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Effective Thermal Conductivity of Cucurbit as a Function of Temperature by Thermal Probe Method

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Abstract

Effective thermal conductivity of cucurbit was determined at temperatures ranging from 0–45^{0}C. Thermal conductivity was measured by the rapid transient technique using a thermal probe. The probe was inserted in the center of the sample for sufficient time so that the needle maintains temperature equilibrium with the sample and also sample in equilibrium with the surroundings. The temperature distribution generated in the sample was measured through digital micro-voltmeter which measured the voltage generated due to the rise in temperature at the probe situated in the sample. It was found that the effective thermal conductivity of Cucumis sativus (L.) ranged from 0.36 W/mK to 0.56 W/ mK when the temperature varied from 272 K to 298 K, however for Luffa acutangula L.), it is varied from 0.30 W/m K to 0.42 W/m K. It was also observed that near room temperature there was a fall in thermal conductivity with increasing temperature.

Keywords: Thermal conductivity, probe method, cucurbit, temperature.

Introduction

Knowledge of thermal properties of food substances is essential to researchers and designers in the field of food engineering. The solid and semisolid foods like fruits and vegetables are sensitive to thermal and mechanical stresses and require specialized processing equipment which will minimize the damage to the quality of the products. Even a small physical and chemical change in raw fruits and vegetables affects the color, flavor or texture of the final product. Therefore, it is necessary to know the thermal conductivity, diffusivity and other transport properties of food in their natural form. It will also help in predicting the drying rate or temperature distribution within the food. Thermo-physical properties which play an important role in the design and analysis of food processes and processing equipments are thermal conductivity, thermal diffusivity, specific heat, heat storage coefficient and mass density. The knowledge of the thermal properties and how these properties change during processing as a function of temperature are of primary importance in heat transfer processes.

Several methods have been developed to measure the effective thermal conductivity of foods by analyzing the heat conduction equation and they can be classified into two broad categories: steady and transient-state methods. The steady-state methods needed a long time to complete and therefore moisture migration may introduce significant measurement errors. The transient hot strip, needle thermal probe and parallel wire probe are the methods preferred for the measurement of effective thermal conductivity in porous materials. In the present work the needle type thermal probe is used[1-3]. It has the advantage of least disturbance in actual physical state of food materials. The thermal probe method is the most widely used transient-state method and can be employed for the determination of thermal conductivity and thermal diffusivity, simultaneously. It has been recommended for many food applications due to its short response time, simplicity, low cost and adequacy for small sample sizes. Recently, similar attempt has been made for the measurement of effective thermal conductivity of perishable foods[4-9].

The objective of this work was to determine the thermal conductivity of Cucurbit using the thermal probe method and to obtain good empirical models as a function of temperature.

Theoretical analysis of the method: The thermal probe method is based on the principle that when a line source of heat is buried in an infinite sample, the temperature rises with time at a point near the line source and depends upon the rate of energy input and various thermal properties of the surroundings The temperature rise θ at a distance r from the line source of heat is given as a function of time t by the following equation,

$$\theta = \frac{q}{2\pi\lambda_e}\int \frac{e^{-\beta^2}}{\beta}\,d\beta = \frac{q}{2\pi\lambda_e} I\left(r\xi\right) \qquad (1)$$

where, β is a dimesionless parameter equal to $\frac{r}{2\sqrt{\alpha\theta}}$.

ξ and $I\left(r\xi\right)$ are given by

$$\xi = \frac{1}{\sqrt{4\alpha t}} \qquad (2)$$

$$I\left(r\xi\right) = C' - In\left(r\xi\right) + \tfrac{1}{2}\left(r\xi\right)^2 - \tfrac{1}{8}\left(r\xi\right)^8 + \ldots \qquad (3)$$

where, λ_e is the effective thermal conductivity of the sample, α is the thermal diffusivity of the sample, *C′* is Euler's constant having a value 0.5772, *q* the rate of heat generation in line source per unit length per unit time, *r* is the distance of any point inside the sample from the line source and *t* is time from start of heating. When *r* is small aid *t* is large, the third and subsequent terms of the equation 3 can be neglected. Therefore,

$$I(r\xi) = 0.5772 - In\left(\frac{r}{\sqrt{4\alpha t}}\right) \tag{4}$$

and

$$\theta = \frac{q}{2\pi\lambda_e}\left(C' - In\frac{r}{\sqrt{4\alpha t}}\right). \tag{5}$$

