IOP Conference Series: Earth and Environmental Science

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IOP Conf. Series: Earth and Environmental Science **653** (2021) 012097 doi:10.1088/1755-1315/653/1/012097

Determination of thermal diffusivity of bulk corn kernel and bulk milled corn kernel using numerical method

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Abstract. Drying and storage of agricultural products are often related to heat transfer processes, both within the material and between the material and its environment. Thermal diffusivity is one of the thermo-physical properties related to the heat transfer processes in the material. This study aims to measure the thermal diffusivity of shelled corn, milled corn passed mesh 6, milled corn passed mesh 8, and milled corn passed mesh 16 (corn flour) fed by an axial heat source of 50 °C and 70 °C. The temperature sensors LM35 were used to gauge temperature history and were placed at 9 points in the test cylinder. The thermal diffusivity is then estimated from the temperature distribution data using numerical method. We found that the thermal diffusivity of shelled corn, milled corn passed mesh 6, milled corn passed mesh 8, and milled corn passed mesh 16 (corn flour) are (1.35, 1.38, 1 , 69, and 2.30) x10^{-7} m^2/s, respectively, at axial heat source of 50 °C and (1.39, 1.42, 1.72, and 2.36) x10^{-7} m^2/s, respectively, at axial heat source of 70 °C. The smaller the bulk density and the larger the heat source provided, the higher the thermal diffusivity.

1. Introduction

Corn (*Zea mays*) or maize is a very popular cereal plant that produces carbohydrates. It uses to substitute rice as fulfilling food demand for people or as raw material for animal feed. The amount of Indonesian maize production in the last 2014 - 2018 period increased by an average of 12.49% per year in line with the increase in harvested area. In 2018 maize production reached 30 million tonnes of dry shelled [1].

Drying and storage of agricultural products are always related to the physical condition of the surrounding environment, including the heat transfer process. Thermal diffusivity is one of the physical properties related to heat transfer processes in the material or defined as the rate at which heat diffuses out or into the material which naturally distributes heat to all parts of the product [2]. According to Singhal et al. [3] thermal diffusivity can be used to determine the optimal energy or time requirement in drying or the other product handling.

Thermal diffusivity measurement can be performed in two ways, direct method and indirect method [4]. Determination of heat diffusivity using the indirect method can be done by substituting the values of heat conductivity, density, and density of the material that have been previously known into the formula. However, the measurement of the value of heat diffusivity is indirectly considered to be less than perfect, because the empirical approach to forming values sometimes varies under the same conditions [5]. Therefore, in this study, a direct method was used to determine the heat diffusivity value, namely the numerical method.

Thermal diffusivity for several agricultural products has been reported. For example, the thermal diffusivity of melons was calculated numerically by analytical methods and obtained values 1.5996 - 0.5515 x 10^{-7} m^2/s [6]. Using the method of mixtures, Kuswardana [7] calculates the thermal diffusivity of Malang apples and the obtained values are 1.4896 - 2.2535 x 10^{-7} m^2/s, while Kostaropoulos and Saravacos [8] determined the thermal diffusivity of flour rice, raisins using the direct transient heating method and found that thermal diffusivity of foods is strongly affected by the physical structure of the food material. Meanwhile, the transient technique using a line heat source has been used by Yang et al. [9] to determine the thermal diffusivity of borage seeds in low water content range and obtained the thermal diffusivity 2.32 - 3.18 x 10^{-7} m^2/s and the same method was used by Wahyuni [5] to determine the thermal diffusivity of Lampung robusta coffee beans. A fairly new method has been developed by Golovin et al. [10]. They used the thermograpy technique to determine the thermal diffusivity of materials nondestructively. However, this method is only suitable for homogeneous materials. Meanwhile, most agricultural products are non-homogeneous materials.

