International Journal of Advances in Engineering and Management (IJAEM)
Volume 3, Issue 7 July 2021, pp: 3773-3778 www.ijaem.net ISSN: 2395-5252

Indirect Measurements of Thermal Properties of Food Materials

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Submitted: 15-07-2021 Revised: 29-07-2021 Accepted: 31-07-2021

ABSTRACT

Thermal diffusivity is an important transport property needed in modeling and computations of transient heat transfer in basic food processing operations. In addition, the prediction of nutritional and microbial changes occurring in food during thermal processing requires knowledge of thermal diffusivity of foods. This method has been developed for the simultaneous estimation of thermal diffusivity, thermal conductivity, volumetric heat capacity and the heat transfer coefficient for foods heated/cooled by convection. The method uses experimental time-temperature data of the food and the medium, which are used in a parameter estimation procedure based on the conduction heat transfer equation in one dimension for an infinite cylinder. To increase the accuracy in the results the estimations are performed in a number of sub-steps under varied model conditions, for example is an inner fictive cylinder used. The suggested method estimated the thermal diffusivity, the heat conduction and the volumetric heat capacity with a maximal relative error in the interval 6-9%. This study shows the well-known difficulty of separating the thermal conductivity and the volumetric heat capacity in the expression for the thermal diffusivity, caused among other things by the uncertainty in the estimation of the heat transfer coefficient.

I. INTRODUCTION

To enhance and guarantee food safety, and to decrease the risk of foodborne illness, the contamination and increase of undesirable microorganisms in foods must be controlled throughout the production-to-consumption chain. Thermal pasteurization is a traditional physical process of food decontamination that is still commonly used today (Silva and Gibbs 2012). The temperature profile inside foods can be used to predict a survival curve for microorganisms. Thermal diffusivity indicates how fast heat propagates through a material while heating or cooling at an unsteady state (Rahman and Al-Saidi 2009). Therefore, thermal diffusivity values are needed to predict temperature profiles for the thermal pasteurization process and to establish an adequate heat treatment in the food industry.

Heating and cooling of food products are common in food processing; heat transfer is one of the most important phenomena in the food industry. The mathematical basis of thermal processes is well established, frequently by use of the conduction heat transfer equation with a convective boundary condition. Improvement in the design or optimization of thermal processes requires reliable thermo-physical data. The food material is often inhomogeneous and in some cases composed by pieces of different sizes and density. Accurate predictions of the thermo-physical data are not available for many semisolid and multiphase food, therefore are experimental determinations required. In a thermal process the necessary thermal properties are the density, the specific heat and the thermal conductivity, or the thermal diffusivity. The thermal properties are often affected by water content, temperature, composition, porosity and kinetic reactions.

There are several different methods available for measuring the thermal diffusivity of foods. Critical reviews have been written by Nesvadba (1) and Singh (2) among others. An experimental apparatus was designed by Dickerson (3) to measure the thermal diffusivity of foods. This experimental apparatus has been used and adapted by many researchers. Magee and Bransburg (4) and Gordon and Thorne (5) estimated α using a thermal diffusivity tube under transient heat transfer conditions by the lag method and the slope method. Kee et al. (6) used a similar thermal diffusivity tube and measured the thermal diffusivity using the log method. The drawbacks with these methods are that they are limited to homogeneous, isotropic foods of certain geometry. Jaramillo-Flores and Hernandez-Sanchez (7) used heat penetration curves to estimate the thermal diffusivity.

Most methods estimate only one parameter under constant temperature. The temperature dependency and the mutual interactions between the parameters is then lost. Nahor et al. (8) measure the volumetric heat capacity and the thermal conductivity of heated foods simultaneously and uniquely using the hot wire probe method.

The objective of this study is to demonstrate a method where thermal properties (k, ρc_p, αandh) of foods are estimated simultaneously by use of experimental data and a theoretical model. Primary, semisolid and bulk foods are considered. The optimization routines are based on the least squares method, where the parameters are estimated sequentially in a number of sub- steps.