If the temperature at a certain point be measured at two different times t_1 and t_2 then,

$$\lambda_e = \frac{q}{4\pi}\frac{In(t_2/t_1)}{(\theta_1 - \theta_2)}. \tag{6}$$

Now, again if *I* be the current passing through the heater wire having resistance *R* of the probe length *L,* then the power per unit length,

$$q = \frac{I^2 R}{L}. \tag{7}$$

Therefore, the effective thermal conductivity of the sample can be written as,

$$\lambda_e = \frac{I^2 R}{L}\frac{In(t_2/t_1)}{(\theta_1 - \theta_2)}. \tag{8}$$

If a graph between the functions *In*(*t*) and θ is plotted a straight line is obtained and slope of this line $\frac{In(t_2/t_1)}{(\theta_1 - \theta_2)}$ comes out to be

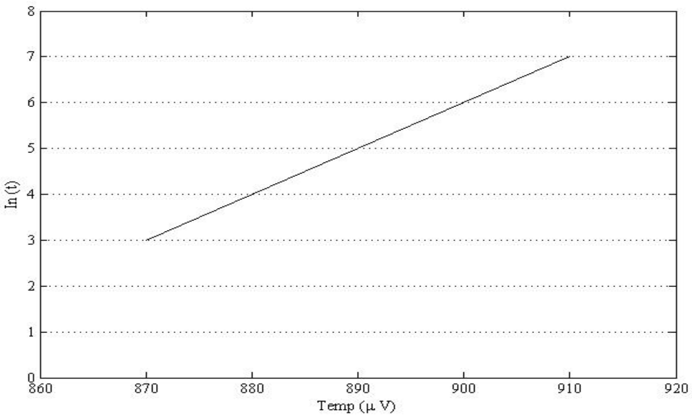

Figure-1
Variation of temperature with *In*(*t*) for *Cucumis sativus* (L.) at temperature $\theta = 293K$

Therefore, effective thermal conductivity λ_e of the material under test can be determined by measuring the rate of heat generation in the heating source per unit length and the values of temperature at two times t_1 and t_2 by using equation 6.

For short times, graphical procedure can be used for determining the effective thermal conductivity from the temperature time relationship. The application of these equations to thermal conductivity probe is straight forward if the temperature sensor is located at a measurable distance from the source. For probes where the heater and sensor are located within the same sheath, the value of distance *r* used in equations (1) – (3) is indeterminate. If the probe is considered to be a line heat source and equation 6 is accepted, the value of *r* becomes immaterial. This consideration generally used in the calculations. In the development of equation it was assumed that the cylindrical heat source was infinitely long and it was placed in a sample with an infinite diameter. Blackwell[2] found that although probes of finite length departed from the assumption, the errors in the measured values of the conductivity would be small (less than 10%) if the length to diameter ratio of the probe was greater than 25, this error due to axial heat flow in the probe is time dependent, however, for the probe and samples used in this study the duration of the test period is limited in order to make it negligible. In the determination of effective thermal conductivity the temperature rise during the first few seconds is disregarded in order to eliminate spurious effects associated with contact resistance and warming up of the probe.

Material and Methods

To determine the effective thermal conductivity, cucurbits of different species were chosen as experimental sample. The samples *(Cucumis sativus (L)* and *Luffa acutangula (L))* were used in natural form as they found and were purchased from the local market. The laboratory developed and designed thermal conductivity probes were standardized by measuring the thermal conductivity of pure glycerin to be 0.282 W/mK at 303 K. Since the value reported in literature[10] is 0.286 W/mK at 303 K, the error is not more 1.4%. However, theoretically the least count of various appliances used in the experiment, an experimental error of 5.0% through the equation 8 is expected.

A schematic circuit diagram and arrangement of the experimental set-up are shown in figures 2 and 3.

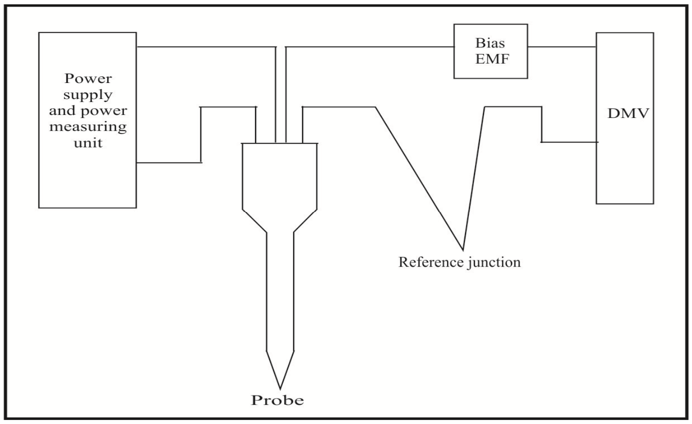

Figure-2
Circuit diagram for the measurement of effective thermal conductivity by using thermal probe

