Thermal and Physical Properties of Shallots (Allium cepa L. var. ascalonicum)

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Abstract. The purpose of this study was to analyze the thermal and physical properties of shallot (Allium cepa L. var. ascalonicum). The thermal and physical properties are density, thermal conductivity, specific heat, and thermal diffusivity. The methods of determining density, heat conductivity, and specific heat, were using the Archimedes principle, the transient method with probe and the mixture method, respectively. Thermal diffusivity was determined by numerical analysis of the cooling temperature of shallot. Mathematical equations of these physical and thermal properties at various water contents have been obtained from the results of this study. Based on the results of measurements, it was obtained the value of the apparent density of shallots of 929.67 kg/m³ and the bulk density of shallots 767.2 kg/m³. The value of thermal conductivity of shallot leaves ranged from 0.529 W m⁻¹ K⁻¹ to 0.758 W m⁻¹ K⁻¹, and the thermal conductivity of shallot bulbs was 0.841 W m⁻¹ K⁻¹ to 0.991 W m⁻¹ K⁻¹. The specific heat was 3530.5 J g⁻¹ °C. Based on the numerical analysis of Fourier series of cooling temperature data, the thermal diffusivity value of shallots of 4.868 x 10⁻⁶ m²/s was obtained.

1. Introduction

A very common spice that is used to make various dishes is shallot (Allium cepa L. var. ascalonicum). Shallot is used not only in Indonesia but also in the world. Indonesian shallot production has grown by 2.26 % per year, with a total of 1.5 million tons in 2018 [1]. Considering the number, shallot production should be accompanied by postharvest handling to maintain the quality and to increase the added value of shallots. The method of postharvest handling and the appropriate handling machine of shallot is also playing an important role in the above-mentioned requirement. Several handling processes of shallot after harvesting are sortation, drying, cooling, cutting the leave, packaging, and then transportation. The skin (outer layer) of shallot bulbs and the leaves must be dried; however the bulbs should be kept freshly. Traditionally, the farmer dried the shallot after harvesting under the sun, but some of them used the drying machine to dry the shallot.

In order to produce shallot seeds, normally shallot is dried or cooled to minimized rotten shallot bulbs during storage and to keep the high viability of the seeds [2]. Another example of the handling process is packaging and transportation. To avoid deterioration of shallot bulbs during transportation from the farmer to consumers, the shallot should be packaged. Parameter of temperature, moisture content, bulk density and apparent density, heat specific, thermal conductivity, and thermal diffusivity of shallot are important to be understood. The objectives of the measurements are to specify the design of drying system operation and cooling as well as to design the dryer or cooler for shallot, to obtain the time requirement of the cooling process and energy efficiency of the process and to decide the optimum packaging dimension. These important parameters are called the thermophysical properties of shallot bulbs and the leaves, especially the Bima variety. To the best author's knowledge, it has not
been available in the literature; therefore, this paper is aiming at the determination of the thermophysical properties of shallot bulbs and leaves, i.e., moisture content, apparent density, bulk density, specific heat, thermal conductivity, and thermal diffusivity.

2. Methods
The material used in this research is fresh shallots of Bima variety, which harvested from the Brebes region Indonesia. The shallots consist of bulbs and leaves to keep the freshness during transportation to the research location. About 10 kg of fresh shallots were needed for this measurement.

2.1. Experiment
The experiment was carried out for determining six thermophysical properties, i.e., moisture content, apparent density, bulk density, thermal conductivity, heat specific, and thermal diffusivity. Fresh shallot bulbs and leaves were dried at 30°C to prepare the sample of thermophysical properties measurement. The drying process used oven drying to keep the constant temperature. The drying process was carried out intermittently for 8 hours per day until the shallot dry for about 6 days.

2.2. Moisture content
The moisture content of the sample is measured every day (every 8 hours drying time) until 6 various moisture content obtained. The sample was also used for another thermophysical property. Both of shallot bulbs and leaves moisture content were measured. The drying oven was used to measure the moisture content at 100°C for 24 hours. Furthermore, the moisture content was calculated by using equation (1), (2), and (3).

\[
MC = \frac{m_w}{m_w + m_s} \times 100\% \quad (1)
\]

\[
m_w = m_i - m_f \quad (2)
\]

\[
m_i = m_w + m_s \quad (3)
\]

Where, MC = moisture content (% wb); \( m_w \) = mass of water (kg); \( m_s \) = mass of total solid (kg); \( m_i \) = initial mass (kg); \( m_f \) = final mass (kg).

