열탐침을 이용한 식품의 열전도도 측정

THERMAL CONDUCTIVITY MEASUREMENT OF LIQUID AND SOLID FOODS USING A THERMAL PROBE

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적 요

열전도도, 열확산도, 비열로 대표되는 열적 특성은 식품의 가열 및 냉각공정의 설계에 사용되는 주요 설계인자로서, 정확한 열적특성 자료가 있으면, 각 공정에서 가하거나 감해야 하는 총 열량과 단위 시간당 가감되어야 하는 열량을 정확히 결정할 수 있다. 본 연구에서는 액상과 고상 식품의 열전도도를 신속 정확하게 측정하기 위여 열 탐침을 사용하는 열전도도 측정장치를 개발하였다. 본 장치는 기존 열전도 측정장치와 달리 열전도도가 알려진 표준시료를 사용하는 Calibration을 하지 않고, 직접 열전도도를 측정할 수 있도록, 열탐침의 직경대 길이의 비가 100으로 설계하였다. 증류수와 글리세린의 열전도도를 본 측정장치로 측정한 결과, 증류수는 문헌값보다 1.2%미만, 글리세린은 0.7%미만의 측정오차를 보였다. 소고기 Frankfurter의 열전도도를 20°C 에서 80°C의 온도범위에서 측정한 결과 0.389에서 0.350 W/mK이었다.

주요용어(Key words): 열전도도(Conductivity), 열탐침(thermal probe)

INTRODUCTION

The transient hot-wire method is regarded as the most accurate method for the measurement of the thermal conductivity of materials in liquid phase (Nietro de Castro et al., 1986; Ramires et al., 1995). However, it is expensive and not suitable for solid materials.

The thermal conductivity probe method is a modification of the line heat source method and is used extensively for conductivity measurements of a number of non-food materials in both liquid and solid states. These included soil (Hooper and Lepper, 1950)

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and liquid chemicals (Asher et al., 1986). Studies on thermal conductivity of agricultural products have included tomato juice (Choi and Okos, 1983), fruits and vegetables (Sweat, 1974), beef (Baghe-Khandan and Okos, 1981), and potato (Wang and Brennan, 1992).

The thermal probe method assumes one dimensional heat conduction of an infinite cylindrical body with a line heat source at its center. However, because of sample size and convenience of probe construction, many thermal probes have been designed with a probe length/diameter ratio (L/D) smaller than 50 and/or with the size larger than 0.9 mm in diameter. Because of these finite probe length and size restraints, a time correction method (Van der Held and Van Drunen, 1949) or calibration factor is generally required for acceptable use of such probes. D'Eustachio and Schreiner (1952) have suggested that using a thermal probe of very small size would probably eliminate the need for a time correction factor for most measurements. Hooper and Lepper (1950) recommended L/D of 100 to minimize the effect of axial heat flow due to the finite length of the probe. For foods in liquid phase or soft solid foods with a long shape, the larger L/D and smaller diameter probe design is more desirable.

The probe constant (calibration factor) can be obtained by calibrating the thermal probe with reference materials of a known conductivity such as glycerin (Sweat et al., 1973; Baghe-Khandan and Okos, 1981) or water containing agar (Sweat et al., 1973; Wang and Brennan, 1992). Asher et al. (1986) measured absolute conductivity of liquids including water and reported accuracy better than 5%, without using a probe calibration factor. However, the probe designed by Asher et al. (1986) still has room for improvement by using a smaller probe diameter, larger L/D, less air space inside the probe, and better homogeneity of the probe material throughout its entire length.

The objectives of this study were to develop a thermal conductivity probe with a small diameter and an L/D of 100 suitable for measuring the thermal conductivity of liquid and solid food materials and to determine the effects of temperature on the thermal conductivity of beef frankfurters.

THERMAL CONDUCTIVITY PROBE METHOD

Theory of the thermal conductivity probe methods is based on the line heat source method. The theory assumes one dimensional heat conduction of an infinite cylinder with a line heat source at its axial center. The body is initially at a uniform temperature and thermophysically homogeneous. At the time zero, a constant rate of heat is generated and conducted only in the radial direction. Then the rise of temperature at any point near the line heat source will be a function of the thermal properties of the material including thermal conductivity. The differential equation of Fourier for this conduction process is:

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

Where *r, t,* , and *T* denote radial distance from the heat source, time, thermal diffusivity, and temperature, respectively.

For the case of a finite temperature rise at the line heat source, Van der Held and Van Drunen (1949) reported a solution of Equation (1). The first two terms of the solution is:

$$T = \frac{q'}{4\pi k}\left[-\ln\left(\frac{r^2}{4\alpha t}\right) - 0.577216\right] \quad (2)$$

Where *q'*, , *k*, and *r* denote the heat input per unit length of the heat source, thermal diffusivity of the medium, thermal conductivity of the medium, and the radius of the line heat source, respectively. The rest of the solution is negligible compared to the first two terms for a very small value of $(r^2/4\alpha t)$.

