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THERMAL PROPERTIES OF SELECTED FOODS USING A DUAL NEEDLE HEAT-PULSE SENSOR.

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Summary:

There is an increasing need for accurate and rapid thermal measurement of food products. Recently, a Dual Needle Heat Pulse (DNHP) probe has been developed with capability to determine simultaneously specific heat capacity (C_p), thermal conductivity (k) and thermal diffusivity (D) of foods. Existing equipment such as the differential scanning calorimeters are expensive, and thermal conductivity probes uniquely measure thermal conductivity. The dual needle heat-pulse sensor consists of two needles spaced 6mm apart. One needle is a line heat source and the other is a thermocouple. A short duration pulse is applied to the heater and the thermocouple's temperature response to the heat pulse is used to simultaneously determine C_p, k and D of the sample. The objective of the study is to evaluate the performance of the DNHP probe for the measurement of C_p, k and D of selected foods: 'Red Delicious' apple, beef eye-round steak, egg yolk and egg white. These results were within 7% with respect to published data. This novel DNHP probe provides a rapid, accurate and economic means for measuring not only k but also C_p and D in foods, simultaneously.

Keywords:

Dual Needle Heat Pulse Probe, thermal conductivity, thermal diffusivity, specific heat

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INTRODUCTION

Heating and cooling of food is one of the earliest methods of applying 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 to 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 specific heat (C_p). 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.

Specific heat (C_p - J cm^{-3} C^{-1}) of a substance is the amount of heat (J) needed to raise the temperature of a unit volume of the substance by one degree. It is a measure of the ability of a substance to store heat.

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. Specific heat is the ability of a food product to store heat relative to its ability to conduct (lose or gain) heat. It is strictly based on how much energy is needed not the rate at which it takes to raise the temperature.

There is a demand for accurate, rapid and inexpensive measurement of specific heat (C_p), thermal conductivity (k) and thermal diffusivity (D) of foods. 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 is expensive, and single needle thermal conductivity probes can only measure one thermal parameter (Sweat, 1974a). Recently, Campbell *et al.* (1991) developed a dual-needle heat pulse (DNHP) probe that can determine simultaneously C_p, k and D. In addition to its economical advantage, measurements are rapid. The DNHP has successfully been used to rapidly and accurately measure the thermal properties of soils (Campbell *et al*., 1991; Bristow *et al*., 1994). The objective of the study was to evaluate the performance of the DNHP probe for the measurement of C_p, k and D in selected foods.

THEORY

The Dual-Needle Heat-Pulse (DNHP) sensor consists of two stainless steel 304 parallel needles spaced 6mm apart (Figure 1). One needle contains a line heat source and the other is a thermocouple. An epoxy material of high thermal conductivity fills the gap between the heating wire or the thermocouple and the needle. A short duration pulse is applied to the heater and the temperature of the thermocouple is monitored. The thermocouple's temperature response to the heat pulse is used to simultaneously determine the thermal conductivity k and thermal diffusivity, and calculate the volumetric heat capacity, that is the product of the heat capacity and the density, of the sample.

