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DETERMINATION OF THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF PAPAYA (*Carica papaya* L.) AS A FUNCTION OF TEMPERATURE

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Abstract. In the food industry, knowledge of thermal properties is of fundamental importance to analyze transport phenomena and to design food processing equipment, such as heat exchangers, chillers and evaporators. Several methods are available to measure food thermal properties. The line heat source probe method can be employed for the simultaneous determination of thermal conductivity and thermal diffusivity. It consists of applying a constant heat flux to a semi-infinite solid by a line heat source with an infinitesimal diameter and an infinite length. The temperature rise at a point close to the line heat source is a function of time, thermal properties of the material and source power. The advantages of this technique are short time, simplicity, low cost and possibility to use small sample sizes. As little published work on the thermal properties of tropical fruits are available, the objective of this paper was to determine the thermal conductivity and the thermal diffusivity of papaya as a function of temperature using the probe technique. A probe, with a heater wire to apply an electrical current of 3.6A, was used to measure simultaneously the thermal conductivity and the thermal diffusivity. It was totally inserted in the fruit samples. The probe was tested by determining the thermal properties of water. Error due to natural convection was avoided by adding 2% agar to the water. Papaya thermal properties were measured for the temperature range of 20ºC-40°C. Thermal conductivity ranged from 0.58 W/m°C to 0.62 W/m°C, and thermal diffusivity varied from 1.03 x 10^{-7} m^2/s to 1.18 x 10^{-7} m^2/s. Both properties varied linearly with temperature. They were found to increase with increasing temperature.

Keywords: Papaya, thermal conductivity, thermal diffusivity, line heat source probe method.

1. Introduction

Papaya is a typical fruit of tropical and subtropical countries. It is rich in minerals (calcium, iron, sodium and potassium) and vitamin A and C (ascorbic acid). In addition, it contains papain, an important digestive enzyme that is used to tenderize meat (BAHIA, 1994).

Knowledge of the essential thermophysical properties is of primary importance to the food industry. This information is required to make proper design of food processing equipment such as tanks, pumps, pipes, chillers and evaporators (de Moura et al., 1998).

Over the years both measured and calculated values of thermophysical properties of food have been published (Bhumbla et al., 1989; de Moura et al., 1998). However, most of the available data are for subtropical fruits. Little published information is available about the thermal properties of tropical fruits.

The objective of this paper was to determine the thermal conductivity and the thermal diffusivity of papaya as a function of temperature using the probe technique, and to compare the experimental data obtained in this work with those found in the literature.

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2. Theory

Several steady and unsteady state methods have been used to estimate the thermal properties of food. The line heat source probe method can be employed for the determination of thermal conductivity and thermal diffusivity simultaneously (Choi & Okos, 1983). It has been employed in many food applications due to its experimental short time, simplicity, low cost and adequacy for small sample sizes (Voudouris & Hayakawa, 1994).

This technique consists of applying a constant heat flux to a semi-infinite solid by a line heat source with an infinitesimal diameter and an infinite length. The temperature increase at a point close to the line heat source is a function of time, thermal properties of the material and source power (Choi & Okos, 1983). The equation, by which the thermal conductivity can be obtained, is:

$$k = \frac{Q}{4\pi.(T_2 - T_1)} \ln\left(\frac{t_2 - t_0}{t_1 - t_0}\right) \tag{1}$$

in which k is the thermal conductivity (W/m°C), Q is the power released by the heater wire (W/m), t_1 and t_2 are the initial and final times (s), and T_1 and T_2 are the temperatures (K) at times t_1 and t_2, respectively. The equation can be used when ln(t) versus T plot becomes linear.

To minimize the effect of finite heater diameter and any resistance to heat transfer between the heat source and sample, Van der Held & Van Drunen (1949) introduced a time correction factor (t_0)

The determination of thermal diffusivity (α) using the line source technique is possible without information of density and specific heat by using the following equation:

$$t = \frac{Q}{2\pi.k} \int_{\beta}^{\alpha} \frac{\exp\left(-\beta^2\right)}{\beta} d\beta \tag{2}$$

in which β is inversely proportional to $(\alpha)^{0.5}$:

$$\beta = \frac{r}{2\sqrt{\alpha.t}} \tag{3}$$

in which r is the distance between the heat line and the point where temperature is measured.

