Effective thermal diffusivity of perishable produce as a function of temperature by transient method

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Received 28 March 2008; revised 25 September 2008

Effective thermal diffusivity of vegetables/fruits has been determined in the temperature range 0 – 45°C. The thermal diffusivity is measured by a transient technique using temperature probes (thermocouples) inserted in the sample at a distance of 2 mm. One dimensional transient temperature distributions \( T(r, t) \) generated in the sample are measured at different positions at discrete times. An ADAM data acquisition module is used to simultaneously read and store the temperature after every one second interval with a precision of 0.001°C by GeniDaq software. The cubic spline interpolation technique is used to calculate effective thermal diffusivity. The temperature dependent thermal diffusivity has been determined for \( Cucumis \) sativus (L.), \( Luffa \) acutangula (L.), \( Lagenaria \) siceraria (L.), \( Malus \) domestica (L.) and \( Musa \) acuminate (L.). The effective thermal diffusivity increases continuously with temperature.

**Keywords:** Effective thermal diffusivity, Transient technique, Vegetables, Fruits, Temperature

1 Introduction

Thermo physical properties play an important role in the design and analysis of the food processes and processing equipments. The properties of fruits and vegetables in their natural form are difficult to predict due to their variable heterogeneous structure. Therefore, experimental measurements are especially important. Thermal diffusivity indicates how fast heat propagates through a sample while heating or cooling and is used to calculate time-temperature distribution in the materials. It is influenced by compositions, its distribution and temperature of the food samples. To determine thermal diffusivity of porous materials at constant temperature many techniques viz. parallel wire method\(^2\)\(^-\)\(^3\), transient hot strip method\(^4\), acalorimeter method\(^5\) are available. However, these techniques are neither suitable for food sample in natural form nor able to measure temperature dependence of thermal parameters.

Tavman\(^6\) measured thermal diffusivity of granular food materials at constant temperature. Kee et al.\(^7\) used similar method for thermal diffusivity of pet food. The diffusivity is evaluated at constant temperature which is the average of chamber and sample temperature. Moreover, precise measurement of temperature at center/axis is needed. It is not easy for food samples in natural form. Therefore, this will not be useful to predict temperature dependences of thermal parameter. Glavina et al.\(^8\) applied transfer functions methodology.

To overcome this lack of precision, temperature is measured along the diameter of the sample, as a function of time and position (discrete function values). Using the piece-wise interpolating polynomial for temperature distribution, temperature as a continuous function of \( r \) is obtained. The temperature versus distance along diameter graph is a parabola with minimum or maximum temperature at the center. Thus thermal diffusivity may be determined by finding the position of local extrema of temperature distribution and at this extremum position change in temperature with time is also observed. A continuous measurement of temperature at these points also gives thermal diffusivity as function of temperature. Therefore, in the present paper to measure thermal diffusivity of vegetables/fruits in natural form a transient method is used. Its variation in temperature range of 0 to 45°C is seen for \( Cucumis \) sativus (L.), \( Luffa \) acutangula (L.), \( Lagenaria \) siceraria (L.), \( Malus \) domestica (L.) and \( Musa \) acuminate (L.).
2 Methodology

2.1 Method of the measurement

The uniformly cooled or heated sample is placed in a double walled and insulated chamber which is maintained at constant temperature by flowing a fluid in the outer. The transient temperature distribution inside the sample is measured by an array of eight thermocouples. The thermal diffusivity measuring apparatus is shown in Fig. 1.

The sample is kept in a double walled cylindrical copper vessel of 15.5 cm length and 7.3 cm inner diameter. The fruit sample, which is cooled and has constant temperature throughout, is placed in constant temperature chamber. The constant temperature is maintained by flowing fluid in the outside of chamber. The fluid at constant temperature with variation < ± 1°C is circulated from a constant temperature bath (Julabo F32). The chamber is insulated by foam rubber.

The temperature probe is made of eight copper-constantan thermocouples. These thermocouples are arranged on a teflon sheet with the help of needles of diameter 1.6 mm. Each thermocouple is placed in a needle with insulating powder and packed with araldite. The temperature probe is inserted across the diameter of the sample. All the thermocouples are connected to an ADAM data acquisition module which is setup to simultaneously read and store the temperature in computer after each second interval with a precision of 0.001°C. The GeniDaq software is used for storing the data. Each experimental run takes about three to four hours. Each experiment is iterated 2-3 times and average values are reported.

2.2 Calculation of thermal diffusivity

The calculation of thermal diffusivity from the measured time-temperature distribution is based on the assumption that heat flow is along the direction of radius and the temperature is only a function of $r$. Then, the temperature distribution is solution of the heat conduction equation

$$\rho(T) C(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial r} \left( \lambda(T) \frac{\partial T}{\partial r} \right) + \frac{1}{r} \frac{\partial T}{\partial r} \lambda(T)$$

for $r < a$ ... (1)

with boundary conditions

$$T(a,t) = T_{\text{chamber}}$$

for all $t$, and the initial condition $T(r,t) = T_s$ for $r \leq a$

where $t$ is time, $T$ is temperature and $a$ is radius of the sample.

