Lecture 4

Thermal Properties of Foods:

Most processed and fresh foods receive some type of heating or cooling during handling or manufacturing. Design and operation of processes that involve heat transfer require special attention due to the heat-sensitivity of foods. Thermal properties of foods are related to heat transfer control in specified foods and can be classified as thermodynamic properties (enthalpy and entropy) and heat transport properties (thermal conductivity and thermal diffusivity). Thermophysical properties not only include thermodynamic and heat transport properties, but also other physical properties involved in the transfer of heat, such as freeze and boiling point, mass, density, porosity, and viscosity. These properties play an important role in the design and prediction of heat transfer operations during the handling, processing, canning, storing, and distribution of foods.

Heat can be transferred three different ways: by radiation, conduction, or convection.
• Radiation is the transfer of heat by electromagnetic waves (as in a microwave oven).
• Conduction is the transfer of thermal energy due to molecular oscillations (for example, heating of food by direct fire through metal containers).
• Convection is the transfer of heat by bulk movement of molecules in heated fluids such as liquids or gases (for example, air in heated oven or in tank during juice evaporation).

Although all three types of heat transfer can take place simultaneously, generally only one is predominant, depending on the state of the food and the heating system. In many heat transfer processes associated with storage and processing, heat is conducted through the product; heat is transferred by forced convection between the product and a moving fluid (for example, hot air during tray drying), which surrounds or comes in contact with the product.

Basic definitions of thermal properties of foods related to conduction within the product, with reference to properties associated with forced convection through the surface (such as surface heat transfer coefficient) will be mentioned in this section. Measuring techniques will be briefly described, as well as parameters involved during processing applications.

Definitions

The thermal properties of foods can characterize heat transfer mechanisms in different unit operations involving heating or cooling. Specific heat, thermal conductivity, thermal diffusivity, boiling point rise, and freezing point elevation are defined as follows:

(a) Specific heat, Cp, is the amount of heat needed to raise the temperature of unit mass by unit degree at a given temperature. The SI units for Cp are therefore (kJ kg–1 K–1). Specific heat of solids and liquids depends upon temperature but is generally not sensitive to pressure. It is common to use the constant pressure specific heat, Cp, which thermodynamically represents the change in enthalpy H (kJ Kg–1) for a given change in temperature T when it occurs at constant pressure P:

$$C_p = (\delta H/\delta T)_P \quad (1)$$

Only with gasses is it necessary to distinguish between Cp and Cv, the specific heat at a constant volume. Assuming there is no phase change, the amount of heat Q that must be added to a unit mass M (kg of mass or specific weight kg/m3) to raise the temperature from T2 to T1 can be calculated using the following equation:

$$Q = MC_p (T_2 - T_1) \quad (2)$$

(b) Thermal conductivity, κ , represents the quantity of heat Q that flows per unit time through a food of unit thickness and unit area having unit temperature difference between faces; SI units for κ are [W m–1 K–1]. The rate of heat flow Q through a material by conduction can be predicted by Fourier's law of heat conduction. A simplified approximation follows:

$$Q = \kappa A (T_1 - T_2) / x \quad (3)$$

where A is the surface area of the food, x is its thickness, T1 is the temperature at the outer surface where heat is absorbed, and T2 is the temperature at the inner surface. In other words, κ represents the ability of the food to transmit heat. Unlike specific heat, κ depends on mass density.

(c) Thermal diffusivity,α, SI units [m2/s], defines the rate at which heat diffuses by conduction through a food composite, and is related to κ and Cp through density ρ [kg/ m3] as follows:

$$\alpha = \kappa / \rho C_P \quad (4)$$

Thermal diffusivity determines the speed of heat of three-dimensional propagation or diffusion through the material. It is represented by the rate at which temperature changes in a certain volume of food material, while transient heat is conducted through it in a certain direction in or out of the material (depending if the operation involves heating or cooling). Eq. (4) shows that α is directly proportional to the thermal conductivity at a given density and specific heat. Physically, it relates the ability of the material to conduct heat to its ability to store heat. In liquid foods, boiling refers to water evaporation, in which water changes from the liquid phase to steam or vapor phase, and water vapor pressure equals the external pressure. Liquid foods contain high molecular weight solids that cause the boiling point to be elevated above that of pure water. The boiling point rise, ΔTr, is known as the increase in boiling point over that of water in a given liquid food. As the vapor pressure of most aqueous solutions is lower than that of water at the same temperature, the boiling temperature (boiling point) of the solution is higher than that of pure water. During freezing, water in the food changes to ice while heat is removed by a refrigeration system. During heat removal, the unfrozen water will still contain dissolved food solids. The presence of dissolved solids will depress the initial freezing point a certain amount ΔTf below the expected solidification temperature for pure water. Freezing point depression is defined as the temperature reduction ΔTf. Both the boiling point rise and the freezing point depression of a food are related to its solutes concentration