Nix et al. (1967) suggested the following series expression for evaluation of the above definite integral, in which C_e is the Euler constant (0.577):

$$T = \frac{Q}{2\pi .k}\left[-\frac{C_e}{2} - \ln\beta + \frac{\beta^2}{2.1!} - \frac{\beta^4}{4.2!} + \ldots\right] \tag{4}$$

Equation (4) is used to determine the thermal diffusivity. Nix et al. (1967) found that the first 40 terms of the above equation need to be evaluated to ensure convergence for values of $0.16 < \beta < 3.1$. However, for values of $\beta < 0.16$, the error is negligible if only the first two terms of the series are regarded. This condition is easily attained if the probe and the point where temperature is measured are closely located and the time is in the order of minutes (Urbicain & Lozano, 1997).

Several mathematical models have been proposed to predict thermal properties of fruits. Some models that relate thermal conductivity k (W/m°C), temperature above freezing T (°C) and water content X_W (kg H_2O/kg wet material) are given by Equations 5-7 (Vagenas et al., 1990):

$$k = -0.015 + 1.914x10^{-3}T + 0.590X_W \tag{5}$$

$$k = -0.022 + 1.924x10^{-3}T + 0.587X_W \tag{6}$$

$$k = -0.026 + 1.88x10^{-3}T + 0.618X_W \tag{7}$$

Choi & Okos (1986) proposed - based on literature data - the following general model to predict the thermal conductivity of foods for temperatures between 20°C to 100°C:

$$k = \sum k_i X_i \tag{8}$$

in which the subscript i refers to a particular pure component.

The values of thermal conductivity (k_i) of each pure constituent can be estimated as a linear function of temperature:

$$k_W = 5.9075x10^{-1} + 9.8601x10^{-4}T \tag{9}$$

$$k_p = 1.8730x10^{-1} + 7.8776x10^{-4}T \tag{10}$$

$$k_f = 1.8022x10^{-1} + 1.614x10^{-4}T \tag{11}$$

$$k_c = 1.9306x10^{-1} + 8.4997x10^{-4}T \tag{12}$$

$$k_a = 1.2863x10^{-1} + 3.9130x10^{-4}T \tag{13}$$

in which the subscript w, p, f, c and a are, respectively, water, protein, fat, carbohydrate and ash.

Riedel (1969) developed a mathematical model to predict the thermal diffusivity α (m^2/s) as a function of water content (Equation 14). This expression is adequate for a wide range of food products:

$$\alpha = 0.088x10^{-6} + (\alpha_W - 0.0088x10^{-6})X_W \tag{14}$$

in which α_W is the thermal diffusivity of water (m^2/s).

Martens (1980) performed multiple regression analysis on 2446 published values on thermal diffusivity of a variety of food products and obtained:

$$\alpha = \left[0.057363.X_W + 0.000288.(T + 273)\right]10^{-6} \tag{15}$$

Choi & Okos (1986) proposed the following general model to predicted the thermal diffusivity of foods based on literature for temperatures between 20ºC to 100°C:

$$\alpha = \sum \alpha_i X_i \tag{16}$$

in which the subscript *i* refers to a particular pure component.

The values of thermal diffusivity (α_i) of each pure constituent can be estimated as a linear function of temperature:

$$\alpha_W = 1.3988x10^{-1} + 3.0429x10^{-4}T \tag{17}$$

$$\alpha_p = 8.7055x10^{-2} + 2.4021x10^{-4}T \tag{18}$$

$$\alpha_f = 1.0306x10^{-1} + 1.5507x10^{-4}T \tag{19}$$

$$\alpha_c = 9.0371x10^{-2} + 2.4548x10^{-4}T \tag{20}$$

$$\alpha_a = 8.3039x10^{-2} + 1.1764x10^{-4}T \tag{21}$$

3. Material and Methods

Fresh ripe papayas (*Carica papaya* L.) were obtained in the local market. Fruit sampling was based on total soluble solids (10 - 12 ºBrix) and weight (3.5 kg - 4.0 kg). The main characteristics of this fruit are summarized in Table 1.

