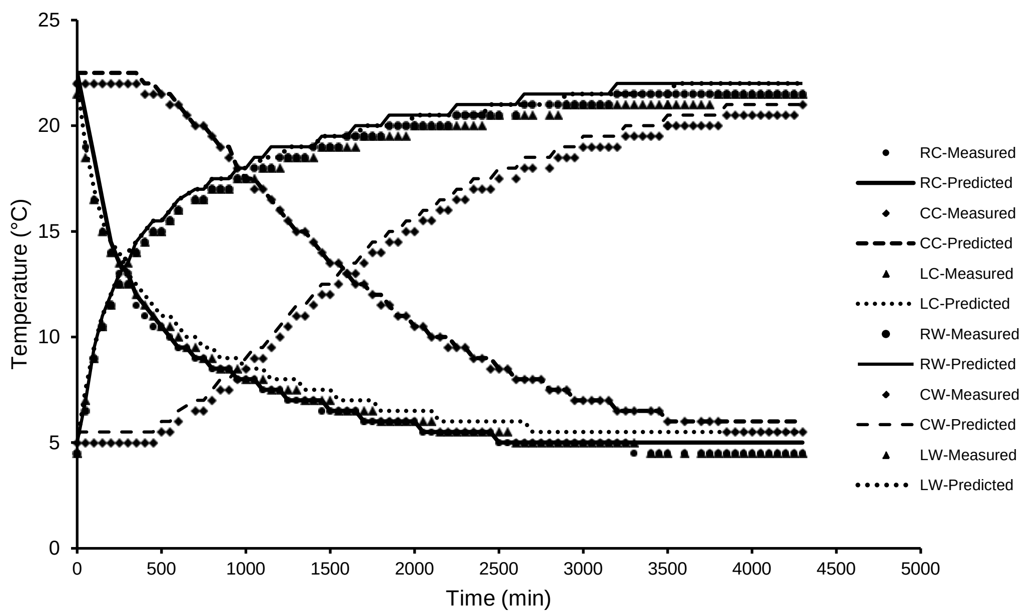

Figure 5. Measured and predicted maize grain temperature over time from the room to cooler and from cooler to back room temperature in the radial direction. RC= Right cooling, CC= center cooling, LC= left cooling, RW= Right warming, CW= center warming, LW=left warming.

change from room to freezing condition is shown in Figure 7. The bottom temperature was sharply decreased at the initial 600 min and slowly afterward. The top was second to change and was laid between bottom and

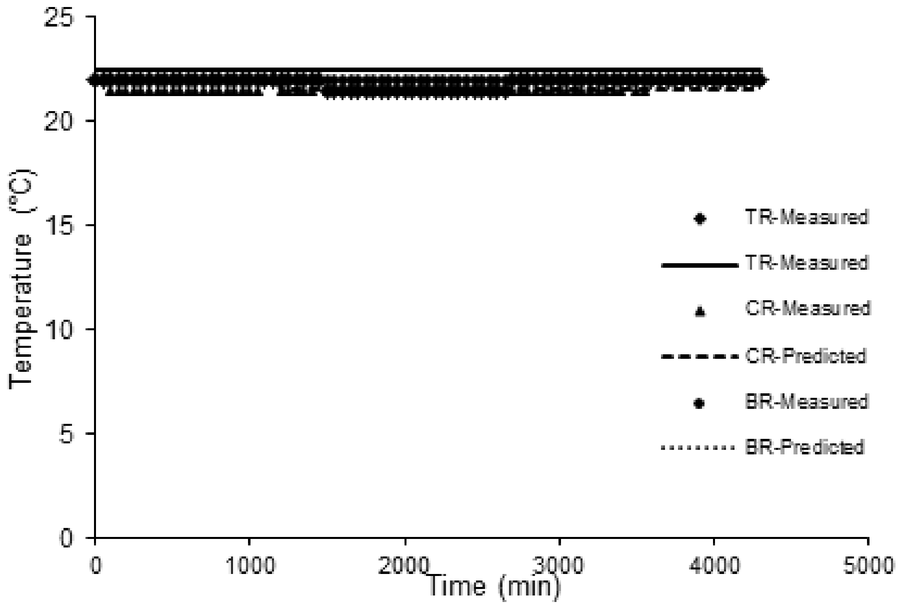

Figure 6. Measured and predicted maize room temperature changes over time at room temperature in the vertical direction (before the freezing experiments). TR= Top room, CR= center room, BR = bottom room.