In determining the heat diffusivity by numerical methods, the temperature distribution data on the material is needed. Determination of heat diffusivity using numerical methods has been carried out by Wahyuni [5], when the process of data collection of temperature distribution used a thermocouple and data storage was done manually. When recording data manually, it can cause the less accuracy level and less data accuracy because during recording, the temperature continues with increasing time and depends on a person's reading level of the thermocouple measurement results. To make it easier to get temperature readings from various layers of material, a temperature sensor is needed. A temperature sensor can be integrated with a microcontroller which functions as a manager of the measurement results information system [11]. The advantage of using a microcontroller on Arduino is that it is able to measure, acquire, and store data from various analog or digital sensors in a very fast time [12, 13]. For this reason, this study uses an integration between the LM35 temperature sensor, microcontroller, LCD, MMC, to reduce the occurrence of measurement errors, simplify recording, and data storage.

2. Methods

2.1. Apparatus and materials

Thermal diffusivity measurement was determined with a transient method using an axial cylindrical heat source. The apparatus used are cylindrical test chamber, Arduino Mega 2560 R3, temperature sensors LM35, SD Card Module, Real Time Clock (RTC), Liquid Crystal Display (LCD), and power supply as shown in Figure 1. The cylindrical test chamber is made of aluminum (0.35 mm thickness, 14.5 cm in diameter and 15 cm height). In the center of the chamber, a pipe is installed for the temperature sensors installation line. The temperature sensors (LM35) were placed at 9 points representing the heat propagation from the heat source into the bulk material.

The temperature sensors LM35 were connected to the Arduino Mega 2560 which was equipped with RTC, LCD, and micro SD. The interface program was developed on the basis of Arduino software version 1.6.12 so that the LM35 temperature sensors can read the temperature of the material being tested. The heat source comes from the surrounding of the test cylinder which is immersed in waterbath that is set at a certain temperature. The RTC panel shows the time when the sensors read the heat, the LCD displays the time and temperature data, and the micro SD is used to record time and temperature data. The temperature data were recorded with time intervals of 30 seconds until the temperature in the center of the test cylinder approaches the heat source.

To ensure the validity of temperature measurement data, the temperature measurement results from the LM35 sensors need to be compared with the output values read with a standard temperature measuring instrument. The data from the two measurements were then analyzed using the regression method to determine the correlation between the temperature data from the LM35 sensors and the calibrator. The regression equation is then used to correct the sensor output.

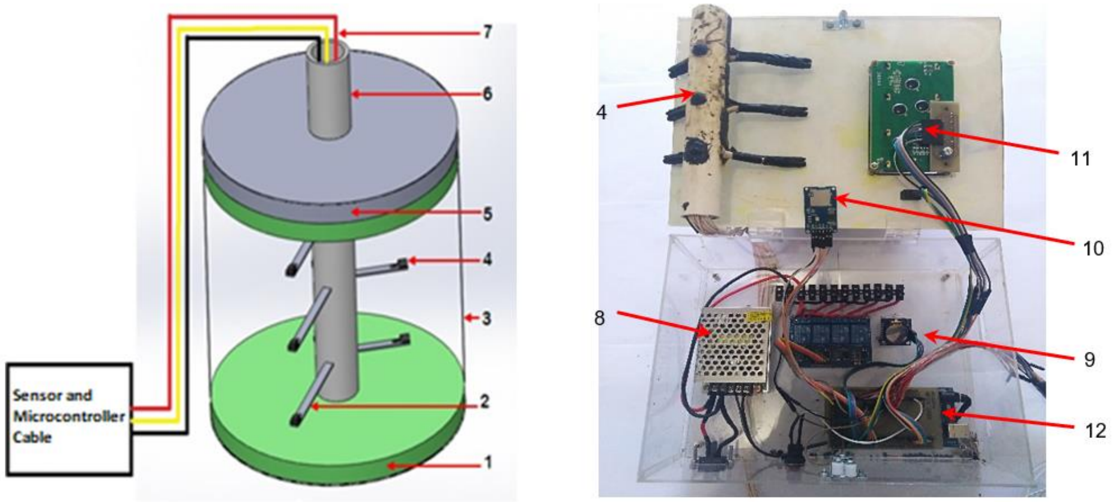

Figure 1. Test chamber and temperature measuring elements

where :