Table 1. Papaya Composition.

Component	Content (%)
Moisture	87.73
Total sugars	10.19
Reducing sugars	10.16
Fibers	1.27
Fat	0.50
Ash	0.40
Proteins	0.31

The thermal conductivity and diffusivity were measured simultaneously for the temperature range 20°C and 40°C using the linear heat source probe. The probe (Figure 1) encloses a heater wire and a thermocouple junction contained in hypodermical needles (length = 5 cm, diameter = 0.2 cm for the thermal conductivity probe and length = 5 cm, diameter = 0.1 cm for the thermal diffusivity probe). The line heat source probe is described in detail by Choi & Okos (1983).

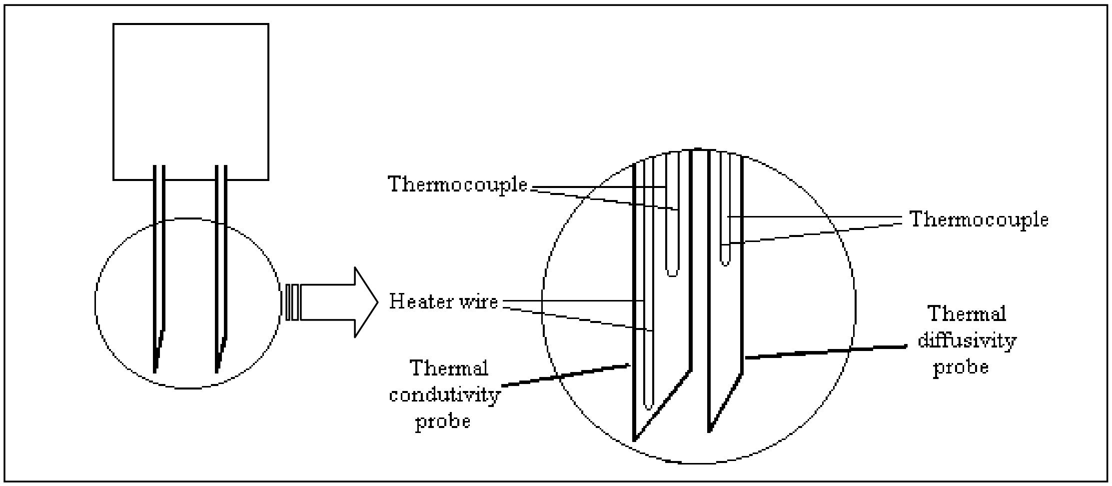

Figure1. Thermal conductivity and thermal diffusivity probes.

A constant electrical current of 3.6 A was applied to the heater wire. The Scanlog data aquisition software recorded the thermocouple readings every four seconds, during 20 minutes (Figure 2). A digital multimeter was used to check the voltage during data aquisition. The sample temperature was controlled by imerging the sample in a constant temperature bath.

The thermal conductivity and the thermal diffusivity probes were placed in the samples in such a way that the full length of the probes were covered. The experiment was repeated three times. Thermal conductivity was calculated according to Equation. 1. The heat input Q in this equation was calculated from the heater resistance and the electrical current by:

$$Q = I^2 R \tag{22}$$

in which I is the electrical current (A) and R the is resistance (Ω).

