Using Thermal Properties Measurements to Predict Food Temperature During Processing

The earliest processes applied to food by humans involved the heating and cooling of the food. These processes are important for almost all aspects of food preparation, and play a key role in determining food safety. The thermal properties of a food product determines its ability to transfer and store heat. For a given thermal process, the spatial and temporal distribution of temperature in the food is determined by the thermal properties of the product.

The thermal properties are thermal conductivity, *k* (W m^{-1} C^{-1}), heat capacity or specific heat, C_p (J m^{-3} C^{-1}), and thermal diffusivity, α (m^2 s^{-1}). The thermal conductivity is a measure of the heat flux density (Joules of heat per square meter per second) when the temperature gradient is one degree per meter. The specific heat is the number of joules of heat required to raise the temperature of one cubic meter of the substance by one degree. The thermal diffusivity is the ratio of thermal conductivity to specific heat and is a measure of the rate at which thermal disturbances propagate in the medium.

Thermal properties depend on the composition of the food. Table 1 shows thermal properties for air, water, and organic material. Air has a very low thermal conductivity and specific heat, while water has much higher values. The values for organic constituents are intermediate between air and water. It is therefore possible to manipulate the thermal properties of foods through changing the water and air content of the food, and this manipulation will influence the heating and cooling properties.

Table 1. Thermal properties

Component	Density Mg m^{-3}	Specific Heat J m^{-3} C^{-1}	Conductivity W m^{-1} C^{-1}
Water	1.00	4.2 X 10^6	0.57
Organic Matter	0.0012	1.2 X 10^3	0.025
Air (20 C)	1.30	2.5 X 10^6	0.25

Modeling Spatial and Temporal Variations of Temperature

An example of an application of thermal properties measurements is the modeling of the temperature inside a hamburger patty as it cooks. The temperature changes in space and time are modeled using Fourier's heat laws. Fourier's first law states that the heat flux density for steady heat flow is directly proportional to the temperature gradient. In symbols, this is

$$H = -k\frac{dT}{dz} \qquad (1)$$

where *H* is the heat flux density, and *dT/dz* is the temperature gradient. When the heat flow changes with time, as it does in the hamburger, we need to combine eq. 1 with the continuity equation to model the temperature

$$C_p\frac{\partial T}{\partial t} = -\frac{\partial H}{\partial z} \qquad (2)$$

The left hand side of eq. 2 represents the rate of heat storage at a point in the hamburger, and the right hand side represents the heat flux divergence, or rate of change of heat flux density with depth. Combining eqs. 1 and 2 gives Fourier's second heat law:

$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) \qquad (3)$$

If thermal conductivity is constant with depth, *k* can be taken outside the derivative. We can also divide both sides by C_p to obtain a more familiar form of Fourier's second law:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \qquad (4)$$

where $\alpha = k/C_p$ is the thermal diffusivity. According to eq. 4, the locations in the hamburger where temperature will change fastest with time is the location where the change with depth of the temperature *gradient* is largest.

Equation 4 can be solved to determine the temperature within the meat at any location and time if we know: 1) the temperature of the griddle, 2) the initial temperature of the meat, and 3) the thermal properties of the meat. Solutions to this kind of problem are complex, mathematically, but are standard fare in engineering heat transfer. Often they are done using computers and numerical methods. The important point to make here is that the thermal properties must be known in order to solve the problem.

Determining the Thermal Properties of Foods

As previously mentioned, the thermal properties of food products depend strongly on the composition of the product. If the composition of the product is known, and specific heat data for each of the components are available, the specific heat of the product can be computed. It is just the sum of the volume fractions of each of the components multiplied by their respective specific heats. The thermal conductivity of a mixture of components is not easily obtained, since it is determined not only by the thermal conductivity and volume fraction of the components, but also by how they are mixed. In practice it is often easiest to just measure the thermal properties. The measurement is made by applying a known amount of heat to the material in a specified configuration, and using Fourier's laws in an inverse mode to find the thermal properties.

Thermal properties measured with a dual probe technique

A method has been developed which allows measurement of all three thermal properties in a single measurement. This is the method used by Decagon's ThermoLink®. Two stainless steel needles are mounted 6 mm apart. A heating wire is in one needle and a thermocouple in the other. The two needles are placed in the sample and the heater is pulsed for 8 seconds. The temperature rise above ambient, and total power dissipated is monitored by a microcontroller.

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

$$\Delta T = \frac{q}{4\pi k t}\exp\left(\frac{-r^2}{4\alpha t}\right) \qquad (5)$$

where *r* is the distance between the line heat source and the temperature sensor, ΔT is the temperature rise measured by the temperature sensor, *q* is the power dissipated by the heater, *k* is the thermal conductivity, and α is the thermal diffusivity. Equation 5 is used with a mathematical inverse method to determine the thermal conductivity and thermal diffusivity. Once conductivity and diffusivity are known, then heat capacity can be found from

$$C_p = k/\alpha \tag{6}$$

Thermal conductivity measured with a single probe

Another method for measuring thermal conductivity is somewhat similar. A single needle is heated and its rate of temperature rise is measured. Shiozawa and Campbell (1990) give an equation for converting this rate of temperature rise to thermal conductivity. The relationship between temperature of the heated needle and time is

$$\Delta T = \frac{q}{4\pi k}\ln(t + t_o) \tag{7}$$

where ΔT is the temperature rise, q (W/m) is the rate of heat input to the needle (note that it is not the total heat input as it was with the dual needle sensor), k is the thermal conductivity, and t_o is a time offset. The temperature rises quickly when heat is first applied, and then much more slowly with longer heating times. The needle is usually heated for about 60 s. Table 2 shows some comparisons of thermal conductivity measured with single and dual needle probes, and measurements of thermal properties made with the dual probe sensor.

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	0.42 ± 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

References:

Campbell, G. S., C. Calissendorff, and J. H. Williams. 1991. Probe for measuring soil specific heat using a heat-pulse method. Soil Sci. Soc. Am. J. 55:291-293

Shiozawa, S. and G. S. Campbell. 1990. Soil thermal conductivity. Remote Sensing Reviews. 5:301-310.

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