1. *Styrofoam*
2. Sensor holder
3. Cylinder
4. Temperature sensor LM35
5. Cylinder cover
6. Pype
7. Jumper cables
8. Arduino and shield
9. RTC
10. LCD
11. SD card module
12. Power supply

For experiments, the hybrid DK 77 corn kernels at various bulk densities were used, approximately 12 kg of each sample (shelled corn, milled corn passed mesh #6 (3.35 mm), milled corn passed mesh #8 (2.36 mm), and the milled corn passes mesh #16 (1.18 mm)). Each sample was then measured for moisture content and bulk density prior to thermal diffusivity measurements. The thermal diffusivity measurement was carried out at 50 °C and 70 °C.

2.2. Moisture content

The water content was determined by the oven method. This method uses the principle of evaporating the water in the material by heating. The oven temperature is set at 105 °C and the samples were dried until stable weight is obtained. The moisture content of the material was then calculated by Eq. (1):

$$\text{KABB} = \frac{(MB - \text{MC})}{MB}\ X\ 100\% \quad \ldots\ldots\ldots\ldots \quad (1)$$

where:

KABB : Water content (wet basis, %)
MB : Weight of sample at t = 0 (kg)
MC : Weight of dried sample (kg)

2.3. Bulk density (ρ_b)

Bulk density is determined by measuring the sample volume using a measuring cup, then the sample is weighed. Bulk density is then calculated by Eq. (2) [14]:

$$\rho_b = \frac{M}{V} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where:

ρ_b : bulk density (kg/m^3)
M : sampe weight (kg)
V : volume (m^3)

2.4. Temperature profile and distribution
Waterbath with ± 14 cm depth of water was set up the desired temperature (50 °C and 70 °C). After temperature of the water reaches the set temperature, the test cylinder which had already contained the sample is then immersed into the waterbath. Furthermore, the temperature sensors LM35 will read and record the temperature every 30 second until temperature at the cylinder center approaches the temperature of the heat source.

2.5. Thermal diffusivity (α)
The thermal diffusivity is determined by numerical method using Equation (3).

$$\alpha = \left| \frac{(\Delta r)^2}{\Delta t} \frac{r(T_r^{t+1} - T_r^t)}{(\Delta r + r)T_{r+1}^t + rT_{r-1}^t - (\Delta r + 2r)T_r^t} \right| \quad \text{......} \quad (3)$$

The accuracy of the calculated thermal diffusivity value is known by comparing the measured (actual) temperature with the estimated temperature. Estimated temperature can be calculated by Equation (4).

$$T_r^{t+1} = \left| \frac{\alpha(\Delta t)\{(\Delta r + r)T_{r+1}^t + rT_{r-1}^t - (2r + \Delta r)T_r^t\}}{r(\Delta r)^2} + T_r^t \right| \quad \text{......} \quad (4)$$

while the accuracy is calculated using Equation (5).

$$K = \left(1 - \left|\frac{T_{duga} - T_{ukur}}{T_{ukur}}\right|\right) \times 100\% \quad \text{......} \quad (5)$$

where:

T_{r-1}^t : temperature at r-1 at time t (°C)
T_r^t : temperature at r at time t (°C)
T_{r+1}^t : temperature at r+1 at time t (°C)
T_r^{t+1} : temperature at r at time t+1 (°C)
Δt : interval time (s)
K : the accuracy of measured temperature and estimated temperature (%)
α : thermal diffusivity (m^2/s)
r : measurement distance (m)

3. Results and discussion
An example of a graph of the LM35 sensor calibration is shown in Figure 2, while the calibration equations for all LM35 sensors used are shown in Table 1. From the graph it can be seen that there is a high correlation between the calibrator and the sensor. It means that the LM35 sensors used have high accuracy. Furthermore, this regression equations are then be used for conversion the LM35 sensor data.