Thermal Variations in Properties

Foods show extended variability in composition (mainly water, proteins, carbohydrates, fat, ash, and fiber) and structure, and can be turned into even more complex composite materials when heated together, as in the case of many canned and packed foods, pastry, confectionery, and a wide variety of prepared foods. Thermophysical properties depend on the chemical composition of the structure, determined by the physical arrangement and phase distribution of a system. Thus, heat transfer by conduction may take place in several forms depending on the tortuosity of the material, which may vary at different locations. As porous materials contain a gaseous phase, the value of the thermal conductivity κ , specific heat Cp, and thermal diffusivity α will depend on the internal and external pore space represented by its porosity (see Mechanical properties). Thermophysical properties are significantly influenced by changes in water content and temperature. During drying, the transfer of heat into food products is accompanied by simultaneous diffusion of water through the product to the surrounding air, provoking differences in thermophysical properties at different regions of the food. Pore size and distribution not only affect heat transfer because of air retention, but also because of the affinity pores have to retain water. The smaller the pore diameter, the greater the surface tension forces, and the more affinity it has for water. Specific heat Cp of foods is drastically influenced by water content. For example, specific heat has been found to vary exponentially with water content in fruit pulps at above ambient temperatures. Furthermore, nonaqueous components show lower Cp. The specific heats of oils and fats are usually about one-half the specific heat of water, while the specific heat of dry materials in grains and powders is approximately one-third to one-fourth that of water. As a result of solute water interactions, the Cp of each individual component in a food differs from the Cp of a pure component, and usually changes with the concentration of soluble solids. The same occurs with thermal conductivity κ , where water shows greater relative magnitudes in comparison to other food constituents. Thus, both κ and Cp increase with increased moisture content. It is common to find a linear relation between thermal conductivity and moisture content at ambient conditions.

The effect of temperature on thermophysical properties is not easy to establish because solids (or semisolids), liquid foods, and food emulsions undergo structural changes. Thermophysical properties of foods change dramatically during the freezing process. Specific heat changes are difficult to predict when free water becomes solid. Bound water or unfrozen water has a different Cp than bulk-frozen water, and ice has a Cp of about one-half that of liquid water. Thus, Cp below freezing is approximately half that of Cp above freezing. Continuous changes in the fraction of frozen water as temperature varies below the freezing point explain this similarity. In fact, specific heat can be utilized to predict the state of water in frozen foods. Thermal conductivity, however, has been found to be high when temperatures allow water to be in liquid or solid state at very low or high temperatures. Yet when temperatures are within the range of –10 º to 0 ºC, κ shows its lowest values. Freezing point depression has been modeled with the initial freezing point as a function of water content using linear and quadratic equations. Some thermophysical property models for food systems have been developed as a function of water content or temperature. Additionally, as composition greatly differs between one food and another, other models are linear combinations of water, fat, protein, carbohydrate and/or ash content, and temperature. Cp has been measured at different temperatures in fresh and dried fruits, meats, cereal grains and cereal products, oils and fats, powders, and other dry foods. Although linear correlations of Cp with concentration are known in liquid foods, variations are often neglected for engineering calculations at near room temperature.

General correlations also predict thermal conductivity κ , of food materials for use in process design equations. Linear, quadratic, and multiple correlations of moisture, temperature, and composition can be found for κ in food materials. Some models consider that different components of foods (for example, fibers) are arranged in layers either parallel or perpendicular to the heat flow. In products such as meats, heat is usually transferred parallel to fibers and κ is dependent on the direction of the heat flow. More general in nature are the randomly distributed models, which consider that the food is composed of a continuous phase with a discontinuous phase dispersed within (solid particles being in either regular or irregular array). In porous materials, porosity must be included in the model because air has a κ much lower than that of other food components. Models including density or porosity, and pressure, have been developed in fruits and vegetables, meat and meat products, dairy products, cereals, and starch. Several models for predicting α in foods have also appeared in literature; however, mostare product specific and a function of water content or temperature. Although the influence of carbohydrates, proteins, fat, and ash on thermal diffusivity has been also investigated, it was found that temperature and water content are the major factors affecting α. Above freezing temperatures, diffusivity varies linearly with temperature or water composition in some foods, while this is not valid at below-freezing temperatures