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A novel instrument for rapid measurement of temperature-dependent thermal properties of conduction-heated food up to 140 °C

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ABSTRACT

Estimating thermal properties for thick or solid foods at temperatures greater than 100 °C is challenging for two reasons: the long time needed to reach a constant temperature, and the pressure needed to be maintained in the sealed container. An instrument ("Thermal Properties Cell", or "TPCell") was developed based on a rapid non-isothermal method to estimate the temperature-dependent thermal properties within a range of commercial food processes (20–140 °C). The instrument design consists of a custom sample holder and special fittings to accommodate the heater within a pressurized environment. The total time of the experiment is less than 1min., compared to existing isothermal instruments requiring 5–6 h to cover a similar temperature range. Thermal conductivities of different food materials were estimated for the temperature range of commercial food processes. The novelty of the instrument lies in its ability to analyze transient temperature data using a nonlinear form of the two-dimensional heat conduction equations.

1. Introduction

Thermophysical properties, especially thermal conductivity and specific heat, are very important in designing and developing processes such as heat exchangers, aseptic processing systems, etc. Thermal properties are also critical in determining scheduled thermal processes for a specific product. Modeling kinetics of thermal degradation of nutrients and thermal inactivation of microorganisms requires reliable estimates of the thermal properties of foods. Mathematical modeling is used for new and novel processes to design and optimize food quality. However, input of thermophysical properties to these models is often a limiting step. For example, maximizing quality and ensuring safety of solid or thick foods requires tracking the food temperature during the process. Thermal properties are needed to predict the food temperature. The "isothermal" (0.5–2 °C temperature rise) line-source method has been commonly used, because it is fast at lower temperatures. Yet determining thermal properties at higher temperatures (>100 °C) is challenging, because by the time the entire food sample in the container reaches a constant temperature, the quality is grossly degraded. It is at higher temperatures where rates of quality degradation and microbial inactivation increase very rapidly. Therefore, accurate thermal properties are critical for process design of foods, as well as for other materials, such as biomass, foams, pastes, and thick slurries.

The most common method to estimate thermal properties is the hot-wire probe. Heat-flux boundary conditions or volumetric generation in the heat-transfer partial differential equation allows for simultaneous estimation of thermal conductivity and volumetric heat capacity (Beck and Arnold, 1977). A heat pulse method can be used to estimate thermal properties (Bristow et al., 1994). Nahor et al. (2001) performed temperature-independent simultaneous estimation of thermal conductivity and volumetric heat capacity at room temperature, and an optimal design of a heat-generation profile was presented to estimate the parameters. The optimal design for the placement of the sensor was also studied for the estimation of thermal parameters (Nahor et al., 2001). In another study, a hot-wire probe method using nonlinear regression

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was employed for the simultaneous estimation of thermal conductivity and volumetric specific heat (Scheerlinck et al., 2008). Scheerlinck et al. (2008) also studied the optimum heat-generation profiles and applied a global optimization technique for optimization of the heating profile and the position of the sensor. One important issue to consider with the hot-wire probe method is the design of the probe and sources of error. Design of a thermal conductivity probe was considered and the possible sources of error were analyzed for the construction of such a probe (Murakami et al., 1996). Carefully designed probes have higher accuracy in thermal parameter estimation.

The thermal conductivity and specific heat of carrots at elevated temperatures were estimated by linear regression using the line heat-source probe by performing several experiments at a predetermined initial temperature of the food material (Gratzek and Toledo, 1993). The transient line heat-source technique was used to estimate thermal conductivity of potato granules and maize grits over a temperature range of 30–120 °C (Halliday et al., 1995). The line heat-source probe method was also used to estimate thermal conductivity of food in a high-pressure (up to 400 MPa) system (Denys and Hendrickx, 1999). Thermal conductivity of food material was estimated under heated and pressurized conditions using the transient hot-wire method (Shariaty-Niassar et al., 2000). In their study, thermal conductivity of gelatinized potato starch was determined at 25–80 °C, 50%–80% moisture, and 0.2–10 MPa. They also found that the thermal conductivity of starch gel increases with temperature and moisture content up to 1 MPa pressure. A dual-needle probe was used to estimate thermal properties under high-pressure processing conditions, and (Zhu et al., 2007) found that thermal conductivity and thermal diffusivity increased with increasing pressure. Temperature-dependent thermal conductivity was estimated using nonlinear estimation (Yang, 1999). The temperature used in the experiment was in the range of 0–30 °C. Simultaneous estimation of temperature-dependent thermal conductivity and specific heat was performed using a nonlinear method and nonisothermal experiments (Yang, 2000). Estimation of temperature-dependent specific heat capacity of food material by the one-dimensional inverse problem was solved for the thawing of fish (−40 to 5 °C) (Zueco et al., 2004).