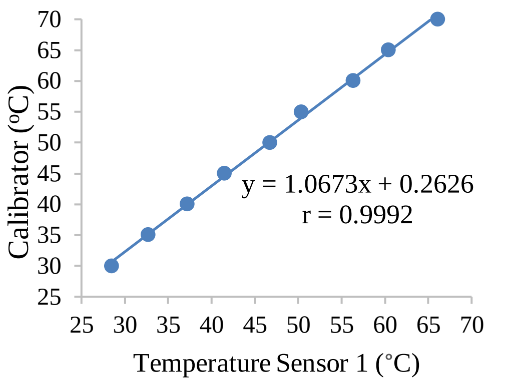

Figure 2. An example of a graph of the LM35 sensor calibration.

Table 1. Calibration of sensor LM35

Number of sensors	Regression Eq. (y)	Correlation value (r)
Sensor 1	1.0673x + 0.2626	0.9992
Sensor 2	1.0462x - 0.1451	0.9978
Sensor 3	1.0450x + 0.1737	0.9967
Sensor 4	1.0554x + 0.3125	0.9986
Sensor 5	1.0629x + 0.3826	0.9974
Sensor 6	1.0634x + 0.3723	0.9979
Sensor 7	1.0578x + 0.9041	0.9981
Sensor 8	1.0527x + 0.9364	0.9968
Sensor 9	1.0551x + 0.5022	0.9993

The moisture content and bulk density of the sample tested are presented in Table 2. The moisture content of the samples can be assumed to be uniform, while the bulk densities of the samples are significantly different at the 0.05 confidence level.

Table 2. Moisture content and bulk density of the samples

Material type	Moisture content (%db)	Bulk density (kg/m^3)	Thermal diffusivity ($x 10^{-7} m^2/s$)	
			At 50 °C	At 70 °C
Corn kernel	14.68[a]	732.41[a]	1.35	1.39
Milled corn (passed mesh #6)	14.31[a]	743.84[b]	1.38	1.42
Milled corn (passed mesh #8)	14.30[a]	753.77[c]	1.69	1.72
Corn flour (passed mesh #16)	14.10[a]	782.79[d]	2.30	2.36

The result showed that the bulk density of the test sample increases if the grain size of the sample is smaller (Table 2). The smaller the grain size, the denser the bulk material. These results are similar with the Isar report [15], the bulk density of hybrid yellow maize var. Bima-1. The data obtained shows that the particle size greatly affects the bulk density because the larger the particle size the smaller the bulk density. The thermal diffusivity is strongly influenced by bulk density. The greater the bulk density of the material, the higher its thermal diffusivity.