From Equation (2), a change in temperature at the surface of the line heat source between times t_1 and t_2 is reduced to the following equation:

$$T_2 - T_1 = \frac{q'}{4\pi k} \ln\left(\frac{t_2}{t_1}\right) \quad (3)$$

The heat input *q'* is usually calculated as I^2R per unit length of the heat source, where *I* is the input current in amps and *R* is the resistance of the heater wire in Ω/m. Since *q'* and *k* are constants, the temperature rise is a linear function of *ln*(*t*). As shown in Equation (3), *k* can be calculated by measuring the slope of a temperature-*ln*(*t*) plot.

DESIGN OF THERMAL CONDUCTIVITY PROBE

The thermal probe developed in this study consisted of a thermal conductivity unit, a diffusivity unit, and a small cylindrical Teflon block as a holder as shown in Figure 1. The thermal conductivity unit consisted of a constantan wire for heating, a thermocouple, and stainless steel tube. A 52 mm long stainless steel hypodermic needle tube with 0.51 mm OD and 0.1 mm thick wall (Popper & Sons, Inc., NY) was used as sheathing material for the thermal conductivity and the thermal diffusivity units. The diameter to length ratio of the probe is 100 to minimize the effect of axial heat flow due to the finite length of the probe, as Hooper and Lepper (1950) recommended. Teflon-insulated 40-gauge constantan wire with a resistance of 111.07 Ω/m (Physitemp Instrument Inc., NJ) was used as the heater wire. Teflon-insulated 44-gauge type-T thermocouples (Physitemp Instrument Inc., NJ) were used to measure the temperature rise of the thermal conductivity unit and the thermal diffusivity unit.

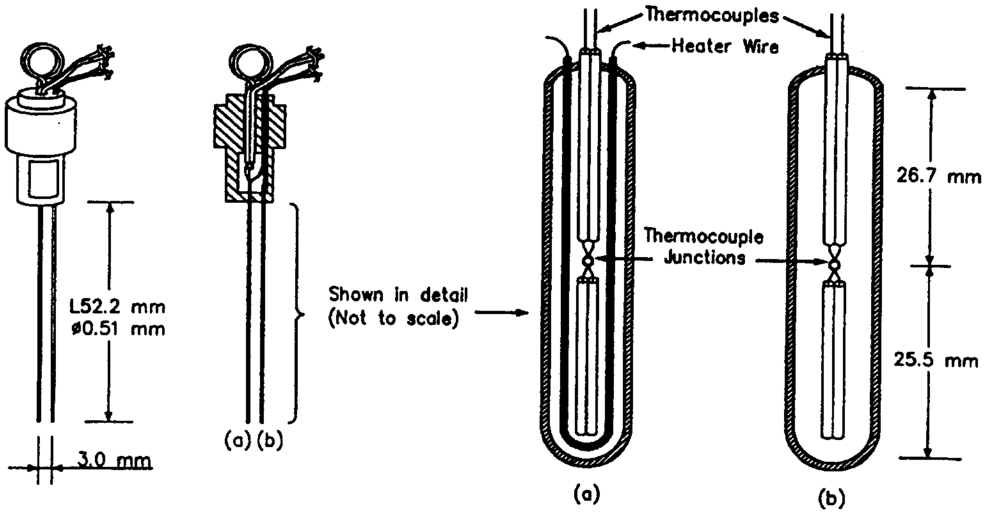

Figure 1. Schematics of the thermal probes and cross sections of (a) thermal conductivity probe and (b) thermal diffusivity probe.

THERMAL CONDUCTIVITY MEASUREMENT

As a standard reference material in liquid phase, distilled/deionized water was used for checking the accuracy of the probe. Thermal conductivity of water was measured over the temperature range of 21.8°C to 81.9°C. As a second reference material for the thermal conductivity measurement verification, 99.5% pure glycerin (Fisher Scientific, Co., PA) was used. Thermal conductivity of glycerin was measured over the temperature range of 20.1°C to 50.1°C. As a solid food material, thermal conductivity of beef frankfurter meat was measured over the temperature range of 20°C to 80°C. The Oscar Mayer brand Beef Franks was obtained from a local grocery store and used as the test meat. The mean moisture content and density of these beef frankfurters were 53.7 ± 0.44% (wet basis) and 1033 ± 20 kg/m^3, respectively. Moisture content of the beef frankfurters was determined using a convection oven method at 75°C for 24 hours and density was determined using a graduated cylinder and a balance. The effect of temperature on thermal conductivity of beef frankfurters were tested using General Linear Model Procedures (GLM) of SAS (SAS, 1990).