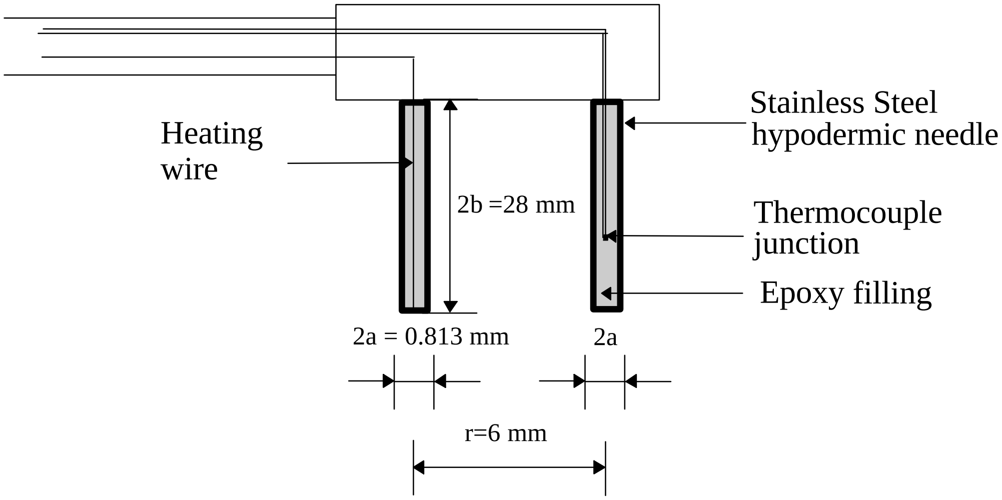

Figure 1. Schematic representation of the dual-needle heat-pulse (DNHP) sensor

Campbell *et al.* (1991) gives the equation for the temperature rise at some distance, r, from a pulsed line heat source as

$$\Delta T = \frac{q}{4\pi \mathrm{k} t} \cdot \exp\left(- \frac{r^2}{4\mathrm{D} t} \right) \tag{1}$$

where r is the distance between the line heat source and the temperature sensor, ΔT is the temperature rise measured by the thermocouple, q is the power dissipated by the heater, k is the thermal conductivity, D is the thermal diffusivity, and t is time. Equation 1 is used with a mathematical inverse method to determine the thermal conductivity and thermal diffusivity. Once thermal conductivity and thermal diffusivity are known, then volumetric specific heat can be found from equation 2.

$$\mathrm{C_p} = \frac{\mathrm{k}}{\mathrm{D}} \tag{2}$$

Infinite line heat source theory or transient heat-pulse methodology is now well established for obtaining measurements of thermal properties (Jackson and Taylor, 1986; Campbell *et al.*, 1991). This methodology is based on the application of a heat pulse to a line source and analysis of the temperature response at the line source or at some distance from the line source (Carslaw and Jaeger, 1959). The design theory, operation and error analyses of single needle thermal conductivity probe is well documented (Lentz, 1961; Sweat and Haugh, 1974; Gratzek and Toledo, 1993; Murakami *et al.,* 1996a,b). Sweat (1986) notes that the technique is simple, fast, and requires relatively small samples.

Heat-pulse theory was developed for an idealized situation, namely, application of an instantaneous heat pulse to an infinite line source in an infinite, homogenous, isotropic medium with a uniform initial temperature. These ideal conditions seldom occur in foods, thus one must be aware of possible sources of error if DNHP is to be applied with success. The operation of the DNHP probe is based on the following assumptions: 1) the material to be measured is isotropic, 2) the heating wire is long enough so that the end effects are negligible, 3) the size of the sample, (i.e. the available radius with respect to the heating probe) is large enough to allow the heat pulse to propagate without reaching any boundary during the time the measurement takes place, 4) no movement of any kind is induced during the measurement and 5) the thermal properties (k, D and C_p) are constant in the range of temperatures of the heat pulse.

In designing the DHHP probe the length, diameter, and spacing between the needles are important. The analysis of error showed that assuming an infinite length for a heat source of finite length caused errors <2% and assuming the cylindrically shaped heater to be a line heat source caused errors of <0.6% in the measurement of thermal properties (Kluitenberg *et al*., 1995). As this spacing between the needles increases, the maximum temperature change at the thermocouple decreases, the time required to reach the maximum temperature increases, and the accuracy in determination of the maximum temperature decreases. In addition, the heat pulse duration and intensity must be considered to emulate instantaneous heating. Thus, the infinite line source theory is appropriate for use in the DNHP probe.

Other potential sources of error with the DNHP technique are in the properties of the material being tested and in operation of the probe. Non-isotropicity, non-isothermal homogeneity and convection in liquid samples are material sources of error. The DNHP should not be used on low viscosity liquid samples, only highly viscous or gelled samples. Movement of the probe during measurement or changes in the needle spacing during insertion will cause errors.

MATERIALS AND METHODS

The dual needle heat pulse probe described above was used in this study to measure the thermal properties of several food products (apples, beef and eggs). The DNHP probe was connected to ThermoLink® (Decagon Devices, Inc.). The performance of the DNHP was evaluated using glycerin (Fisher Scientific) as a standard reference material. Measurements of thermal conductivity were also compared to measurements made using a single needle probe (Thermal Logic) connected to a 21X Datalogger (Campbell Scientific, Inc.).