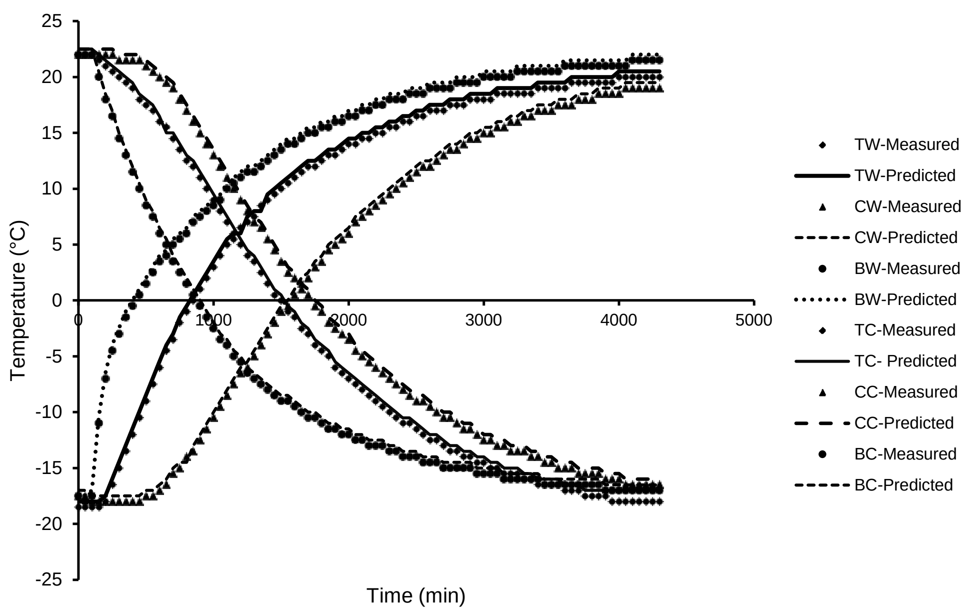

Figure 7. Measured and predicted maize grain temperature change over time from room to freezing temperature and from freezing to room in the vertical direction. TW= Top warming, CW= center warming, BW= bottom warming, TC= top cooling, CC= center cooling and BC= bottom cooling.

center temperature. Likewise, the center temperature was last to change as shown at Figure 7. The predicted temperatures for the room and freezing to room temperature were very close tomeasure temperature. Furthermore, for the temperature change from freezing conditions to room at vertical direction is shown at Figure 7. The top and the bottom temperature were first to change, although at different rates, top temperature was

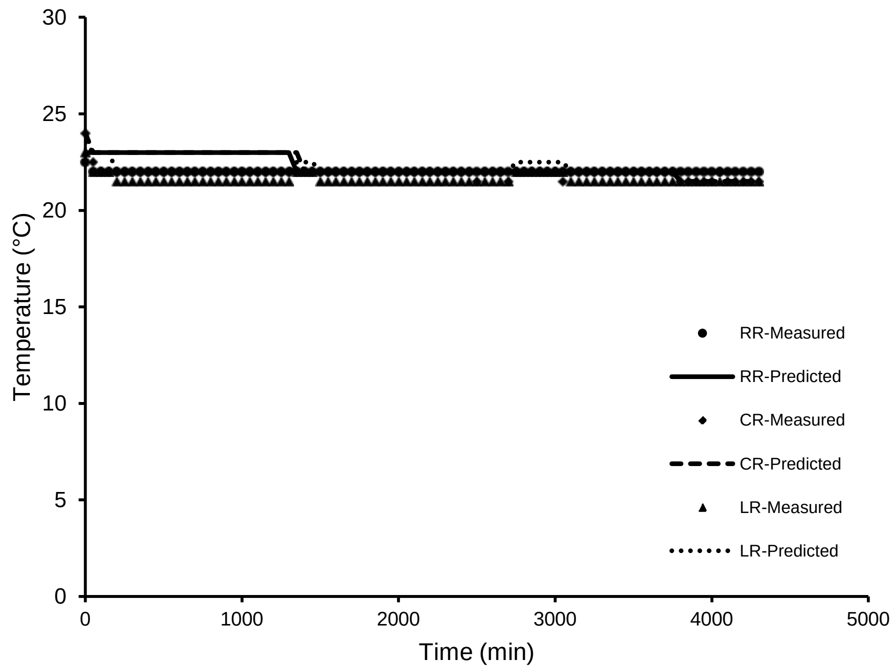

Figure 8. Measured and predicted maize grain room temperature change over time at room temperature in the radial direction (before the freezing experiments). RR= Right room, CR= center room, LR= left room.

the first to response followed by the bottom and the center was the lagging (Figure 7). Moreover, in a radial direction for the room temperature, the right measured temperature was first to change followed by the left and center temperature (Figure 8). For the temperature change from room to freezing conditions, the left and right responded simultaneously as shown in Figure 9. Similarly, the center temperature was lagging for about 500 min. All the measured and predicted temperatures follow the similar trend. In addition, the temperature change from freezing to room temperature is shown in Figure 9. The right and left temperature moved on the same path, the temperature started to rise sharply after -19°C and began to decrease when the temperature reached about 5°C as shown in Figure 9. There are close agreements between the measured and predicted temperatures at radial direction.