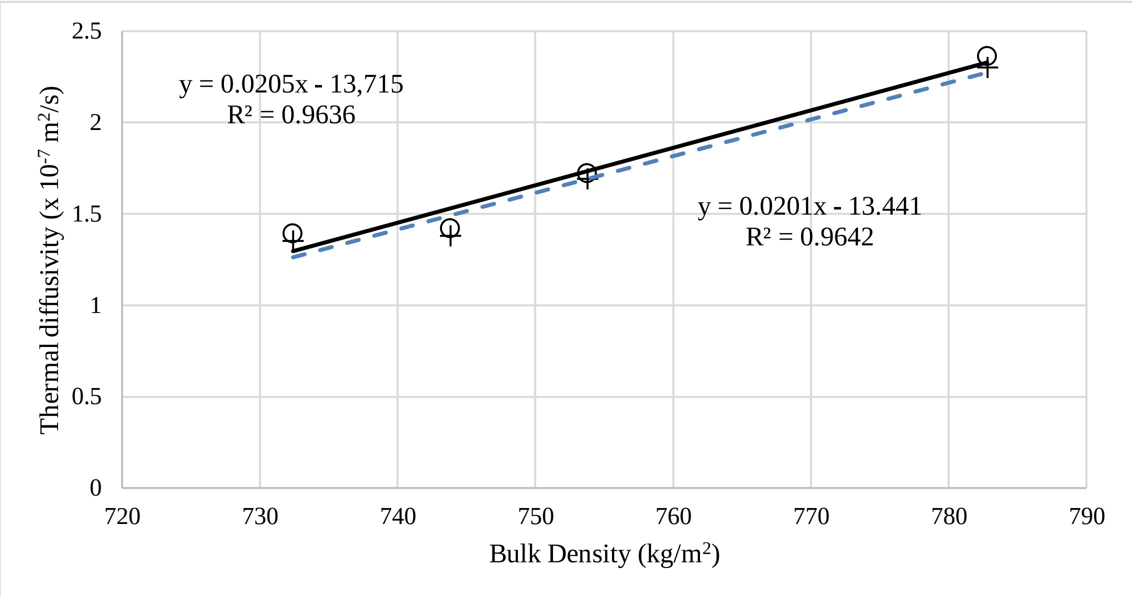

Figure 3. The measured (scattered dots) and the estimated (solid and dashed lines) values of thermal diffusivity in relation to bulk density for two temperatures. + 50 °C and ○ 70 °C.

3.1. Temperature profile during testing

From the temperature distribution data as shown in Figure 4 and 5, it can be seen that there is a difference in temperature response in each part of the test cylinder due to differences in the distance from the heat source. The sensor closest to the heat source will have a higher temperature and the sensor farthest from the heat source has a smaller temperature. However, gradually as a function of time, the temperature of the material body continues to rise, approaching the magnitude of the heat source temperature. Wahyuni [5] reported that the graph of the temperature distribution of Robusta coffee beans against time follows an exponential function, where at the beginning of heating, the rate of temperature increases faster, and tends to fall to a constant at the end of heating.

From the temperature distribution graph, it appears that the speed of temperature propagation is influenced by the size of the material and the amount of heat source given. The smaller the material size, the greater the heat propagation speed. This is because the distance between the particles is close together and the pores between the materials are small, so that heat is easy to flow. This is in accordance with research by Nirwana [16] that heat distribution in large diameter sand (1.2 - 2) is slower than sand with small diameter (0.6 - 1.2).

Meanwhile, if the heat source provided is greater, the heat flowing will be faster due to a large temperature gradient. This is supported by the research of Taufiq [17] which reported that drying of corn with higher heat source will shorten the drying time. This is because the higher the temperature of the drying air, the higher the heat energy carried by the air so that the more water in the material evaporates more quickly.