Average value of the five measurements was calculated and used to represent the thermal conductivity of each sample. Thermal conductivity of a sample was calculated from Equation (3) using the least square method. The current level of the probe heater was measured to the nearest 0.01 mA with the CR7X by measuring the voltage drop across a MP821 resistor (Caddok Electronics, Inc., OR) connected in series with the probe heater. The value of the resistance of the MP821 was measured as 1.000 ± 0.001 Ω using a Fluke 5100B calibrator and a Fluke 8086A Digital Multimeter (Fluke Corp., MA). A current level of 100 mA was used for all tests and the variation of the measured current level during any experiment was less than 0.01 mA. For the current level of 100 mA, the power dissipated by the probe was 2.33 W/m. An HP6236B triple output power supply (Hewlett Packard Company, CA) was used as the power supply to the probe.

A series of linear regression analyses was performed to determine the starting and end points of the linear section. This preliminary analysis produced the most consistent results with the starting point at two seconds. Starting from two seconds, the point which yielded the maximum R^2 value was chosen as the end point. The R^2 values of these linear regressions on the linear temperature rise varied from 0.99976 to 0.99990 for water and from 0.99998 to 0.99999 for glycerin.

RESULT AND DISCUSSION

Measured values of thermal conductivity of distilled/deionized water in the temperature range of 21.8 to 81.9°C are shown in Table 1. The conductivity of water ranged from 0.604 W/mK at 21.8°C to 0.662 W/mK at 81.9°C with the standard deviations of each measurement less than 0.007 W/mK. Measured values were in excellent agreement with reference values published by Ramires et al. (1995). Differences between the measured values and the reference values were less than 1.2% without using either a time correction factor or a probe calibration constant for the thermal probe.

Table 1. Measured and reference values of thermal conductivity of water.

Temperature (°C)	Measured (W/mK)	Std. deviation (W/mK)	Reference* (W/mK)	Difference (%)
21.8	0.604	0.00274	0.601	0.5
41.9	0.632	0.00472	0.632	0.0
61.9	0.647	0.00433	0.655	-1.2
81.9	0.662	0.00667	0.668	-0.9

* Ramires et al. (1995)

Measured values of thermal conductivity of glycerin in the temperature range of 20.1°C to 50.1°C are shown in Table 2. Thermal conductivity of glycerin ranged from 0.284 W/mK at 20.1°C to 0.289 W/mK at 50.1°C. The standard deviations of each measurement were less than 0.0004 W/mK. Measured values were in excellent agreement with reference values published by Eckert and Drake (1972). The differences between the measured values and reference values were less than 0.7% without using either a time correction factor or a probe calibration constant for the thermal probe.

Table 2. Measured and reference values of thermal conductivity of glycerin.

Temperature (°C)	Measured (W/mK)	Std. deviation (W/mK)	Reference* (W/mK)	Difference (%)
20.1	0.284	0.00000	0.286	-0.7
35.1	0.286	0.00043	0.286	0.0
50.1	0.289	0.00043	0.287	0.7

* Eckert and Drake (1959)

Measured values of thermal conductivity of beef frankfurter meat over the temperature range of 20.0°C to 80.0°C are shown in Table 3. The thermal conductivity values were between 0.350 and 0.389 W/mK. Statistical analysis results showed no significant difference in conductivities at different temperatures. As the temperature increased, the thermal conductivity values decreased. Water drip inside the sample cell was observed at high temperatures. A similar observation was reported by Baghe-Khandan and Okos (1981). Water loss could be the cause of the decrease of thermal conductivity values with temperature increases.

Table 3. Measured values of thermal conductivity of beef frankfurter meat.

Temperature (°C)	Measured (W/mK)	Std. deviation (W/mK)
20.0	0.383	0.00632
40.0	0.389	0.01135
60.0	0.369	0.01028
80.0	0.350	0.01370

CONCLUSIONS

The thermal conductivity probe was able to measure thermal conductivity of liquids and solids accurately without using either a time correction factor or a probe calibration factor. Mean values of the measured thermal conductivities of water without using a probe calibration factor showed less than 1.2 percent difference from reference values published by Ramirez et al. (1995). Moreover, those of glycerin showed less than 0.7 percent difference from reference values published by Eckert and Drake (1972).

Thermal conductivities of beef frankfurter meat were measured over a temperature range of 20.0°C to 80.0°C. Thermal conductivity values of beef frankfurter meat ranged from 0.389 to 0.350 W/mK. Thermal conductivities of beef frankfurter meat decreased with an increase in temperature, which might have been caused by changing moisture contents indicated by dripping water inside the sample cell.

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