2.3. Density
Density is classified into apparent density and bulk density. Apparent density is the density of the whole shallot without change shallot structure. Apparent density was measured by the hydrometric method using water as liquid [3] base on the Archimedes theory. Bulk density is the density of shallot in a pile. It was measured by a geometric method at various moisture content. Shallot was put into the box of 203 cm³ volume, and then shallot weighed with digital electric balance (accuracy of 0.01 g). Both of bulbs and leaves density of shallot were measured.

2.4. Thermal conductivity
The method of thermal conductivity of shallots is unsteady heat transfer using KemTherm Thermal conductivity meter QTM-PD3. The measurement is based on the heat transfer of electrical heating transiently for 60 seconds in the center of a probe, which is laid on the shallots sample [4].

2.5. Heat specific
The mixture method [4] was used to determine heat specific of shallots. A total of 10 g of shallots (28°C) was chopped and poured into the calorimeter vessel filled with 200 g of cold water (6°C). The mixture is stirred until it reaches the equilibrium temperature. The temperature of the mixture was
recorded for 10 minutes. The equilibrium temperature is determined by using a graphical method of temperature versus time.

The heat specific is calculated base on the energy balance \((Q)\) among the mixture of shallots \((s)\), water \((w)\), and vessel of the calorimeter \((c)\), as shown in equation (4) to (7).

\[
Q_s + Q_w + Q_c = 0 \quad (4)
\]
\[
Q = m \cdot C_p \cdot \Delta T \quad (5)
\]

Equation (4) may be stated as:

\[
m_s \cdot C_p_s \cdot (T_s - T_e) + m_w \cdot C_p_w \cdot (T_w - T_s) + m_c \cdot C_p_c \cdot (T_c - T_e) = 0 \quad (6)
\]

Furthermore, the heat specific of shallot is determined by equation (7).

\[
C_{p_s} = \frac{m_w \cdot C_p_w \cdot (T_s - T_w) + m_c \cdot C_p_c \cdot (T_c - T_e)}{m_s \cdot (T_s - T_e)} \quad (7)
\]

Where \(m\) = mass \((g)\); \(C_p\) = heat specific \((J/g^\circ C)\); \(T_e\) = equilibrium temperature \((^\circ C)\). The parameter of “\(m, C_p\),” were determined as a constant value of 21.045 \(J/\circ C\), which influenced by material and structure of calorimeter.

2.6. Thermal diffusivity

Thermal diffusivity of shallots was determined by using a numerical method base on analysis of the cooling temperature of shallot. The temperature of shallot bulbs is measured by using 5 thermocouples \((CA\text{ type})\) along the radius of shallot, as depicted in figure 1. Temperature distribution of shallot was measured during the cooling process in the refrigerator \((5^\circ C)\) until the center temperature of shallot attained cooling room temperature and logged by the hybrid thermal recorder for every 5 minutes.

\[\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (8)\]

Where \(T\) = temperature \((^\circ C)\); \(t\) = time \((\text{second})\).
The shallot bulbs are assumed as sphere geometric and isotropic (uniform), so $\nabla^2 T$ might be written as equation (9).

$$\frac{\partial^2 T}{\partial t^2} = \alpha \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$$  \hspace{1cm} (9)

with initial condition at $t=0$ so $t=f(r)$ and boundary condition at $t=0$ then $t=f(r,t)$. Where $r =$ radius of shallot or distance from the center (m).

Furthermore, equation (9) is solved by a numerical method, as shown in equation (10).

$$H_{n+1}^m = H_n^m + \frac{\Delta t}{\Delta r^2} \left[ H_n^{m+1} - 2H_n^m + H_{n+1}^m \right]$$  \hspace{1cm} (10)

$$\alpha = \frac{\Delta r^2}{\Delta t} \frac{H_{n+1}^m - H_n^m}{H_n^{m+1} - 2H_n^m + H_{n+1}^m}$$  \hspace{1cm} (11)

$$T = T_x r$$  \hspace{1cm} (12)

The numerical method must meet a certain condition for stability of calculation, where,

$$\frac{\Delta t}{\Delta r^2} < 0.5$$  \hspace{1cm} (13)

Thermal diffusion is calculated by equation (11) and analyzed by the finite difference method, as shown in figure 2 that illustrates the temperature position within the shallot $(n)$ at a certain time $(m)$.

