



An optimized method for thermal diffusivity measurement of peeled off fruits and vegetables

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Abstract

The aim of the present work was to find out the most suitable method for thermal diffusivity measurement of peeled off fruits and vegetables. Three methods reported in the literature, have been examined. One of them is finite difference method, which needs temperature-time measurements at three equidistant locations in the food flesh. Another method is the well-known Riedel correlation, which determines thermal diffusivity of food item from its water content. The third method is based on the empirical correlation of the present author and his co-workers and reported earlier. Peeled off fresh potato, cucumber, apple and orange samples were exposed to chilled air blast cooling, and temperature-time records were made at five equidistant locations starting from center and at equal distances of $1/5^{\text{th}}$ the distance between the center and the outer surface. Collected data was used to estimate thermal diffusivity values by the first and the third methods. The second method was also used to calculate thermal diffusivity from measured water content of the produce. After thorough investigations, it was concluded that the third method was most reliable when temperature records at the center were used.

Key words: Measurement, peeled off fruits and vegetables, thermal diffusivity.

Introduction

Fruits and vegetables are seasonal and climate dependent. To make these important food items available round the year and at the places they are not grown, these are extensively preserved in the refrigerated warehouses, but most of the fruits and vegetables are unfit for freeze-preservation. They are generally preserved in unfrozen state at temperatures above 0°C . Different produces have different optimum preservation temperatures. For most of the important produces, these optimum temperatures and expected high quality life have been reported in the literature¹. Due to unfrozen storage, high quality life of such food is quite low. This necessitates a careful design of cooling equipment used in cold storages. For proper design of the system, food thermo physical properties must be accurately known and effects of extraneous parameters on the property must also be investigated before hand. Thermal diffusivity is a very important property in this regard. Numerous steady state and transient methods are available in the literature for measuring thermal diffusivity of food²⁻¹⁵. Some of the important methods reported in the literature are guarded hot plate method, concentric cylinder method, concentric sphere method, heating or cooling methods, line heat source and probe method and freeze-drying method. It is interesting to note that the measured values were strong functions of the method used. The variation in the published data by different investigators was from 50% to as high as 93%¹⁵. This variation is found to be more for the same product by different investigators than the variation between different commodities by the same investigator¹⁴. This prompted the present investigators to make a comparative study of important measurement techniques and find out one, which

gives the most reliable measurements for all the test runs. The selected method must be simple, reliable and worthy of being used by food technologists. As the transient methods of measurement are easy and fast, two such methods were selected along with an empirical correlation for the present experimental and theoretical investigations to make a critical comparative study and find out the best method.

Mathematical Models

The first method is the well-known finite difference technique¹⁵. This method solves the one-dimensional transient heat conduction equation with the help of measured temperatures at three equidistant locations in the food flesh. The second method is the well-known Riedel correlation¹⁶ commonly used in the food industry. It requires only the water content of the produce to estimate its thermal diffusivity. The third method is based on the empirical correlation developed and reported elsewhere by the first author and his coworkers¹⁷⁻²⁰. The correlation is reported to yield reliable results for $0 \leq X \leq 0.6$ and $\tau \geq 0.2$. This method requires temperature-time records only at one location in the food body.

The finite difference solution of one-dimensional transient heat conduction equation for isotropic solids without internal heat generation is described as follows¹⁵:

$$\alpha_i^j = \frac{(\Delta x)^2}{\Delta t} \cdot \frac{(T_i^{j+1} - T_i^j)}{((1-Y)T_{i-1}^j - 2T_i^j + (1+Y)T_{i+1}^j)} \quad (1)$$

where $Y = 0$ for infinite slab, $\frac{1}{2i}$ for infinite cylinder and $\frac{1}{i}$ for sphere.

The equation (1) shall yield thermal diffusivity at every computational time-step if temperatures are known at three equidistant locations inside the food flesh.

The second method is based on the commonly used Riedel's formula as given below¹⁶:

$$\alpha = \alpha_0 + (\alpha_w - \alpha_0)W \quad (2)$$

where α_w is the thermal diffusivity of water at the mean produce temperature available in the literature. The value of α_0 is a constant given as

$$\alpha_0 = 0.833 \cdot 10^{-7} \text{ m}^2/\text{s} \quad (3)$$

Determination of thermal diffusivity by this method needs the knowledge of water content of the produce (W) only.

Earlier, the first author and his coworkers developed empirical correlation by generating data through finite difference solution of the normalized one-dimensional transient heat conduction equation along with appropriate initial and boundary conditions. During data generation, all the significant parameters varied in their normal encountered ranges. Least square analysis of these data points yielded the following normalized correlation¹⁷⁻²⁰:

$$\tau = \frac{\left[a + b \cdot \ln \left(\frac{1}{X + 0.2} \right) - \ln U \right]}{\left[\frac{c}{\left(1 + \frac{d}{Bi^2} \right)} \right]} \quad (4)$$

In Equation 4, the regression constants a, b, c, d and e for the three regular shapes of infinite slab, infinite cylinder and sphere are different and have been reported earlier¹⁷.