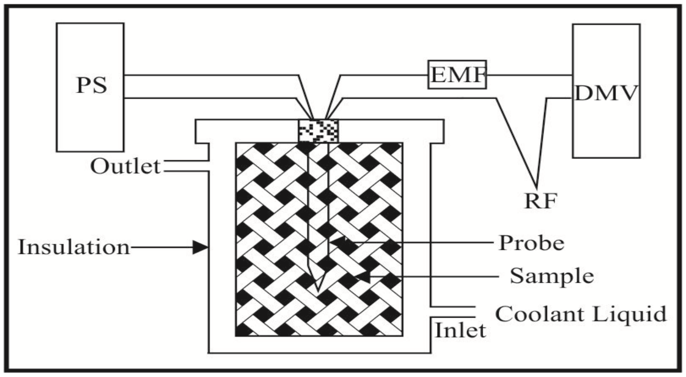

Figure 3
Experimental arrangement for the measurement of thermal conductivity by using thermal probe, where PS = power supply and power measuring unit, EMF = electro-motive field, DMV = digital micro-voltmeter and RF = reference junction

The experimental arrangement consisted mainly of three units: i. Sample container, ii. Constant temperature bath and iii. Power and temperature measuring units.

The sample container was doubly walled cylindrical copper vessel of 15.5 cm length and diameter of 7.3 cm. The sample container had an arrangement for water circulation around the sample to achieve required sample temperature. The water of fixed temperature was circulated from the constant temperature bath (Julabo F–30 VC Model from W. Germany) having temperature range –30° C to 200 °C with accuracy of ± 0.02° C. A stable power supply from a regulated power supply of having least count 0.1 mA was supplied to the probe heater. In order to reduce moisture migration by temperature difference, the rise in temperature due to probe was kept as low as possible by regulating the value of the power supplied to the probe heater so that the temperature rise should be within stated limitations. The copper constantan thermocouple was calibrated to determine temperature developed per degree. It was found from this experiment that 40.2 μV corresponds to 1°C. The digital micro-voltmeter was used for the temperature measurement of least count 0.1 μV and for time a clock of least count 1 sec.

A power supply of high regulation supplies the current to the probe heater. The reference junction of thermocouple was at the ice point. The probe was inserted in the center of the sample and sufficient time was allowed to be elapsed in order that the needle was close to the temperature equilibrium with the sample and also sample in equilibrium, with the surroundings. The probe thermocouple and heater points were connected to the digital micro-voltmeter and a stabilized power supply. A digital micro-voltmeter measured the voltage generated due to the rise in temperature at the probe situated at the sample. To maintain constant temperature a double walled brass chamber with the inlet-outlet fluid (water/ alcohol) was taken. The temperature chamber maintained a constant temperature by continuous circulating liquid (alcohol) from ULTRATEMP 2000. The considered temperature range was 273 K to 318 K. After the sample and probe had attained temperature equilibrium, the probe temperature was measured with the help of digital micro-voltmeter. After switching the circuit as shown in figure 2, readings of the voltage versus time were recorded at constant current flowing through the heater wire. The heating current of the order of 50 mA was taken, so that the power dissipated in the sample is low. It gave a temperature rise of less than 3°C in the sample, whereas a current of 70 mA raised the temperature to ~ 6°C. A plot for temperature rise (in micro-volts) in natural logarithm versus time was drawn for each observation. By knowing the slope of this straight line and power per unit length supplied to the probe, effective thermal conductivity was calculated using equation 8. The sample-probe system was left for few hours to achieve thermal equilibrium. Then, the power to the heater circuit was switched on.

According to the approximation taken in deriving the equation 6 the initial rise in temperature for 30 seconds was dropped. Each measurement lasted, approximately for 6 to 7 minutes. Experimental observations were made for sample at varying temperatures. At the conclusion of the test, the power was cut off and whole system was allowed to come to equilibrium state again. All the tests were repeated and the results of three runs were average out. Practically, in all tests the probe inserted directly in the samples. In this process, some local compaction might occur. This tends to increase the thermal conductivity of the sample in the immediate vicinity of the probe and alter the contact resistance between the probe and sample material. However, the probe measures the thermal conductivity of the sample over a fairly large area and the small compaction in the vicinity of the probe should not affect the measured thermal conductivity of ire sample.

Results and Discussion

The effective thermal conductivity of cucurbits of different species at temperatures from 0°C to 45°C is determined by thermal probe method. The experimental observed variation of effective thermal conductivity with temperature for *Cucumis sativus (L.) and Luffa acutangula (L)* are shown in figures 4 and 5 respectively.

