Simultaneous Thermal Conductivity and Thermal Diffusivity Measurement of Foods

Introduction

Heating and cooling of food is one of the earliest applications of science to foods. A thermal process is applied to any system in which heat energy is transferred to or from the product. The thermal properties of food are its ability to conduct, store, and lose heat. These properties are inherent in today's food processing and preservation practices. Thermal properties are important for modeling processes (microwave heating, extrusion, freezing, etc.), engineering design of processing equipment, calculating energy demand, and development of sterilization and aseptic processing. Besides processing and preservation, thermal properties also affect sensory quality of foods as well as energy saving from processing. The important thermal properties are: thermal conductivity (k), thermal diffusivity (D), and thermal resistivity (R). Simple definitions are as follows:

- **Thermal conductivity** (k - W m^{-1} $°C^{-1}$) is the ratio of heat flux density to temperature gradient in a material. It measures the ability of a substance to conduct heat.
- **Thermal diffusivity** (D - mm^2 s^{-1}) is the ratio of thermal conductivity to specific heat. It is a measure of the ability of a material to transmit a thermal disturbance.
- **Thermal resistivity** (R - m °C W^{-1}) is computed as the reciprocal of thermal conductivity.

The importance of thermal conductivity is to predict or control the heat flux in food during processing such as cooking, frying, freezing, sterilization, drying or pasteurization. It is necessary to ensure the quality of the food product and the efficiency of the equipment. Thermal diffusivity determines how fast heat propagates or diffuses through a material. It helps estimate processing time of canning, heating, cooling freezing, cooking or frying. Water content, temperature, composition, and porosity affect thermal diffusivity. There is a demand for accurate, rapid and inexpensive measurement of thermal conductivity (k) thermal diffusivity (D), and thermal resistivity (R) of foods and soils. These properties are necessary for calculating energy demand for the design of equipment and optimization of thermal processing of foods (Polley *et al*., 1980).

However, existing equipment such as the differential scanning calorimeters are expensive, dual needle probes have spacing concerns, and single needle thermal conductivity probes can only measure one thermal parameter (Sweat, 1974). Recently, Decagon Devices has developed the KD2, a handheld readout and single needle probe that simultaneously measures thermal conductivity, thermal diffusivity, and thermal resistivity. The objective of the study was to evaluate the performance of the KD2 for the measurement of k, D, and R in selected foods and soil.

Theory of Operation

KD2 calculates its values for thermal conductivity, resistivity, and diffusivity by monitoring the dissipation of heat from a line heat source given a known voltage. The equation for radial heat conduction in a homogeneous, isotropic medium is

$$\frac{\partial T}{\partial t} = D\left(\frac{\partial^2 T}{\partial r^2} + r^{-1}\frac{\partial T}{\partial r}\right) \quad (1)$$

where T is temperature (°C), *t* is time (s), D is thermal diffusivity (m2 s-1), and *r* is radial distance (m). When a long, electrically heated probe is introduced into a medium, the rise in temperature from an initial temperature, T0, at some distance, *r*, from the probe is

$$T - T_0 = \left(\frac{q}{4\pi k}\right) E_i \left(\frac{-r^2}{4Dt}\right) \quad (2)$$

where q is the heat produced per unit length per unit time (W m^{-1}), k is the thermal conductivity of the medium (W m^{-1} C^{-1}), and E_i is the exponential integral function

$$-E_i(-a) =$$

$$\int_a^\infty \left(\frac{1}{u}\right) \exp(-u) du = -\gamma - \ln\left(\frac{r^2}{4Dt}\right) + \frac{r^2}{4Dt} - \left(\frac{r^2}{8Dt}\right)^2 + \ldots \quad (3)$$

with a = r2/4D*t* and γ is Euler's constant (0.5772…). When *t* is large, the higher order terms can be ignored, so combining Eqs. (2) and (3) yields

$$T - T_0 \cong \frac{q}{4\pi k}\left(\ln(t) - \gamma - \ln\left(\frac{r^2}{4D}\right)\right) \quad (4)$$

It is apparent from the relationship between thermal conductivity and $\Delta T = T - T_0$, shown in Eq. (4), that ΔT and ln(*t*) are linearly elated with a slope m = (q/4πk). Regressing ΔT on ln(*t*) yields a slope that, after arranging, gives the thermal conductivity as

$$k \cong \frac{q}{4\pi m} \quad (5)$$

where q is known from the power supplied to the heater. The diffusivity can also be obtained from Eq. (4). The intersection of the regression line with the *t* axis (ΔT = 0) gives

$$\ln(t_o) = \left(\gamma + \ln\left(\frac{r^2}{4D}\right)\right) \quad (6)$$

From the calculated *t*0 (from the intercept of T vs. ln(*t*)) and finite *r*, Eq. (6) gives the diffusivity. Because the higher order terms of Eq. (3) have been neglected, Eq. (4) is not exact. However, if the slope and intercept are computed only for T and ln(*t*) values, where *t* is large enough to ignore the higher order terms, Eq. (5) and (6) give correct values for k and D. To verify these relationships, realistic values of k and D were supplied to Eq. (2), varying both k and volumetric heat capacity (ρcp), and the resulting slope and intercept tabulated for *t* ranging from 1 to 30 s.

Plots of slope vs. theoretical k and ln(intercept) vs. ln(theoretical D) show an exact linear relationship (Fig. 1 and 2, respectively) with low cross-covariance. The experimental analysis differs from the theoretical shown in Eq. (2) in that the heater and sensor have their own conductivity and diffusivity, which, in general, differ from those of the medium being measured. We have shown experimentally that the relationships in Eq. (5) and (6) still allow calculation of k and D, but empirical factors must be introduced to correct for heater thermal properties.

Assumptions

The thermal conductivity measurement assumes several things: the long heat source can be treated as an infinitely long heat source, the medium is both homogeneous and isotropic, and a uniform initial temperature, T_0. Although these assumptions are not true in the strict sense, they are adequate for accurate thermal properties measurements.

References

Polley, S.L., Snyder O.P., and Kotnour, P., 1980. A compilation of thermal properties of foods. Food Technology, 34(11):76-94.

Sweat, V.E., 1974. Experimental values of thermal conductivity of selected fruits and vegetables. J. Food Science, 39:1080.

Fontana, A.J., Wacker, B., Campbell, C.S., and Campbell, G.S., 2001. Simultaneous Thermal Conductivity, Thermal Resistivity, and Thermal Diffusivity measurement of Selected Foods and Soils. 2001, ASAE Meeting Paper No: 01-610

Decagon Devices, Inc.
2365 NE Hopkins Ct.
Pullman, WA 99163 USA
support@decagon.com