Equation 4 provides the third approach for thermal diffusivity measurements through transient temperature-time records at a single known location in the produce flesh as well as to the Biot number. Once τ is known, thermal diffusivity may be calculated using its definition as given by Equation 5:

$$\tau = \frac{\alpha t}{x_0^2} \quad (5)$$

Materials and Methods

First of all, water content was measured for the four types of fresh fruits and vegetables by means of electronic balance with resolution of 0.001 g and fitted with infrared dryer set at 105°C. Water content of samples was measured by drying it for 16 hours. Mass of thinly cut produce pieces was determined before and after thorough drying until no further moisture loss was obtained. For cooling and temperature-time records, the samples were chilled in an air-blast plant shown schematically in Fig. 1. It consisted of a 4 m long galvanized iron sheet air duct of cross section 0.3 m x 0.25 m. The duct was insulated with 15 mm thick glass wool. The return air was cooled by passing it over the cooling coil of a vapor-compression refrigeration system. Dampers A and B were provided to control the rates of fresh air and return air circulations to maintain constant chilled air temperature at the desired level of 0.5°C. The air speed in the test duct was maintained constant at 5.0 m/s.

Copper-constantan thermocouples were fixed at the centre and four equidistant locations in the food flesh at $x_0/5$, $2x_0/5$, $3x_0/5$

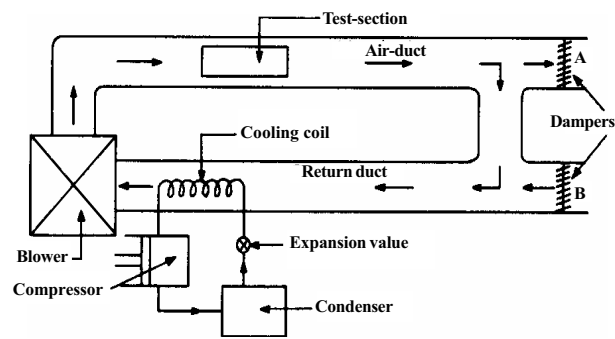


Figure 1. Chilled air duct.

and $4x_0/5$. The refrigeration plant was run for nearly 30 minutes. When the temperature of the inside air came to a steady state, the sample was suspended in the test section of the duct and temperature record was made for one hour at one minute time interval with the help of a data logger. The potatoes, apples and oranges were taken as nearly spherical as possible. Cucumbers were chosen as uniformly cylindrical as possible and its samples were suspended in the test section such that the chilled air stream was parallel to its axis. This was to ensure uniform cooling from the whole produce surface.

Results and Discussion

Temperature-time records at three equidistant locations within the samples were used to solve the finite difference equation (1) giving thermal diffusivity at every computational time step at the middle point. Parabolic interpolation polynomial was used to interpolate temperatures at every computational time-step from the temperature-time records at some different measurement time steps. During computations of thermal diffusivity, instability was encountered in the solution. This instability increased strongly with the distance of sensor location from center of the sample. A comparatively higher value of standard deviation and coefficient of variation was observed during computations. It was an indication of higher dispersion of the result from its mean value. Slightly better results were obtained when the measurement points were away from the surface in the region $0 \leq X \leq 0.6$, especially near the center. The dispersion was found to be maximal at the initial stage of cooling. This was mainly due to the non-linear nature of the cooling curve in the beginning¹⁷⁻¹⁹. Apart from the large dispersions, during the investigations on all the samples, non-convergence was observed at numerous computational time steps. Even negative values of thermal diffusivity had ensued, particularly near the surface. This makes the method unreliable. Although, mean of all the converging values was found to compare with the thermal diffusivity values reported in the literature, the method was discarded due to non-convergence at numerous computational time steps and a high dispersion of computed results.

The second method of thermal diffusivity calculations using Riedel's formula and defined by Equation 2 is the simplest one in terms of data requirements to yield the thermal diffusivity values. This method requires only the water content of the samples to find the thermal diffusivity of food. Measured water content values of the produces were used to determine thermal diffusivity values by this method. The plots of the results are shown in

Fig. 2 by the broken lines. The values by this method are found to vary with temperature, but the variation is very small and the value may be taken almost constantly. Average thermal diffusivity by this method was found to be lower than the values reported in the literature²¹.

Thermal diffusivity was also calculated by the third method using the empirical equation (4) at each measurement time-step. It required time-temperature records at a single location inside the food flesh. This empirical method is reported to give accurate and reliable results for $\tau \geq 0.2$ and $0 \leq X \leq 0.6$. A few time-temperature measurements yielded quite reliable results. This method did not possess the problem of convergence. The standard deviation and coefficient of variation were lower in case of this empirical approach and the dispersions were also very low. The coefficient of heat transfer, needed to solve Equation 4, was calculated by the following Nu-Re relationship for a regular shaped body^{15,22}:

$$Nu = p + q.Re^r . Pr^s \quad (6)$$

The thermal diffusivity values calculated from Equation 4 were found to vary slightly with the location of the temperature sensor. The effective values increased slightly as the sensor was moved towards the surface. On the basis of many investigations, it was found that the values determined on the basis of center temperature records had resulted into best temperature calculations. It may, therefore, be recommended that for the third method, temperature-time records at the center must be used. The average thermal diffusivity value at the central location by this method was generally higher than that reported in the literature²¹. This is supposed to be due to enhanced desiccation effect in the exposed and peeled off produce samples. The thermal diffusivity values obtained by the third method, based on the temperature-time records at the centre, have also been plotted in Fig. 2 by the firm line. The figure reveals dependence of thermal diffusivity value on the temperature of the produce. The variable α value was found to yield improved temperature calculations when used in place of a constant value of α .