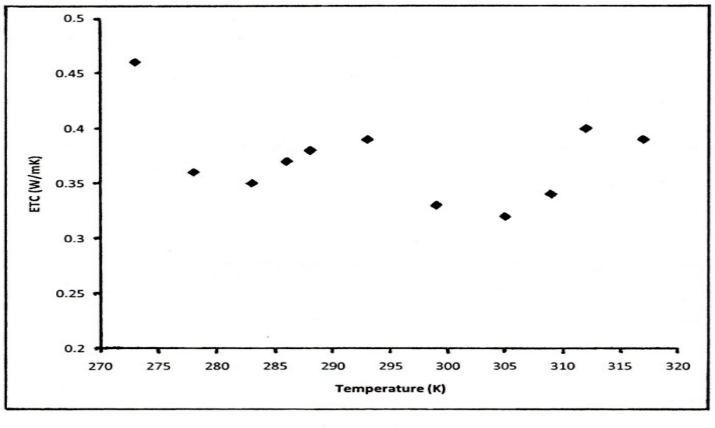

Figure 4
Variation of ETC (Effective Thermal Conductivity) with temperature for *Cucumis sativus* (L.) (water = 93.94%)

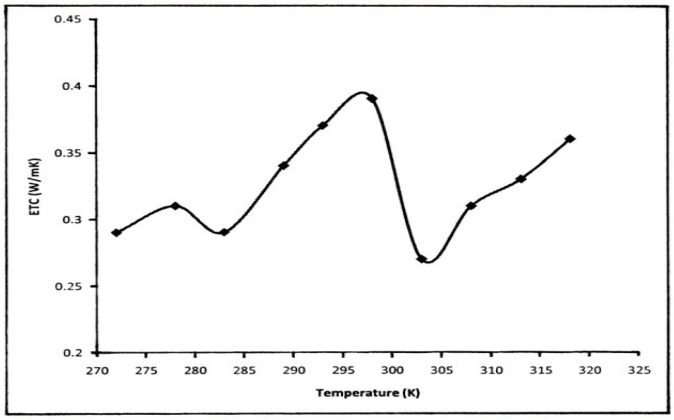

Figure 5
Variation of ETC (Effective Thermal Conductivity) with temperature for *Luffa aculangula* (L.) (water = 90.61%)

The effective thermal conductivity is observed to vary from 0.36 W/mK to 0.56 W/ mK when the temperature is varied from 272 K to 298 K for *Cucumis sativus (L.)* and for *Luffa acutangula L.),* it is varied from 0.30 W/m K to 0.42 W/m K. However, at 298 K (room temperature) there is a fall in conductivity, which again rises beyond room temperature in both the cases. The results showed the same trend as the mathematical models (Equations 6 and 8), by which the thermal properties increase with increasing temperatures.

The water content of cucurbits considered is 94% *(Cucumis sativus (L.))* and 90.6% *(Luffa acutangula (L)).* The water is exceptionally cohesive, but still acts as a solvent for ionic compounds. This is due to reduction in the attractive electric field between the oppositely charged ions due to high dielectric constant. And, since the dielectric constant for water is high ~78.4 at 298 K and a change in dielectric constant with temperature gives rise to considerable and anomalous changes in its solubilization and partition properties. The anomalous dielectric behavior of water is also found at ~298 K over a range of microwave frequencies between 20Hz to 100 GHz. This may cause some type of changes in the form of contents and gives rise noticed change in effective thermal conductivity at 298 K. In this measurement of effective thermal conductivity the current was used of the order of 50, 70, 90, 100, 120, mA. We finally took the current of 50 mA because for other current combinations the temperature gradient was more than 6°C and for temperature dependent study it is not appreciated.

Conclusion

We study the temperature dependence of effective thermal conductivity, using thermal probe method for cucurbit in natural form. The effective thermal conductivity of *Cucumis sativus (L.)* and *Luffa acutangula (L)* increases with increase in temperature as expected. However, there is a fall in conductivity at around 298 K. Both temperature and moisture content had significant effect on the thermal conductivity of cucurbit. Since water is the main constituent, the anomalous change in the solubilization about 298 K may be responsible for this decrease in conductivity. The results were similar to those given in the literature for some other fruits and vegetables, showing that the probe technique was efficient for adequate measurements of the studied thermal properties. However, literature models did not fit well our experimental results, since these models were obtained for a variety of foodstuffs. Therefore, empirical models based on a linear dependence of thermal properties on temperature may provide very good predictive values for cucurbit, in the temperature range of 0 to 45°C. The results of this work have direct application to fruit processes involving heat transfer.

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