II. MATERIALS AND METHODS

Three kinds of low-moisture food: almond meal (ALMOND MEAL/FLOUR, Bob’s Red Mill Natural Foods, Milwaukie, Oreg., U.S.A.), corn meal (ENRICHED YELLOW corn meal, Meijer, Grand Rapids, Mich., U.S.A.), and wheat flour (Gold MEDALTM WHOLE WHEAT FLOUR, Betty Crocker, Minneapolis, Minn., U.S.A.) were used in this study. These samples were purchased from a local market. The moisture content of these samples was measured using a moisture analyzer (MA30, Sartorius AG, Goettingen, Germany). The moisture contents of the samples were 4.0% (wet basis) for almond meal, 11.1% for corn meal, and 9.9% for wheat flour.

The experimental set-up is shown in figure 1. The food is put in a copper cylinder with a diameter of 35 mm and a length of 120 mm, the cylinder has rubber plugs in both ends. Through the rubber plug at the top two bayonet thermocouples are stuck, one at the center of the cylinder and one near the surface (6 mm from the inside of the cylinder). In addition, two thermocouples are placed in the water at different depth and one at the surface of the cylinder. The heating media is water and a mixer is used to create a uniform heat distribution. The thermocouples are connected to a logger and a personal computer , Easy view 5 is used to record the data . The temperatures are measured every 30 s for 20-30 minutes, during the temperature is increased from 20-85 °C. The model food tested was pancake dough and a meat filling of a springroll.

Figure 1 shows a schematic of the thermal diffusivity measurement apparatus used in this study. The apparatus consisted of 3 parts: sample container (steel can), temperature control, and recording unit. Each can had 1 sealed and fixed needle type thermocouple to measure the center or offset temperature at the half height of the can. Another thermocouple (Omega surface

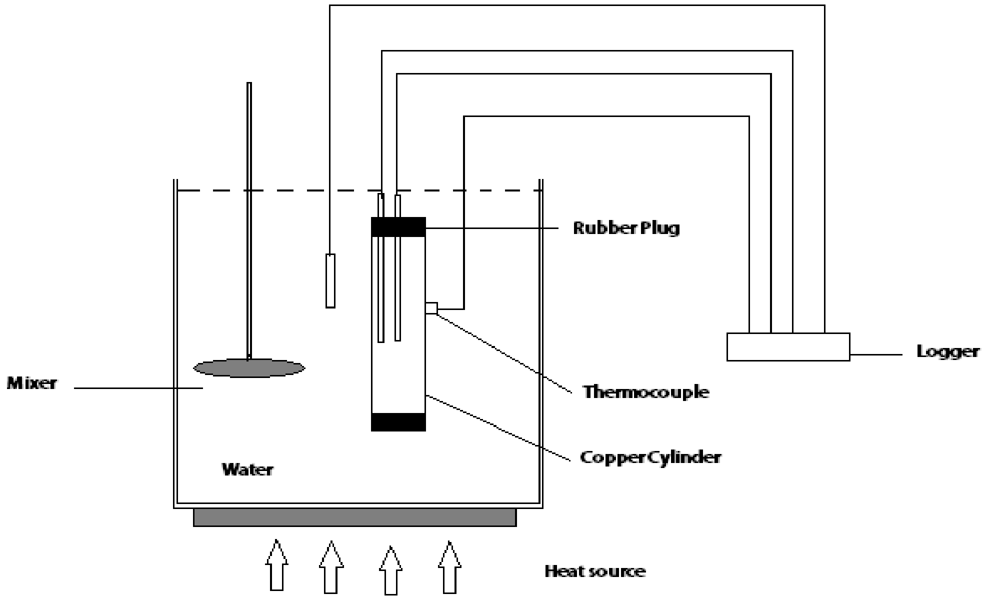

Figure 1. Experimental setup

MATHEMATICAL MODELLING

The heat transfer model for this experiment was for heat conduction in1-dimensional and cylindrical coordinates as follows:

$$\frac{\partial T}{\partial t} = \frac{\alpha}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right), [0 \le r \le R]$$

Where T is the temperature at the center or the offset (°C), t is the time (s), r is the radial coordinate of the can (m), R is the radius of the can (m), and α is the thermal diffusivity of the sample (m2/s).