Standard reference material: Determination of DNHP probe specifications were made using glycerin at 23°C as a standard reference material. The measurements were repeated ten times and the performance was evaluated. Glycerin was poured into two 20mL beakers. DNHP probe was held using a clamp and ring stand to avoid any movement that would disturb heat propagation. The heating needle was placed at the center of the beaker to avoid boundary effects of the beaker. Measurements were conducted between 21.0 to 23.4°C alternating the beakers. After each measurement, glycerin was slowly poured into another beaker to ensure temperature uniformity.

Probe Comparison: Thermal conductivity results from the DNHP were compared to the single needle conductivity probe for apple and beef samples. Thermal conductivity of Red Delicious and Golden Delicious apples at 23°C were measured using DNHP probe and single needle thermal conductivity sensor. Apples were allowed to equilibrate with room temperature (23°C). Both probes were tested in each apple. Both measurements were done in opposite locations of the apple to avoid the effects of heat disturbances caused by the first measurement. Fresh beef eye round steak was cut into 6x6x6 cm cubes to eliminate edge effects during measurements. Meat was allowed to equilibrate with room temperature (20.5°C) for about 5 h wrapped in plastic film to prevent moisture loss. Probes were inserted into the meat in the direction perpendicular to the meat fiber using the single needle probe. After the single needle measurement, the beef temperature was equilibrated at 20.5°C and then measure with the DNHP probe, perpendicularly. Each measurement was repeated 10 times.

Apples: Red Delicious and Golden Delicious, size 100 count, harvested from Washington State University orchard were stored at 3°C-80%RH storage. The average weight loss in cold storage was 0.05 g per day. Before the measurement, the apples were warmed up in room temperature (23°C-45%RH) for one hour. The apple was cut into four pieces, providing four directions for probe penetration as depicted in Figure 2; horizontal-tangent (HT), horizontal-radius (HR), vertical-tangent (VT), and vertical-radius (VR). After each apple measurement, the flesh was bored into 14.4 mm radius with a given diameter and the density was calculated from volume divided by weight of the cylindrical flesh. The measurements were replicated 6 times and analysis of variance for C_p, k, and D determined.

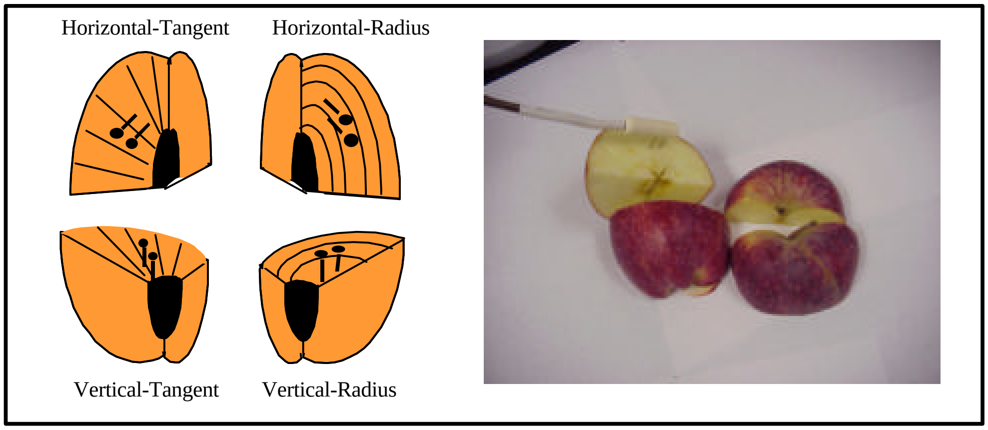

Figure 2. DNHP insertion in apple pieces

Beef: Beef round eye steak was sliced into 6x6x6 cm cubes and the meat temperature was equilibrated to 14 and 23°C (Figure 3). Thermal properties were measured using DNHP probe along and across the meat fiber. Measurements the meat fiber directions (perpendicular and parallel) were randomized. The measurements were replicated ten times. Each cube of meat equilibrated for at least 5 min before the next measurement. Moisture content of meat was determined using a vacuum oven at 70^{o}C for 6 h (AOAC, 1996). Density of beef was determined by a simple mass and volume ratio.