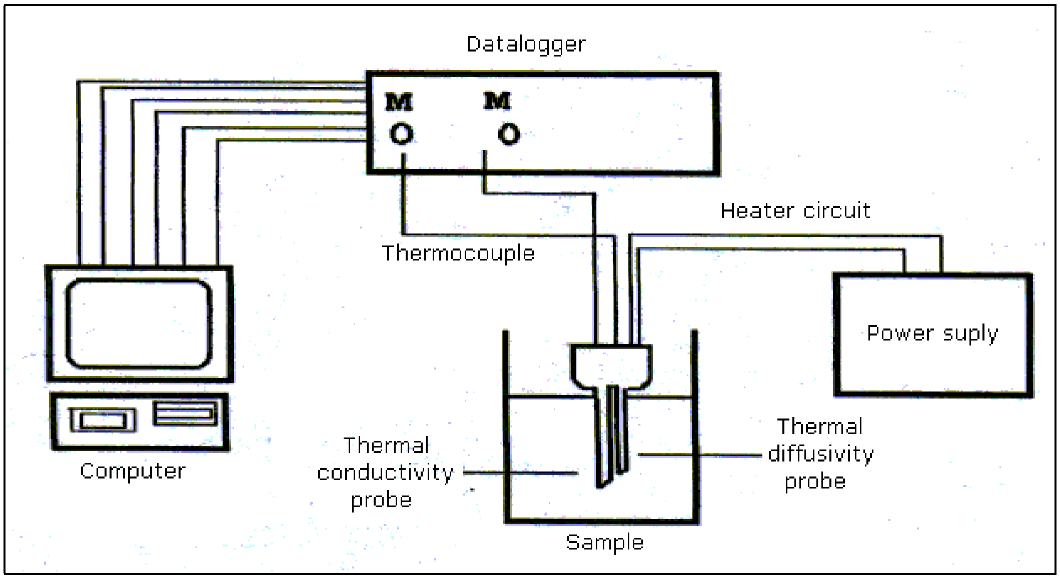

Figure 2. Thermal conductivity and thermal diffusivity measurement apparatus.

The thermal diffusivity was calculated according to Equations 2 to 4, using the non-linear regression of the SAS software.

The probe was tested by determining thermal conductivity and thermal diffusivity of water, with 2% agar to avoid the effect of natural convection.

4. Results and discussion

Results for the thermal conductivity (k) and thermal diffusivity (α) experiments at 20°C, 25°C, 30°C, 35 and 40°C are shown in Figures 3 and 4, respectively. Both thermal properties were found to increase with increasing temperature. A similar behavior was observed by Hu & Mallikarjunan (2004) for oysters, by Telis-Romero et al. (1998) for Brazilian orange juice and by Singh & Goswami (2000) for cumin seed.

Table 2 shows some values of k and α, respectively, for different fruits (Singh & Heldman, 1993; Sweat, 1974). The experimental values obtained for papaya is close to the values reported for other fruits.