The inverse method is a useful tool for parameter estimation (Beck and Arnold, 1977). The inverse method was used to estimate the thermal conductivity of carrot puree during freezing (Mariani et al., 2009) and thermal diffusivity of various foods (Betta et al., 2009; Greiby et al., 2014; Mishra et al., 2008, 2011; Mohamed, 2010). A temperature-dependent estimation of thermal conductivity was done using a polynomial model for sandwich bread using the cooling curve (Monteau, 2008).

One of the drawbacks of these methods is that one has to wait a long time (45 min minimum) from one temperature level to another temperature level, as the probe and food material must be in equilibrium to start the experiment. The experiment can only be performed once the heat source and the sample are in thermal equilibrium. Hence, performing tests at five or six different temperature levels makes the experimental time unacceptably long (5–6 h), and unwanted changes in material properties occur because of long durations at higher temperature.

In the literature reviewed, there was no standard method to estimate thermal properties of conduction-heated materials rapidly over a large temperature range in one experiment. There is a lack of research on rapid estimation of temperature-dependent thermal properties covering the entire relevant food processing temperature range (25–140 °C) using a single experiment. Development of a device would be of great use to a variety of industries, such as the food, pharmaceutical, and chemical industries.

Examples of continuous food processes where product temperature rises 100°C or more within 1 min include waffle and pancake baking; candy-bar wafer cooking; aseptic processing of soups with particulates; impingement cooking of meat patties; extruded snacks, breakfast cereals, and pet foods; spray-dried foods; and roasting of nuts. In each case, the temperature of the product is critical in ensuring both quality and safety. Knowledge of product thermal properties during rapid increases of temperature is needed to predict the temperature. Therefore, the objective of this study was to devise an inverse method and construct a device to accurately estimate temperature-dependent thermal properties from 20 to 140 °C using non-isothermal heating.

2. Material and methods

2.1. Mathematical model and scaled sensitivity coefficients

The transient heat conduction equation in a hollow cylinder for temperature-variable thermal conductivity and volumetric heat capacity (caused by changes in the specific heat) with the heater at the center can be given as

$$\frac{1}{r}\frac{\partial}{\partial r}\left[k_h r\frac{\partial T}{\partial r}\right]+\frac{\partial}{\partial z}\left[k_h\frac{\partial T}{\partial z}\right]+g_0 f(t)= C_h\frac{\partial T}{\partial t}\ \text{for}\ R_0<r\le R_1, 0<z\le Z,\ t>0 \tag{1a}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left[k_1 f_k r\frac{\partial T}{\partial r}\right]+\frac{\partial}{\partial z}\left[k_1 f_k(T,K)\frac{\partial T}{\partial z}\right]= C_1 f_C\frac{\partial T}{\partial t}\ \text{for}\ R_1<r\le R_2, 0<z\le Z,\ t>0 \tag{1b}$$

This problem was solved numerically with finite element software (COMSOL® (COMSOL, 2012),). In this section, scaled sensitivity coefficients are derived using a dimensionless method. The sum of scaled sensitivity coefficients is used in the dimensionless form to provide a method for checking if all parameters are estimable in the model. The sensitivity coefficient of a parameter is the first partial derivative of the function involving the parameter, with respect to the parameter (Beck, 1970). Consider a simple function;

$$T=f(k,C,x,t) \tag{2}$$

where k and C are parameters of the function T. The sensitivity coefficient of k and C are $\frac{\partial T}{\partial k}$ and $\frac{\partial T}{\partial C}$, respectively. After multiplying the sensitivity coefficient by the parameter, we get the scaled sensitivity coefficient represented by $\hat{X}_k=k\frac{\partial T}{\partial k}$ and $\hat{X}_C=C\frac{\partial T}{\partial C}$ for k and C, respectively.

The heat conduction problem is made dimensionless, as follows: Let,

$$\tilde{k}=\frac{k_2}{k_1},\tilde{C}=\frac{C_2}{C_1} \tag{3}$$

Linear functions of temperature for the thermal conductivity and volumetric heat capacity are considered; they are

$$f_k\left(T-T_0,\tilde{k}\right)=1+\frac{(T-T_0)-(T_1-T_0)}{(T_2-T_0)-(T_1-T_0)}\left(\tilde{k}-1\right) \tag{4}$$

$$f_C\left(T-T_0,\tilde{C}\right)=1+\frac{(T-T_0)-(T_1-T_0)}{(T_2-T_0)-(T_1-T_0)}\left(\tilde{C}-1\right) \tag{5}$$

When Eqs. (4) and (5) are multiplied by k_1 and C_1, respectively, then the thermal conductivity values k_1 and k_2, and the heat capacity values C1 and C2 are given at T_1 and T_2. The temperature