Figure 3. Measurement of beef using DNHP and single needle probes

Egg: Eggs were put into: 1) a refrigerated room at 7ºC, 2) at room temperature 19.5ºC and 3) in a water bath at 32ºC. Eggs were allowed to equilibrate with the surrounding temperature and broken just before each measurement. Yolk was separated from the white and both were poured into 25mL beakers. The DNHP probe was inserted into the yolk or white, perpendicular to the surface of the product, placing the heating probe at the center of the beaker as illustrated in Figure 4. The experiment was carried out in a completely randomized design using three replicates for each temperature level.

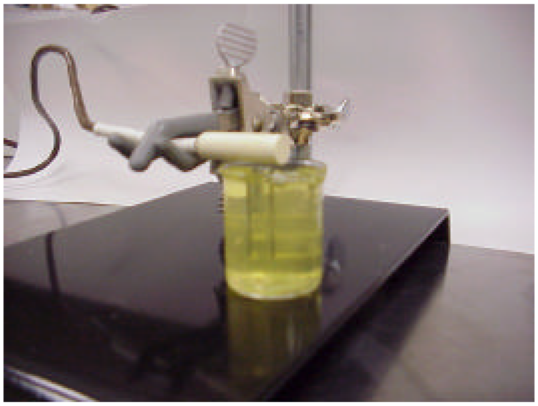

Figure 4. Measurement of egg using the DNHP probe.

RESULTS AND DISCUSSION

Standard Reference Material

The mean thermal properties by DNHP probe of glycerin and data reported by Rahman (1995) were compared and are shown in Table 1. Deviation was 0.04 W/m.K for k, 0.213 kJ/kg.K for C_p and 0.1 mm^2/s for D. Results showed the best accuracy (±3.1%) of DNHP probe was for measurement of thermal conductivity compared to heat capacity and thermal diffusivity (±8.9% and ±10.3%, respectively).

Table 1. DNHP results from measurements on glycerin

	Temp °C	k $W\ m^{-1}\ C^{-1}$	C_p $kJ\ kg^{-1}\ K^{-1}$	D $mm^2\ s^{-1}$	Source
Glycerin	23	0.29	2.215	1.05	DNHP
Glycerin	27	0.286	2.427	0.95	Rahman 1995

DNHP probe specifications

	k $W\ m^{-1}\ C^{-1}$	C_p $kJ\ kg^{-1}\ K^{-1}$	D $mm^2\ s^{-1}$
Accuracy	±3.1 %	±8.9 %	±10.3 %
Precision	0.01	0.09	0.001
Sensitivity	0.01	0.01	0.001

Accuracy is the percent deviation from reported literature data. Precision is the standard deviation of the measured values or the agreement between measurements. Sensitivity is the smallest change that the probe can reliably measure.

Probe Comparison

Measurements of thermal conductivity by DNHP and single needle probes on apples showed no significant differences among means, while beef value differed significantly (p=0.0003), though the two are still reasonably good and within acceptable values for beef. These results suggest that both probes have similar accuracy. However, the DNHP probe has about half the standard deviation as the single needle probe.

Table 2. Comparison of Dual Needle to Single Needle probes

		DNHP k ($W\ m^{-1}\ C^{-1}$)	SN k ($W\ m^{-1}\ C^{-1}$)
Apple	- Red	0.42 ±0.023	0.43 ±0.044
	- Golden	0.45 ±0.020	0.46 ±0.044
Beef		0.46 ±0.014	0.50 ±0.018

DNHP - Dual needle heat pulse probe
SN - Single needle thermal conductivity probe
mean value of ten replicate measurements

Apple

The results from the thermal analysis of apples are listed in Table 3. No significant difference (p>0.05) between direction and variety on the apple was observed. Specific heat and thermal diffusivity were within 4% and 5%, respectively, of the reported literature values. Reported literature values of thermal conductivity varied depending on the source of data; however, our experimental results fell within the range of those values. The mean specific density of Red Delicious and Golden Delicious were 918.9 and 849.3 kg/m^3, respectively.

