THE INFLUENCE OF RIND OF WATERMELON IN THE HEAT TRANSFER CALCULATION

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ABSTRACT

The knowledge of temperature field in any product is essential for the design and optimization of the conductive heat transfer from its boundary for the optimum storage conditions. It becomes even more critical for fruits since they require to be maintained slightly higher than the freezing point of it, constantly, to avoid the damages at a premature state. It is interesting to observe that the rind and the juicy part of the fruit have different thermal conductivity and the heat transfer calculations assume it to be the same. This paper investigates the differences in heat transfer calculations arising due to this assumption inside a watermelon that is subjected to a varied temperature of the surrounding condition. The experimental results show that there is a significant change in the heat transfer and the temperature drop across the rind of the watermelon.

KEY WORDS: Transient Conduction, Heat Transfer, Thermal Conductivity, Pre-cooling

1. INTRODUCTION

The cooling of food products is a process in which their temperature is reduced to the required storage temperature in order to prevent their early spoilage and also to maintain their quality. The phenomena involved in food processing and preservation are closely tied to thermodynamics, transport, reaction kinetics, and other principles of chemical engineering science [1,2,3]. The temperature field in the medium resulting from conduction is important for every process that involves unsteady heat transfer [4].

At lower temperatures, fruits are susceptible to chilling injury and decay [5,6]. Accurate thermal conductivity, density, viscosity, and specific heat data for fruits and fruit juices are needed for a variety of research and engineering applications [7]. This includes designing food processes and processing equipment, the control of products, filters and mixers, quality evaluation and an understanding of the structure of food and raw agricultural materials which are essential for the food industry [8]. Modelling, optimization and automation of food processes is difficult because of the complexity of the raw materials and products that are involved. Watermelon is cultivated in large areas and it is one of the most important and economical crops due to being very rich in nutrition [9]. The juice and pulp are used for human consumption whereas the rind and seeds are considered solid wastes [10]. There are data available from the literature on the physical and engineering properties of many agricultural products [11,12,13]. Generally, watermelons are not required to be refrigerated when handled domestically but is needed during export shipment to extend the shelf-life [14]. Pre-storage conditioning at 26ºC for 4 days reduces chilling injury and increases the percentage of marketable fruit following the storage process [15]. There are not many literatures on thermophysical properties of individual fruit components. However, Chen et al investigated the thermophysical properties of individual kiwifruit components such as skin, flesh, and core.

There is no literature available for understanding the influence of the rind of a watermelon in the heat transfer process. The thermal properties of water are assumed for the temperature distribution predictions inside the fruit

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during its cooling. There are not many literatures for the storage of fruits during the storing and shipping processes. In this paper, the temperature distribution across the radius for a thickness equal to the thickness of the rind of a watermelon is obtained experimentally. The results are compared with that of a theoretical calculation of temperature distribution to compare the effect of the rind in the heat transfer calculation.

The next section will describe the experimental setup and explain the procedure followed to perform the experiment. Finally, the discussion of the experimental results, and the future work are explained in the conclusion.

2. MATERIALS AND METHODS

To obtain the temperature distribution of the watermelon at the outer boundary of the fruit, and at the bottom of the rind inside the fruit, the following procedure was followed. Two watermelons of equal diameter (10 cm) and weight (14 lbs) with a similar skin color were purchased from the local market. The selected watermelons were free of significant visible defects. The same room temperature of 20.8°C was maintained throughout the experiment using a standard housing air conditioner.

One of the watermelons was cut into two equal parts. The cut was perpendicular to the top and bottom of the watermelon so that either stem ends are untouched. The temperature was immediately measured across the radius of the fruit at the outer boundary and at the bottom of the rind. To measure the temperature both a digital thermometer (Taylor Rotating Display Thermometer, model 9834-21) and an infra-red thermal imaging camera (E5 IR CAMERA W/ MSX 120X90 RES) were employed.

Fig. 1 The experimental setup used to take the temperature measurement across the radius of the fruit.

The thickness of the rind was measured using a shock-proof vernier caliper after identifying the transition location of the fruit where the soft, red color begins from the bottom of the rind.

The second watermelon which was at the room temperature was placed in a freezer for 52 minutes which was maintained at -6°C. The fruit underwent the transient heat transfer during this time by which the temperature dropped across its radius from the outer boundary of the fruit. To confirm this, after this time period, the watermelon was taken out and cut to measure its radial temperature distribution with the same procedure as followed for the first watermelon. The experiment was repeated three times with the same conditions and procedures described above for the average temperature data to obtain.