Initial condition was uniform temperature throughout the sample:

$$T(r, 0) = T_i$$

Where Ti is the initial temperature. The governing boundary conditions were:

$$\frac{\partial T(0, t)}{\partial r} = 0$$

(Axisymmetric condition)

$$T(R, t) = T_s(t)$$

WhereTs is outside surface temperature of the can and changes with time as it approximates a sine wave with a mean of 70 °C. As mentioned above, the outside surface temperature of the can was measured with a surface thermocouple taped on the cans outside surface during the test. In this study, the heat conduction inside the steel plate of the can and the heat resistance between the inside surface of the can and the sample were ignored because the can’s thermal conductivity was relatively large.

Governing heat conduction equation for heat conduction in 2-dimensional and cylindrical coordinates:

$$\frac{\partial T}{\partial t} = \alpha\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right\}, [0 \le r \le R, 0 \le z \le H]$$

Where z is the axial coordinate of the can (m) and H is the length of the can (m).

Initial condition:

$$T(r, z, 0) = T_i$$

Axisymmetric condition:

$$\frac{\partial T(0, z, t)}{\partial r} = 0$$

Boundary conditions:

$$h(T - T_\infty) = -k\frac{\partial T(r, H, t)}{\partial z}$$

$$T(R, z, t) = T(r, 0, t) = T_{surf}$$

III. RESULT AND DISCUSSION

The results calculated by COMSOL Multiphysics for 2- dimensional cylindrical heat conduction are shown as an example in Figure 2 for a heating time of 1000 s. Then, the results over the entire heating time were compared with the exact 1 dimensional and cylindrical heat conduction solution (Cole and others 2010), in which the initial and axisymmetric conditions are same as Eq. 2 and 3, and the boundary condition at r = R is expressed as follows:

$$T(R, t) = T_{surf}$$

The can was not taken into account in the exact 1- dimensional heat conduction. The solid line and broken line show the results at the center (r = 0, z = H/2) and the offset (r = R/2, z = H/2), respectively. The 2-dimensional calculated results matched well with the 1-dimensional exact solutions. The similar results were obtained for the high- and middle-moisture foods. There were no significant differences between the 2-dimensional calculated results and the 1-dimensional exact solutions. This result demonstrates that the 1-dimensional heat conduction theory could be applied to the measurement device used in this study and the effect of can on the heat conduction in the sample could be ignored. Therefore, using 1-dimensional heat conduction theory and the steel cans (radius 33 mm and height 143 mm), the thermal diffusivity of the sample was estimated by solving Eq. 1 numerically with initial and boundary conditions (Eq. 2 to 4).

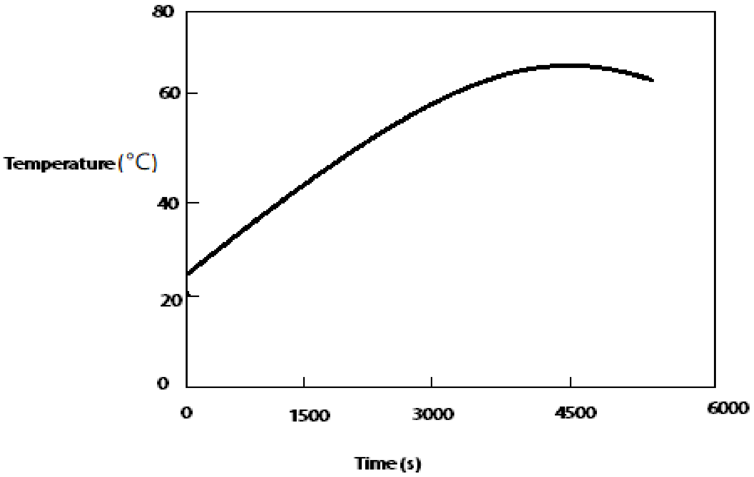

Figure 1. Measured temperature curve.