Variable thermal diffusivity obtained by the third method was found to yield the best temperature calculations for all the fruits and vegetables investigated. For temperature calculations, a correlation was developed between α and T for each sample, and one-dimensional transient heat conduction model was solved for temperature by optimized explicit finite difference method using variable α values as well as constant α values reported in the literature¹⁵. During investigations on seven samples each of the four food produces, a consistently better agreement was observed

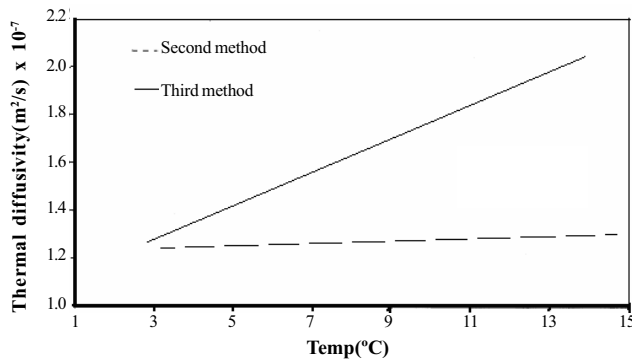


Figure 2. Thermal diffusivity variation trend by the second method.

between the estimated and measured temperatures when variable α value, as yielded by the third method, was used compared to those when constant α value was considered. One such plot for a potato sample is shown in Fig. 3.

Computer programs were written in Fortran language to make α calculations by the three methods. One program was also written to predict the temperature-time variations.

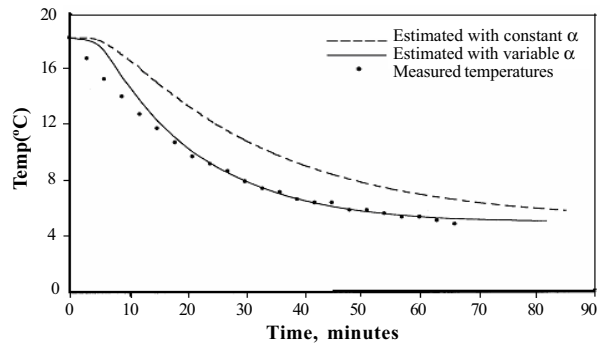


Figure 3. Predicted temperature-time variation for a potato sample.

Conclusions

On the basis of experimental and computational work carried out on seven fresh samples each of peeled off apple, orange, potato and cucumber, the following conclusions may be drawn.

- 1) The finite difference method of determining thermal diffusivity from temperature-time records at three equidistant locations in the food flesh is not conditionally stable. It also gives high value of dispersion in the estimated α values. Due to these limitations, the method was discarded.
- 2) Riedel's formula, commonly used by the food technologists, provides the simplest method in which thermal diffusivity is a function of the produce water content only. This parameter can be easily obtained, but the predicted average values are on the lower side and do not yield accurate temperatures when used.
- 3) The empirical correlation developed by Ansari and co-workers provides more reliable method of thermal diffusivity measurement. It is over and above the fact that the method is stable, convergent, simpler, easier and faster both from measurement as well as calculation points of view. It yields dependence of α on temperature, which when incorporated in the calculation scheme for temperature-time variation, yields much improved results. It implies that the effect of moisture evaporation from the exposed peeled off produce samples was included in the predicted α values by this method. This method may, therefore, be recommended with confidence.

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Nomenclature

Bi	Biot number = $\frac{h \cdot x_0}{k}$ (dimensionless)
h	surface film conductance (W/m ² .K)
k	thermal conductivity of product (W/m.K)
Nu	Nusselt number = $\frac{h \cdot x_0}{k_{air}}$ (dimensionless)
m	= 0 for slab, 1 for cylinder, 2 for sphere
Pr	Prandtl number = $\frac{\mu_{air} \cdot c_{air}}{k_{air}}$ (dimensionless)
Re	Reynolds number = $\frac{\rho_{air} \cdot v_{air} \cdot x_0}{\mu_{air}}$ (dimensionless)
t	time (s)
t ₀	initial time (s)
T	temperature (°C)
U	dimensionless temperature = $\frac{T - T_{cm}}{T_1 - T_{cm}}$
x	distance from center (m)
X	dimensionless space co-ordinate = $\frac{x}{x_0}$
x ₀	characteristic length; half thickness of infinite slab, or radius of cylinder or sphere (m)
Δt	time increment (s)
Δx	space increment (m)
Greek Letters	
α	thermal diffusivity of sample (m ² /s) Fourier number (dimensionless)
Subscripts	
cm	cooling medium
i	space step
j	time step
l	initial