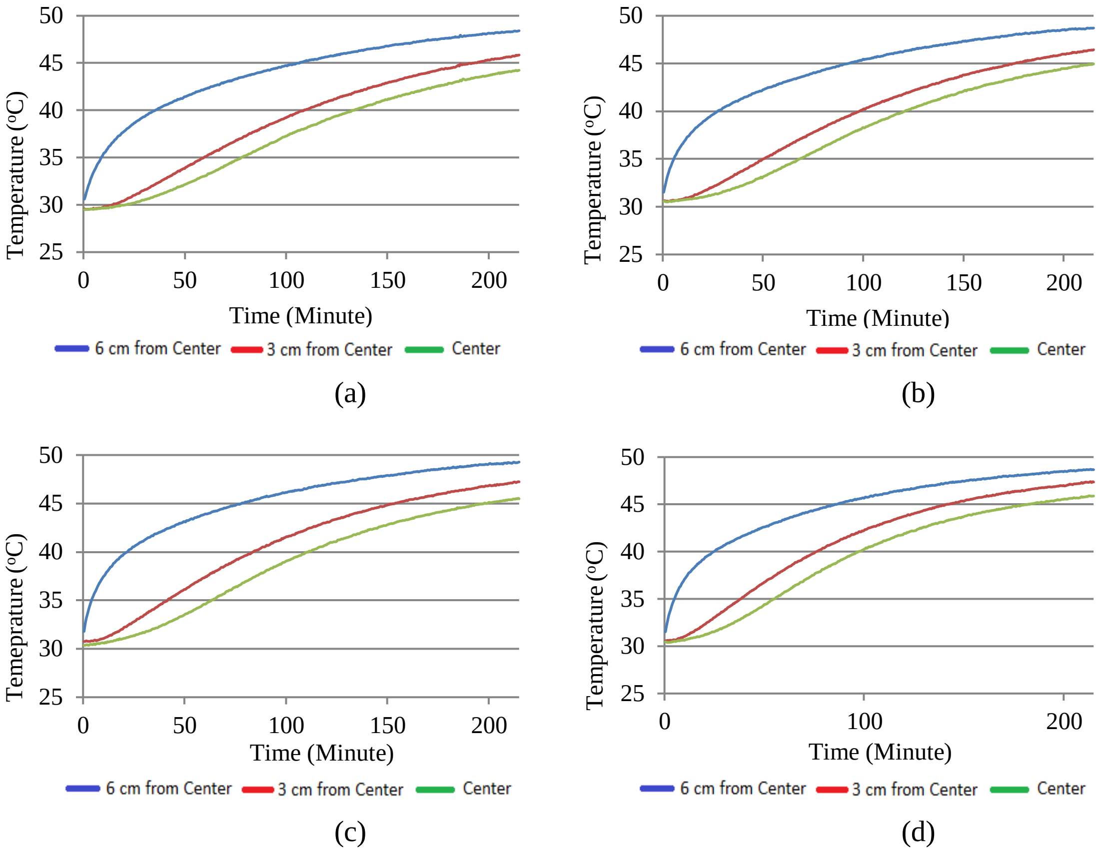

Figure 4. Temperature profile and distribution: (a) shelled corn, (b) milled corn passed mesh #6, (c) milled corn passed mesh #8, dan (d) milled corn passed mesh #16. Heat source at 50 °C.

3.2. Thermal diffusivity

The thermal diffusivity of the corn kernels increased with the smaller the size of the material. The smaller the bulk material size, the higher the bulk density. Materials with smaller sizes have a wider surface area for the same bulk volume. Thus, the probability of heat flow becomes greater. According to Haryanto [18] the faster the heat spread to a medium, the greater the thermal diffusivity. A small value of thermal diffusivity indicates that most of the heat is absorbed in the material and the other part is flowed by conduction. The thermal diffusivity will increase when the heat conductivity is high or the heat capacity is low. The thermal conductivity of the object will be large if the bulk density is small. According to Nirwana [16], the heat conductivity is greater in small sand compared to large sand because there is more contact with the material and the speed of propagation is greater. A material that has heat conductivity has a faster heat propagation.