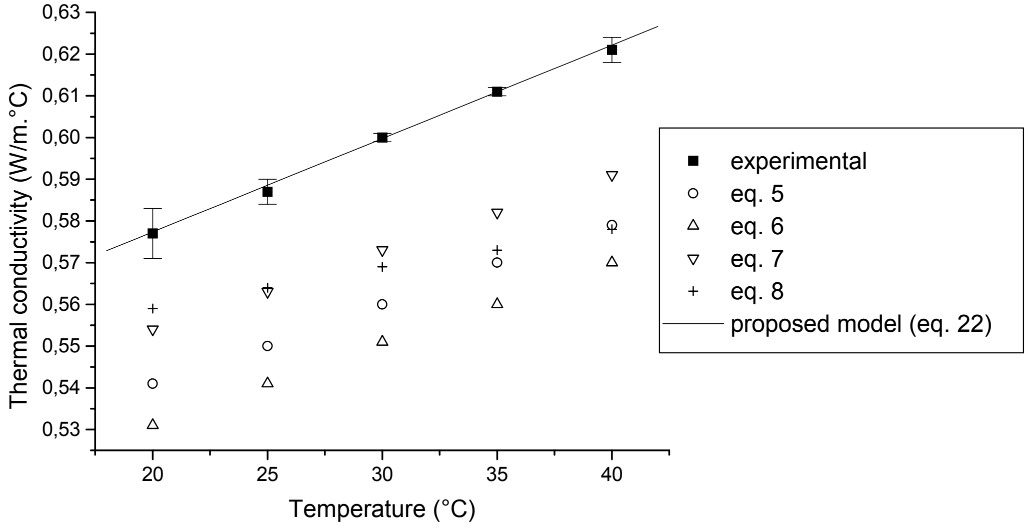

Figure 3: Thermal conductivity of papaya as a function of temperature

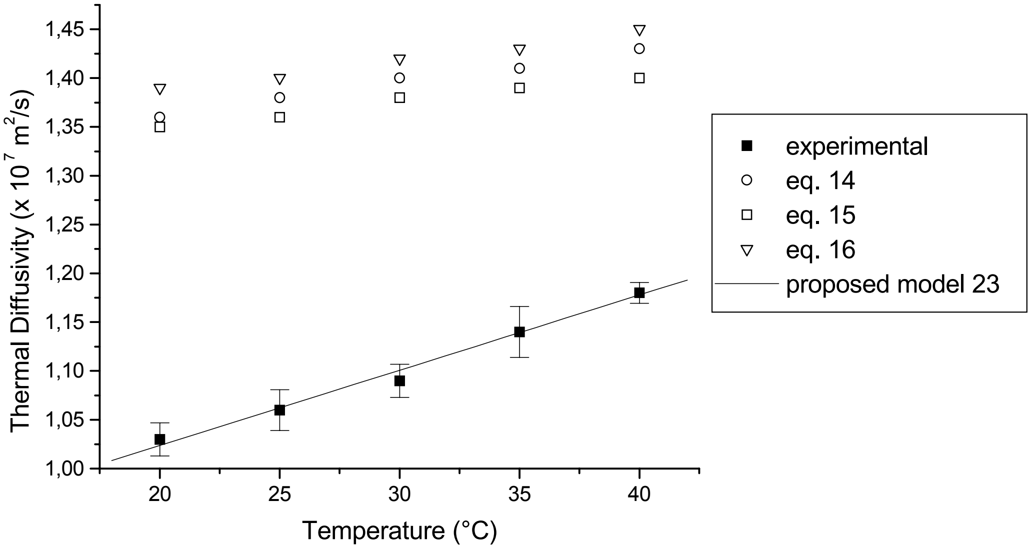

Figure 4: Thermal diffusivity of papaya as a function of temperature

Table 2. Thermal conductivity and thermal diffusivity of fruits.

Fruit	Moisture content (%)	Temperature (°C)	*k* (W/m.K)	α (x 10^{-7} m^2/s)
Apple, red (Sweat, 1974)	84.9	28	0.513	
Apple, red (Singh & Heldman, 1993)	85	0 - 30	-	1.37
Banana (Sweat, 1974)	75.7	27	0.481	
Banana (Singh & Heldman, 1993)	76	5	-	1.18
Banana (Singh & Heldman, 1993)	76	65	-	1.42
Lemon (Sweat, 1974)	91.8	28	0.525	
Lemon (Singh & Heldman, 1993)	-	40	-	1.07
Peach (Sweat, 1974)	88.5	28	0.581	
Peach (Singh & Heldman, 1993)	-	27	-	1.39
Strawberry (Singh & Heldman, 1993)	-	14 - 25	0.675	-
Strawberry (Singh & Heldman, 1993)	92	5	-	1.27

The results obtained showed the same trend of Equations 5 to 8 and 14 to 16, in which the thermal properties increase with increasing temperatures (Figures 3 and 4). However, these models did not fit very well the experimental data. These models were obtained for a wide range of food and do not take into account the sample physico-chemical characteristics. Therefore, polynomial equations are proposed to predict the thermal properties of papaya:

$$k = 0.5326 + 0.00224T \qquad (R^2 = 0.9967) \qquad (23)$$

$$\alpha = 8.69x10^{-8} + 7.71x10^{-10}T \qquad (R^2 = 0.9917) \qquad (24)$$

4. Conclusions

From this study, it was found that papaya thermal properties increase with increasing temperature. The results were similar to those given in literature for other fruits, showing that the probe technique was efficient for obtaining adequate measurements of the studied thermal properties. Equations were obtained to predict papaya thermal properties.

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