DISCUSSION

A comparison of predicted and measured temperatures of maize grain was made for radial and vertical directions. The result in the radial direction in the room condition shows small variations between predicted and measured temperatures. However, the temperatures at the right and left hand sides or at the boundaries of cylindrical bins were either increase for warming conditions or decreased for the cooling conditions at higher rate after 500 min and followed the same path, while the temperature for center positions were lagging behind. These were observed throughout the study. The results concurred with the finding of Zhang et al. (2013) who reported that the temperature of maize grain increase at the points near the boundary and proceeds at a faster rate than the temperature increase at the center points.

Moreover, the study found that the temperature in the hermetic seal cylindrical bins varied, mostly in the radial direction and very little in the axial vertical directions as seen in Figures 3 and 7. Similar results were reported by Khankari et al. (1994), this means heat transfer in the cylindrical hermetic sealed bins occurred mainly due to conduction process. In addition, the maximum difference between predicted and measured temperature of maize grains inside the bins in vertical and radial directions which oscillated around ±1.5°C (as seen in Figures 2 to 9). These results are inconsistent with the results presented by Yaciuk et al., (1975). They found the maximum difference in the simulation model between predicted and measured temperature of wheat inside the storage bins to be 3°C.

Furthermore, the errors and small deviation between the predicted and measured temperatures in the model can be attributed to the combined errors in experimentation, in sensors reading, in numerical computation and in some assumptions made during

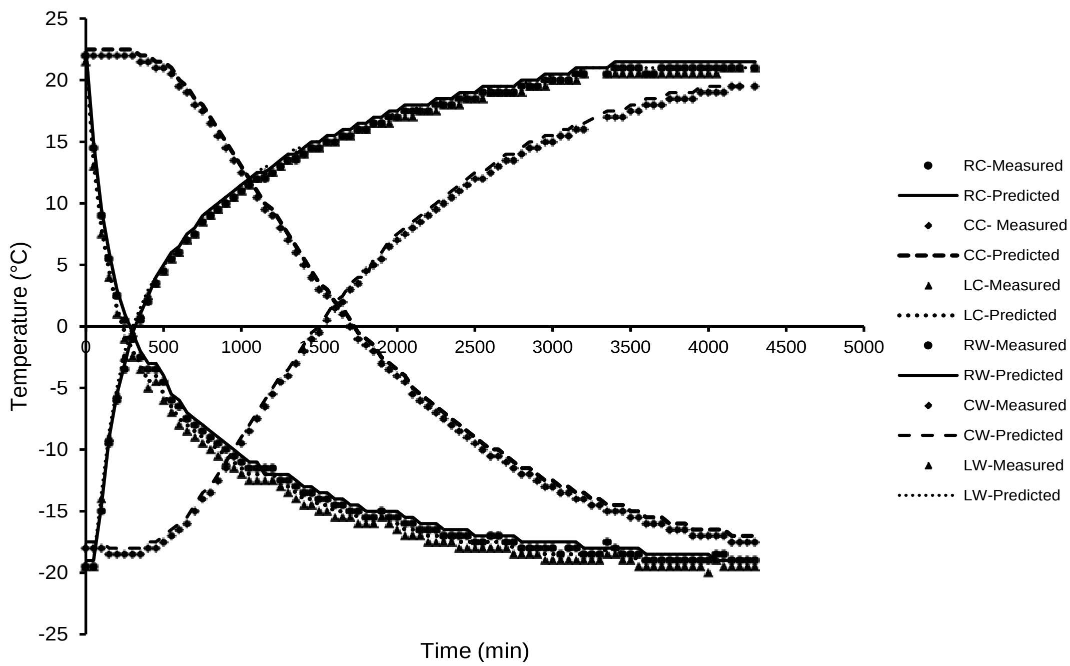

Figure 9. Measured and predicted maize grain temperature change over time from room to freezing temperature and from freezing to room in the radial direction. TW= Top warming, CW= center warming, BW = bottom warming, TC = top cooling, CC = center cooling and BC= bottom cooling.

model development.

According to Lawrence et al., (2013), the physical and the thermal properties of the grain are the important parameters that affect the accuracy of model development and temperature prediction. For instance, the properties of maize grains were assumed to be constant throughout the experiment, but in the actual sense, the thermal conductivity of maize grain will change as the temperature changes. Hence, affect the accuracy of model development. This assumption was made because there is no actual method of monitoring thermal properties of maize grain inside the bins during an experiment. Another factor to consider is the presence of fines and foreign particles in the maize grain; this has a significant effect on the thermal properties of grain, especially thermal conductivity as reported by Lawrence et al., (2013), thus reducing the accuracy of model development.

Conclusions

In general, maize grain temperature oscillated greatly in the boundary of the bin and slightly at the center. Likewise, the predicted temperatures were closely matched with measured values throughout the experiments.

1. Temperature in the hermetically sealed cylindrical bins varied, mostly in the radial direction and very little in the axial vertical directions.
2. No noticeable change was observed in room condition.
3. The lag time between the center temperature and the side (right, left, top and bottom) was greater in the radial direction as compared to the vertical temperature.
4. The temperature in the grain changed more rapidly in the freezing conditions than in the room and cooling conditions.

Conflict of Interests

The authors have not declared any conflict of interests.

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