![Figure 2](image)

**Figure 2.** Illustration of numerical method analysis to predict the temperature in the shallot.

Thermal diffusivity of shallot then validated by comparing calculation temperature $(T_c)$ and measurement temperature $(T_m)$ by equation (14) with the accuracy of equation (15).

$$rT_{n+1}^m = rT_n^m + \alpha \frac{\Delta t}{\Delta r^2} \left[ rT_{n-1}^m - 2rT_n^m + rT_{n+1}^m \right]$$  \hspace{1cm} (14)

$$\text{Accuracy} = \left[ 1 - \frac{T_m - T_c}{T_c} \right] 100\% $$  \hspace{1cm} (15)
3. Results and discussions

3.1. Moisture content
The moisture content of shallot bulbs and leaves were decreased during the drying process, as illustrated in figure 3. The moisture content of fresh shallots bulbs was 83.3 % and after dried reach 76.1 %. The moisture content meets the Indonesian National Standard for shallot for storage of 80 % wb – 85 % wb [6]. Only outer layer skin of shallots and leaves were dried to reach equilibriums moisture content with the ambient relative humidity, while the bulbs should be kept freshly to maintain its aroma and volatile compounds. The moisture content of fresh leaves was 78.6 % wb, and that of dry leaves was 22.6 % wb. The dried leaves are useful for sealing the volatile compounds within the bulbs so as the freshness of shallots could be maintained.

![Figure 3. Moisture content of shallot bulbs and leaves during the drying process](image)

3.2. Density
Bulk density is an important parameter for the drying process and storage of shallot. Figure 4 shows the relation between the bulk density of shallot bulbs with moisture content. Bulk density of shallots seems to decrease nonlinearily with decreasing moisture content, due to the loss of water. However, the poor correlation observed, it is assumed that during the drying process, the bulk density of shallot bulbs do not change significantly. The average bulk density of shallot bulbs is 767.2 kg/m³ at a range of moisture content of 76 – 83 % wb.

![Figure 4. Bulk density of shallot bulbs against moisture content](image)
The average apparent density of fresh shallot leaves is 736 kg/m³ (at the moisture content of 76.6 %wb). The average apparent density of fresh shallot bulbs is 929.67 kg/m³ (at the moisture content of 83 %wb). These values were close to the value of apparent density of three fresh onion varieties at a range of 940 kg/m³ – 1044 kg/m³ at a range of moisture content of 81 % wb - 92 % wb [7]. However, this research result has a higher value than the Indian -Talaja red onion of 548 kg/m³ [8]. The different values are caused by the different varieties that cause different structures. Shallot and onion have their own species, although they are the same family. Shallot is smaller and has a stronger aroma than onions. The true density of onion slices is 1066 – 1416 kg/m³ [9]. Determining true density is a totally different method with apparent density. Usually, true density higher than apparent density, due to the air content within the material is calculated in apparent density.

3.3. Thermal conductivity

Thermal conductivities of shallot bulbs and leaves at various moisture content are given in Figures 5 and 7 as follows. The higher the moisture content, the greater the thermal conductivity. Thermal conductivities of agricultural products and foodstuffs are influenced by several factors, such as the physical structure of the cell, chemical component, and water content [13]. The relation between the thermal conductivity of shallots and moisture content results equation (16) for shallot leaves and equation (17) for shallot bulbs.

\[ k_{\text{leaves}} = 0.003 \times MC + 0.5225 \]  
\[ k_{\text{bulbs}} = 0.016 \times MC - 0.3632 \]

The thermal conductivity of shallot resulted in this measurement are in the range of 0.529 W/m°C up to 0.758 W/m°C (for shallot leaves) at a range of moisture content of 11.8 % wb – 80.6 % wb. The thermal conductivity of whole shallot bulbs obtained from this research is in the range of 0.841 W/m°C – 0.961 W/m°C (at the moisture content of 75 % wb – 85 % wb). The thermal conductivity of shallot bulb slices results in a value of 1.871 W/m°C up to 2.878 W/m°C at the same range of moisture content. Abhayawick et al. [7] have resulted in the fresh thermal conductivity of three varieties onion of 0.55 W/m°C at MC=86 % wb. Krokida et al. [11] have compiled the thermal properties data of foodstuffs and reported the value of onion thermal conductivity of 0.25 W/m°C – 0.83 W/m°C. Data on thermal conductivity have variation result due to diverse experimental methods, the composition and structure of material [11].
3.4. Specific Heat