From Eq. (1), the RHS is

$$\frac{\partial}{\partial r} \left( \lambda(T) \frac{\partial T}{\partial r} \right) = \frac{d\lambda}{dt} \left( \frac{\partial T}{\partial r} \right)^2 + \lambda(T) \frac{\partial^2 T}{\partial r^2}$$

... (2)

First term of the sum involving the first partial derivative of the temperature with respect to coordinate, vanishes at local extrema of the temperature distributions. Thus, at extremum temperature positions thermal diffusivity is

$$\alpha(\text{Te}) = \frac{\partial T}{\partial^2 T}$$

... (3)

The experimental measurement of temperature $T(r, t)$ is made at discrete set of thermocouple positions at discrete times. In order to calculate the derivatives in Eq. (3) from the discrete experimental temperatures, a continuous functions underlying the data $T(r, t)$ is needed. Due to complex shape of the temperature numerical technique is used. Temperature curves consisting of several pieces of cubic polynomials with parabolic runout splines have been considered. This causes the curves to degrade to a single cubic curve over the end intervals, rather than two separate functions. These cubic polynomials also enable to find the local extremum of the temperature distribution. The $\frac{\partial T}{\partial t}$ at max/min is determined by fitting spline to the temperature measured as function of time at extremum position. Thus for each measured temperature distribution as a function of $r$, $t$ the value of thermal diffusivity may be obtained.

3 Results and Discussion

The effective thermal diffusivity of cucurbits i.e. *Cucumis sativus* (L.), *Luffa acutangula* (L.) and *Lagenaria siceraria* (L.) and *Malus domestica* (L.) and *Musa acuminate* (L.) (raw and ripe) is determined.
at temperature ranging from 0 to 45°C. The initial temperature of the sample is 0°C, whereas the constant temperature bath is maintained at 60 ± 0.1°C during the measurements. Since, the rise in temperature at the points along the diameter is continuously recorded, therefore, thermal diffusivity of the sample at any temperature may be determined by numerical technique and using the Eq. (3). The calculations in temperature spread of 1°C have been made. This average thermal diffusivity as a function of temperature for cucurbits is shown in Figs 2-4.

It is seen that in general, the effective thermal diffusivity is an increasing function of temperature. However, for all cucurbit samples a dip in the thermal diffusivity values is observed at 30-35°C. Similar behaviour is also reflected by effective thermal conductivity of cucurbits, determined by thermal probe method. The thermal diffusivity for ripe and raw samples of Musa acuminate (L.) are plotted in Figs 5-6. The qualitative and quantitative nature of both the graphs

![Fig. 2 — Variation of effective thermal diffusivity of Cucumis sativus (L.) with temperature](image1)

![Fig. 3 — Variation of effective thermal diffusivity of Luffa acutangula (L.) with temperature](image2)

![Fig. 4 — Variation of effective thermal diffusivity of Lagenaria siceraria (L.) with temperature](image3)

![Fig. 5 — Variation of effective thermal diffusivity of Musa acuminate (L.) (ripe) with temperature](image4)

![Fig. 6 — Variation of effective thermal diffusivity of Musa acuminate (L.) (raw) with temperature](image5)
widely differs. At a temperature of 30°C the ripe fruit thermal diffusivity is $6.48 \times 10^{-8}$ m$^2$/s and for raw it is $3.17 \times 10^{-8}$ m$^2$/s. The continuous chemical activity in the fruit releases water. And, since the diffusivity of water is $12.97 \times 10^{-8}$ m$^2$/s, thus ripening of fruit may cause increases in thermal diffusivity. Thus continuous chemical activity in food changes the micro composition as well as macro thermal properties.

The variation of effective thermal diffusivity of Malus domestica (L.) with temperature as shown in Fig. 7. It is seen that diffusivity continuous increases with increase in temperature. It may be noted that, in Malus domestica (L.) thermal diffusivity variation with temperature is small in comparison to vegetables and banana. It may be due to low density of Malus domestica (L.)

The present method is reliable as it is transient and it does not consider average temperature of sample and outside constant temperature bath. Observations are omitted for the temperatures above 45°C as the sample condition deteriorates.

4 Conclusions

The technique presented here is easy to apply and it allows us to obtain the effective thermal diffusivity of food samples for a broad and continuous range of temperatures. The present method measures temperature at large number of points along the diameter and then from numerical technique, thermal diffusivity is evaluated. Thus it overcomes the error of measuring the temperature at the point on central axis of temperature.

Acknowledgements

The authors are highly obliged to Institute of Armament Technology, Girinagar, Pune for providing there experimental facilities. One of the authors (DKS) is also grateful to CSIR for awarding SRF.

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