Table 3. Result of the DNHP probe for apple

	k W m^{-1} C^{-1}	C_p kJ kg^{-1} C^{-1}	D mm^2 s^{-1}	Source
Experimental Values				
Red	0.46	3.734	1.33	DNHP
Golden	0.43	3.812	1.31	DNHP
Literature Values*				
Red			1.37	Ramaswamy 1981
Red	0.513			Gaffney 1980
Red			1.37	Bennett 1969
Golden			1.37	Gordon 1990
Golden			1.46	Sweat 1974a
Apple**	0.393	3.726-4.019		Reidy 1968

* Temperature reported was in range of the experimental temperature
** No variety specified.
mean value of twenty four measurements - six replicates per quadrent

<u>Beef</u>
The results from the thermal analysis of beef are listed in Table 4. There was no significant difference ($p<0.05$) between meat fiber orientation, the temperatures investigated, or use of the single needle thermal conductivity probe. The mean density value obtained for the meat was 1055 kg/m^3.

Table 4. Results of DNHP probe for beef

	Temp °C	k W m^{-1} C^{-1}	C_p J cm^{-3} C^{-1}	D mm^2 s^{-1}	Moisture % w.b.	Source
Experimental Values						
Beef (⊥)	14	0.45	3.073	1.39	74.1	DNHP
	22	0.47	3.041	1.47	74.1	DNHP
	22.5	0.48			74.1	SN
Beef (‖)	20.5	0.48	2.202	2.15	74.1	DNHP
Literature Values						
Beef*	above freezing		2.914-3.426		62-77	Rao 1992
Beef, lean (⊥)	7-62	0.476-0.485			78.9	Singh 1992
Beef round chuck	40-65			1.33	71	Singh 1992
Beef round chuck	40-65			1.23	66	Singh 1992

⊥ perpendicular to fiber orientation
‖ parallel to fiber orientation
* part of beef not specified
mean value of ten replicate measurements

Specific heat and thermal conductivity fell within the range of the reported literature values. Thermal diffusivity was about 10.5% higher than the reported literature values; this may have resulted from not having allowed the beef to completely equilibrate with room temperature, or from differences in meat cuts and moisture contents.

Egg

The results from the thermal analysis of eggs are listed in Table 5. No significant difference among means for thermal conductivity and specific heat was found but small differences were found for thermal diffusivity among the three temperatures. This may have resulted from the relationship between k, Cp and D.

Table 5. Results of DNHP for egg yolk and egg white.

	Temp	Yolk			White		
	°C	k	C_p	D	k	C_p	D
Experimental	7.8	0.357^{a}	2.780^{a}	1.24^{ab}	0.500^{a}	3.293^{a}	1.44^{a}
	19.4	0.337^{a}	2.660^{a}	1.22^{a}	0.583^{a}	3.594^{a}	1.54^{ab}
	31.3	0.383^{a}	2.815^{a}	1.31^{b}	0.577^{a}	3.446^{a}	1.58^{b}
Literature (Polley 1980)	2.8	0.338	2.810	NA	0.5435	3.850	NA

Numbers with different letter within a column are significantly different.
mean value of three replicate measurements.

CONCLUSION

A novel Dual-Needle Heat-Pulse (DNHP) probe was used to measure simultaneously specific heat (C_p), thermal conductivity (k) and thermal diffusivity (D) of selected food materials. Accuracy, precision, and sensitivity of the probe were determined using glycerin as a standard. Measured thermal properties of two apple varieties, beef round, and egg white and yolk were compared with values reported in the literature. No significant differences ($p>0.05$) were found in the mean thermal properties with direction or variety for apples, or beef and egg with temperature. However, significant though small differences were found for thermal diffusivity of egg white and yolk between 7.8°C and 31.3°C. Deviation of experimental results for food samples with respect to values in the literature were less than 8%. Accuracy, precision and sensitivity of the probe for measured thermal conductivity values were 3.1%, 0.01 and 0.01, respectively. The DNHP probe is appropriate for the accurate measurement of thermal conductivity, thermal diffusivity and specific heat of food products.

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