The density of the rind of the watermelon was also measured as described below. The rind of the watermelon after the experiment was cut into four equally sized and shaped pieces. Each slice was individually weighed using the Sartorius Practum scientific scale and was dropped gently into a graduated cylinder that contained 50 ml of water. The increase in the water level of the cylinder was recorded and hence the volume of the slice of

the fruit was measured. The procedure was repeated for the remaining three slices to obtain the average value of the volume. The density of the fruit slice was calculated using the equation,

$$\rho = \frac{m}{\Delta V} \tag{1}$$

3. THEORETICAL APPROACH

The temperature at the outer boundary, and at the bottom of the rind across the radius of the fruit were theoretically calculated with the assumed thermal properties of the water for the watermelon. The calculation was also performed by applying the thermal properties from academic literature [18] and both the results were compared with the experimental results to understand the influence of the thermal properties of the rind from the heat transfer viewpoint.

4. THEORETICAL ANALYSIS

In the first part of the analysis, the watermelon is spherical in shape and the heat conduction in the fruit is one-dimensional because of symmetry about the midpoint. The thermal properties are constant as is the case for water. The heat transfer coefficient is considered constant and uniform over the entire surface.

The properties of the watermelon are approximated by those of water at the average temperature of about 5°C, $k = 0.571$ W/m. °C and

$$\alpha = \frac{k}{\rho C_p} = \frac{.571}{(1000 \times 4205)} = 1.357 \times 10^{-7} \frac{m^2}{s} \tag{2}$$

The Biot number is obtained as below.

$$Bi = \frac{h \times r_o}{k} = \frac{(15 \frac{W}{m°C})(0.1m)}{0.571 \frac{W}{m°C}} = 2.6269 \tag{3}$$

The constants λ_1 and A_1 corresponding to this Biot number are from the cengel handbook [18], where λ_1 =1.5 and A_1 = 2.1. The Fourier number is

$$\tau = \frac{\alpha t}{L^2} = \frac{(1.357 X 10^{-6} \frac{m^2}{s})(3926\ s)}{0.1 m^2} = 0.0421 \tag{4}$$

Applying one-term approximate solution, the temperature at the surface of the watermelon becomes:

$$\theta(r,t) = \frac{T(r_o,t) - T_\infty}{T_i - T_\infty} = A e^{-\lambda^2 \tau} \frac{\sin(\lambda_1 \frac{r_o}{r_o})}{(\lambda_1 \frac{r_o}{r_o})} \tag{5}$$

$$= 2.1 e^{-1.5^2 \times 0.0421} \frac{\sin(1.5\ rad)}{1.5} = 0.4992$$

$$\frac{T(r_o,t) - (-6)}{18 - (-6)} = 0.4992 \tag{6}$$

$$\therefore T(r,t) = 2.985°C$$

The temperature at the radius, r = 0.889 m becomes:

$$\theta(r,t) = \frac{T(r_o,t) - T_\infty}{T_i - T_\infty} = Ae^{-\lambda^2\tau}\frac{\sin(\lambda_1\frac{r_o}{r_o})}{(\lambda_1\frac{r_o}{r_o})}$$

$$= 1.5e^{-1.5^2\times0.0421}\frac{\sin((1.5\ rad)(\frac{0.889}{0.1}))}{(1.578)(\frac{0.889}{0.1})} = 0.5950$$

$$\frac{T(r_o,t) - (-6)}{18 - (-6)} = 0.5950$$

$$\therefore T(r,t) = 7.685°C$$

5. ANALYSIS WITH MEASURED PROPERTIES

In this second part of the theoretical calculation, the watermelon is spherical in shape and the heat conduction in the fruit is one-dimensional because of symmetry about the midpoint. The thermal properties are constant and are that of water. The heat transfer coefficient is considered constant and uniform over the entire surface. Properties: The properties of the watermelon are considered at the average temperature of about 5°C from the literature with k = 0.59 W/m. °C and

$$\alpha = \frac{k}{\rho C_p} = \frac{.59}{(1025 \times 3926)} = 1.46 \times 10^{-6}\frac{m^2}{s}$$

The Biot number is obtained as below:

$$Bi = \frac{h \times r_o}{k} = \frac{(15\ \frac{W}{m°C})(0.1m)}{0.59\frac{W}{m°C}} = 1.694$$

The constants λ_1 and A_1 corresponding to this Biot number are from the cengel handbook [19], where λ_1 =1.5 and A_1 =2.1. The Fourier number is

$$\tau = \frac{\alpha t}{L^2} = \frac{(1.46 \times 10^{-6}\frac{m^2}{s})(3926\ s)}{0.1m^2} = 0.4552$$