Specific heat of shallot has been obtained in this research. The average values of specific heat of shallot bulbs and leaves at various moisture content are given in Figures 7 and 8. The specific heat increase with increasing moisture content. The relation of moisture content and specific heat of shallot leaves and bulbs are stated on equation (18) and (19), with an accuracy of 94 % and 98 %, respectively. Application of Siebel equation (equation 20) [4, 10] at equal moisture content gives accuracy 95 % for shallot bulbs specific heat and 67.5 % for the leaves.

\[
C_p_{\text{leaves}} = 18.418 \times MC + 2341.2 \quad (18)
\]

\[
C_p_{\text{bulbs}} = 134.01 \times MC + 7152.3 \quad (19)
\]

\[
C_p_{\text{bulbs}} = 4186.8 \times (0.008 \times MC + 0.2) \quad (20)
\]

The research has obtained the average shallot bulbs specific heat of 3530 J/kg°C and the leaves of 3035 J/kg°C. The value meets with Abhayawick's result [7] for onions of 3580 J/kg°C at the moisture content of 84% wb, which obtained by different methods with this research. Rao [10] declared that the specific heat value of some kind of vegetable was 3800 J/kg°C.

![Figure 6](image_url)  
**Figure 6.** Thermal conductivity of shallot bulbs at various moisture content

![Figure 7](image_url)  
**Figure 7.** Specific heat of shallot leaves vs. moisture content
3.5. Thermal diffusivity ($\alpha$)

Thermal diffusivity is the rate of propagation of heat along with material during the cooling or heating process. The greater thermal diffusivity, the higher propagation velocity [12]. Figure 9 shows the temperature distribution within the fresh shallot bulbs during the cooling process. Based on the three experimental data of temperature distribution, thermal diffusivity in this research is calculated and resulted an average value of $4.867 \times 10^{-8}$ m$^2$/s (table 1). Validation of the numerical model gave an average accuracy of 94%, which shown in Figure 10. This is evident with thermal diffusivity data close to the line with a slope of 45°.

Abhayawick [7] got the average of thermal diffusion of three varieties onion of $1.397 \times 10^{-7}$ m$^2$/s, at a range of MC of 81 % wb – 87 % wb. The value of $\alpha$ of shallot in this research is lower than the $\alpha$ of onion. The different values of $\alpha$ are influenced by the methods of measurement, the variety, composition, and structure of materials. Onion is more porous than shallot. Abhayawick et al. [7] said that the effect of the high porosity of material would result in higher $\alpha$ value at equal moisture content. The problem with the model used in their research was the lack of accurate methods to measure porosity.

| Table 1. Value of thermal diffusivity for three experiments |
|-----------------|-----------------|-----------------|-----------------|
| Experiment   | $\alpha$ (cm$^2$/minutes) | $\alpha$ (m$^2$/dt) | Accuracy (%) |
| 1            | 0.025728101    | 4.28802E-08      | 88.9           |
| 2            | 0.026725917    | 4.45432E-08      | 97.7           |
| 3            | 0.035163892    | 5.86065E-08      | 95.2           |
| Average      | 0.02920597     | 4.86766E-08      | 94.0           |
4. Conclusions
The thermal properties of shallot and the equation of relationship of thermal properties of shallot at various moisture content have been obtained in this research. The moisture content of fresh shallot bulbs and leaves was 83.3 % and 78.6 % wb. The average bulk density of shallot bulbs is 767.2 kg/m³ at the range of moisture content of 76 – 83 % wb. The average apparent density of fresh shallot leaves is 736 kg/m³ (MC=76.6 %wb), whereas the average of apparent density of fresh shallot bulbs is 929.67 kg/m³ (at the moisture content of 83 % wb). The thermal conductivity of shallot resulted in this measurement are in the range of 0.529 W/m°C up to 0.758 W/m°C (for shallot leaves) at the range of moisture content of 11.8 % wb – 80.6 % wb. The thermal conductivity of whole shallot bulbs obtained from this research is in the range of 0.841 W/m°C – 0.961 W/m°C (at the moisture content of 75 % wb – 85 % wb). While the thermal conductivity of slice shallot bulbs resulted in a value of 1.871 W/m°C up to 2.878 W/m°C at the same range of moisture content. The research obtained the average shallot bulbs specific heat of 3530 J/kg°C and the leaves of 3035 J/kg°C. Thermal diffusivity of shallot resulted at an average value of 4.867 x 10⁻⁸ m²/s with the accuracy of numerical temperature model of 94 %.

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