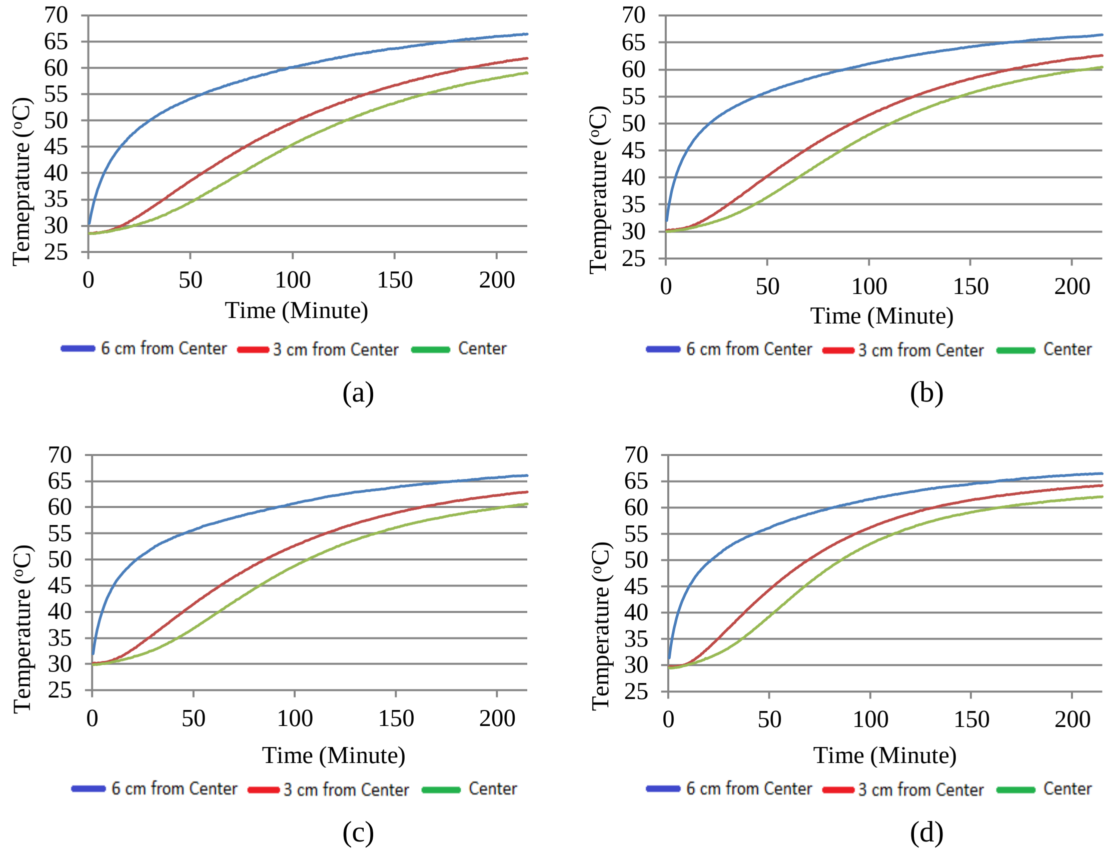

Figure 5. Temperature profile and distribution: (a) shelled corn, (b) milled corn passed mesh #6, (c) milled corn passed mesh #8, dan (d) milled corn passed mesh #16. Heat source at 70 ^{o}C.

The amount of heat source temperature affects the heat diffusivity value. The heat diffusivity value at 50 °C is smaller than the heat diffusivity value at 70 °C. The heat diffusivity value will increase as the temperature increase. A temperature of 70 °C has a greater heat energy than a temperature of 50 °C, thus, the heat energy transferred to the material is much greater and causes the heat flow to the material faster. This is in accordance with Manalu and Abdullah [19] on the cooling process of carrots, that at the beginning the carrot temperature drops rapidly and gets slower when the temperature approaches the temperature of the cooling room air. This shows that the heat diffusivity will also decrease the lower the temperature.

3.3. Accuracy of predicted temperatures
The accuracy of corn seed temperature estimation can be done if previously the estimated temperature has been calculated based on the mean thermal diffusivity value of corn kernels with Equation (3), and the accuracy is calculated by Equation (5). The average accuracy value obtained from the measured and predicted temperature data used in the numerical method of calculating the thermal diffusivity is 99.76 percent. A high precision value indicates the level of accuracy between the measured and predicted temperatures is very close. The estimated temperature calculated based on the average thermal diffusivity value of each treatment, almost all of the points are close to and some coincide with the measured temperature.

4. Conclusions
The temperature sensors LM35 used had been calibrated and worked properly indicated by the r values around 0.997 to 0.999. The smaller the bulk density and the larger the heat source provided, the higher the thermal diffusivity. The thermal diffusivity values of shelled corn, milled corn passed mesh 6, milled corn passed mesh 8, and milled corn passed mesh 16 (corn flour) at axial heat source of 50 °C were 1.35, 1.38, 1.69, and 2.30 x 10^{-7} m^2/s, respectively,

while at heat source of 70 ^oC, the thermal diffusivity were 1.39, 1.42, 1.72, and 2.36 x 10^{-7} m^2/s, respectively.

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