Therefore, the one-term approximate solution is applicable. Then the temperature at the surface of the watermelon becomes:

$$\theta(r,t) = \frac{T(r_o,t)-T_\infty}{T_i-T_\infty} = Ae^{-\lambda^2\tau}\frac{\sin(\lambda_1\frac{r_o}{r_o})}{(\lambda_1\frac{r_o}{r_o})}$$

$$= 2.1e^{-1.5^2\times0.4552}\frac{\sin(1.5\ rad)}{1.5} = 0.521$$

$$\frac{T(r_o,t)-(-6)}{18-(-6)} = 0.521$$

$$\therefore T(r,t) = 6.504°C$$

The temperature at the radius, r = 0.889 m becomes:

$$\theta(r,t) = \frac{T(r_o,t)-T_\infty}{T_i-T_\infty} = Ae^{-\lambda^2\tau}\frac{\sin(\lambda_1\frac{r_o}{r_o})}{(\lambda_1\frac{r_o}{r_o})}$$

$$= 1.5e^{-1.5^2\times0.4552}\frac{\sin((1.5\ rad)(\frac{0.889}{0.1}))}{(1.578)(\frac{0.889}{0.1})} = 0.692$$

$$\frac{T(r_o,t)-(-6)}{18-(-6)} = 0.692$$

$$\therefore T(r,t) = 10.608°C$$

6. EXPIREMENTAL DATA

The temperature details measured from the experiment across the radius of the watermelon are recorded in the table below.

Table 1 The temperature obtained from the experiment across the radius of the watermelon.

Location	Temperature (°C)		Time (min)	Room Temperature (°C)	Freezer Temperature (°C)	Weight of the fruit (lb)
	Initial	After Cooling				
Outer Boundary	18	6.9	52	20.8°C	-6°C	15.28
Bottom of the rind	17	11.9	52	20.8°C	-6°C	15.28

7. RESULTS AND DISCUSSION

The results obtained from the theoretical calculations are compared with the experimental results as shown in the Fig. 1 & Fig. 2. As seen in Fig. 1, the temperature drop across the thickness of the rind is changing for the different methods. The temperature drop is maximum of 5°C for the experimental measurement. It decreases to 4.7°C for the method that had inputs from the literature where as it reaches a minimum of 4.1°C for the theoretical calculation based on the assumed water properties for the watermelon. This variation in the

temperature drop indicates a higher thermal conductivity and diffusivity of the rind than that of water. The same trend is reflected on the heat transfer rate for these methods as shown in the Fig. 2.
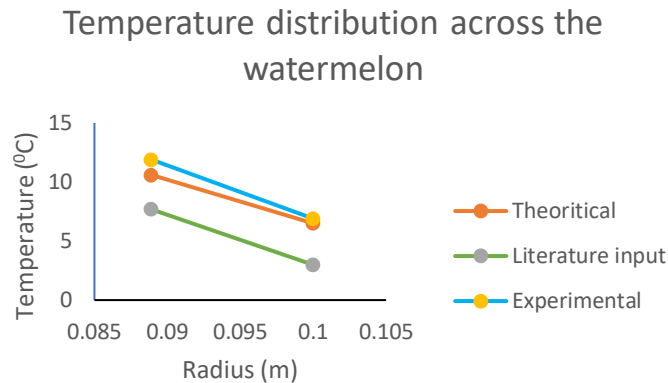

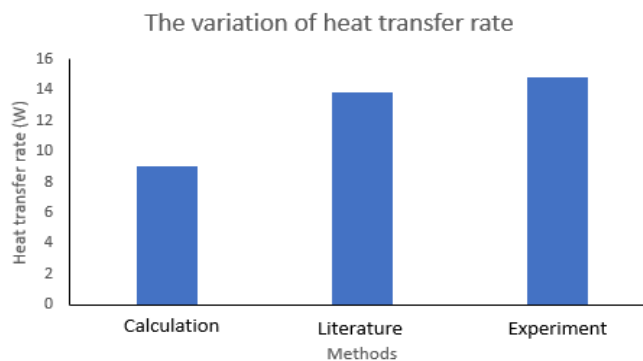**Fig. 2** The temperature distribution of watermelon across the radius with time.

Fig. 3 The variation of heat transfer rate for different approaches.

8. CONCLUSION

In this study, the temperature distribution across the radius of a watermelon was measured, experimentally, for a transient cooling process with a surrounding temperature of -6°C. The experimental data were compared with the theoretical calculations with the assumed thermal properties of water for the watermelon and thermal properties from the literature. The results show that the temperature drop across the rind of the fruit is maximum for the experimental observation whereas it is minimum for the theoretical calculation based on assumed water properties for the watermelon. This change in the temperature drop is significant while designing the thermal process during the storing and transportation of these fruits. A further experimental investigation in the thermal properties of the rind of the watermelon will be part of the future work.

NOMENCLATURE

T	Temperature	^{0}C
C_p	Specific heat	K
k	Thermal conductivity	W/(mK)
α	Diffusivity	m^2/s
Bi	Biot number	-

ρ	Density	kg/m^3
t	Time	s
r	Radius	m
h	Heat transfer coefficient	W/(m^{2}K)
A$_1$	Constant	-
τ	Fourier number	-
λ	Constant	-

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