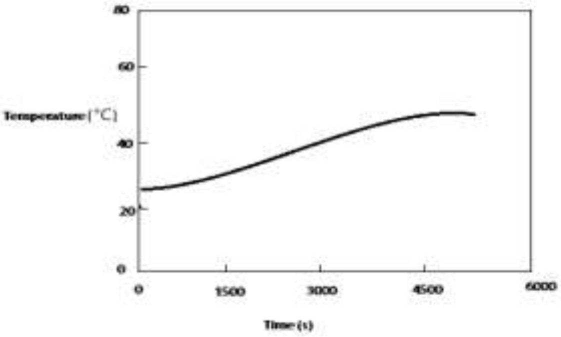

Figure 2. Calculated temperature curve

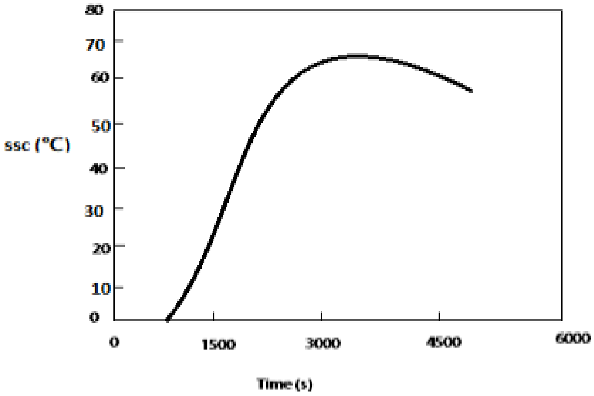

Figure 3. SSC plot

The square mean error was used as a criterion on curve fitting. The suggested method estimates the thermal properties (except for the heat transfer coefficient) with a maximal relative error between 6-9%. The measured temperatures in the cylinder and the calculated temperatures are shown in figure 1 and figure 2. The measured and calculated temperature curves in the center of the cylinder are in well agreement. The value of α is estimated by Dirichlet boundary condition.

Sample	Data set	α **(×10−7 m2/s)**	RMSC (℃)	Confidence Interval
Almond meal	Center	1.532	0.254	1.516-1.520
	Offset	1.522	0.212	1.531-1.533
	Center & offset	1.499	0.277	1.537-1.540
Corn meal	Center	1.247	0.397	1.010-1.012
	Offset	1.194	0.582	0.973-0.977
	Center & offset	1.231	0.645	1.008-1.012
Wheat flour	Center	1.141	0.322	1.154-1.158
	Offset	1.123	0.567	1.144-1.146
	Center & offset	1.134	0.506	1.155-1.157

Table 1. Estimated thermal properties with different starting value

Sample	Data set	α **(×10−7 m2/s)**	RMSC (℃)
Almond meal	Center	1.200	0.156
	Offset	1.215	0.516
	Center & offset	1.302	0.310
Corn meal	Center	1.187	0.771
	Offset	1.140	0.367
	Center & offset	1.152	0.254
Wheat flour	Center	1.048	0.275
	Offset	1.052	0.381
	Center & offset	1.054	0.354

Table 2. Estimation results of thermal diffusivity by sequential estimation.

IV. CONCLUSION

This study provided a new nonisothermal and nonlinear determination method of the thermal diffusivity of food. The method developed in this study will be useful in measuring the thermal diffusivity of food, since this method has advantages, such as being simple, inexpensive, reasonably rapid (approximately 33 min), and requiring no special equipment. The thermal diffusivities of the samples estimated by the OLS were 9.8 × 10−8 to 1.3 × 10−7m2/s. The sequential estimation procedure was also applied to determine the thermal diffusivity. Under sequential estimation, the thermal diffusivity reached a constant value before the experiment ended and the results obtained by sequential estimation procedure were almost the same as those fromOLS procedure. This study also demonstrated the value of the sequential estimation procedure.

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