THERMAL PROPERTIES OF FOODS

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Contents

Summary

Thermophysical properties, a well-known group of thermal and related properties, are necessary for the design and prediction of heat transfer operation during handling, processing, canning, and distribution of foods. In this article, the most important properties associated with the transfer of heat in foods are defined. Measurement techniques, available empirical equations, and mathematical models used for prediction of density, porosity, specific heat, thermal conductivity, and thermal diffusivity are presented and condensed in tables, figures, and graphs. This article also provides data and information for increasing the boiling point of liquid foods over that of water and decreasing the freezing point below that of water, the phenomena known as boiling point rise and freezing depression, respectively.

1. Introduction

Most processed foods and many freshly consumed foodstuffs receive some type of heating or cooling during handling or manufacturing. Design and operation of processes involving heat transfer requires special attention, due to the heat-sensitivity of foods. Both theoretical and empirical relationships used when designing or operating heat processes require knowledge of the thermal properties of the foods under consideration. Food thermal properties can be defined as those properties controlling the transfer of heat in a specified food. They are usually grouped as thermodynamical properties (e.g., specific volume, specific heat, enthalpy, and entropy) and heat transport properties (thermal conductivity and thermal diffusivity). However, when considering the heating or cooling of foods, it is well known that other physical properties must be considered because of their intrinsic relationship with the mentioned “pure” thermal properties. Such is the case of density, porosity, and viscosity (see *Food Rheology and Texture*, and *Engineering Properties of Foods*).

Therefore, a well-known group of thermal and related properties, thermophysical properties, provides a powerful tool for the design and prediction of heat transfer operation during handling, processing, canning, and distribution of foods. In spite of the profuse generation and compilation of thermophysical properties of food, they are not always available to the design engineer. Finding relevant data is usually the controlling step in the design of a given operation, and as foods are such a broad set of materials, the best solution is frequently the experimental determination. This article provides data and information for calculating the thermal processes of foodstuffs, including a brief description of the most widely used methods for the measurement and determination of thermophysical properties.

Thermophysical properties of foods include, in a broad sense, different types of parameters associated with the heat transfer operations of food processing. Heat transfer involves the transfer of heat into or out of a food. There are three ways that heat can be transferred: by radiation, conduction, or convection. Radiation is the transfer of heat by electromagnetic waves (e.g., in a microwave oven). Conduction is the movement of heat by direct transfer of molecular energy within solids (e.g., heating of a food by direct fire through metal containers). Convection is the transfer of heat by groups of molecules that move because of a gradient of density or agitation (e.g., the stirring of liquid foods).

Mechanism	Condition	Governing equation *
Radiation	Infrared heating Microwave heating	$Q=\sigma A T^4$ $X=\lambda_o/\{2\pi(\varepsilon' \tan \delta)^{1/2}\}$
Conduction (unidirectional)	Steady state	$Q = \kappa A(\theta_1-\theta_2)/x$
	Unsteady state	$d\theta/dt= \alpha\, d^2\theta/dx^2$
Convection • natural • forced		$Q= h_s A (\theta_1-\theta_2)$ $Gr= \rho^2 g\beta l^3\Delta T/\mu 2$ $Nu= K (Gr\, Pr)^a$ $Nu= f(Re, Pr)= hl/ k$ $Pr= c\, \mu/\kappa$ $Re= lv\rho/ \mu$
hc= convective heat transfer coefficient; *l*= characteristic dimension; α= Thermal diffusivity; β= coefficient of thermal expansion; κ= Thermal conductivity; δ= Density; ε= Porosity; ε´= dielectric constant; c= Specific heat; μ= Viscosity; Gr= Grashoff; Re= Reynolds; Pr= Prandtl; Nu= Nussell.		

Table 1. Simplified description of heat transfer mechanisms.

Heat transfer can take place in 1) a steady-state manner, by keeping the temperature difference constant between two materials; or 2) in an unsteady-state manner, when temperature is constantly changing. Calculation of heat transfer under these conditions is extremely complicated, but can be simplified by making a number of assumptions and, in some cases, using prepared graphic or tabulated information to give approximate solutions. Table 1 shows the basic equations used to calculate the rate of heat transfers under different mechanisms and conditions.

This information is needed for a variety of research and engineering applications, including design and optimization of handling and processing units such as tanks, pumps, pipes, chillers, evaporators, and heat exchangers. Moreover, information on thermophysical properties is required over a wide range of concentrations and temperatures. The vapor pressure of most aqueous solutions is lower than that of water at the same temperature. Therefore, for a given pressure, the boiling temperature (boiling point) of the solution is higher than that of pure water. The increase in boiling point, or boiling point rise (T_r) of liquid foods, is a property of interest in the design and operation of evaporators.

The temperature at which foods freeze, usually known as the freezing point (T_f), is generally not easily defined, due to the complex changes occurring during phase transition in foods. While the relation between the freezing point and vapor pressure for pure water and simple aqueous solutions has been precisely defined, in the case of food systems where various solutes eventually reach their eutectic temperature (solute crystallization), prediction of depression of freezing point (T_f) requires a more complex treatment.

During processing, the temperature within a food changes continuously, depending on the temperature of the heating medium and two properties of the food: thermal conductivity (κ) and specific heat (c_p). On the other hand, thermal diffusivity (α) is related to κ and c_p through density:

$$\alpha = / c_p \quad (1)$$

When a piece of food is heated or cooled by a fluid, both the surface heat transfer coefficient and κ are the resistance to heat transfer, related as follows:

$$Bi = h\phi/\kappa \quad (2)$$

where h (W m^{-2} K^{-1}) is the heat transfer coefficient, the characteristic half dimension, and (W m^{-1} K^{-1}) is the thermal conductivity. At small Bi (<0.2), the surface film is the predominant resistance, while for Bi>0.2, the thermal conductivity limits the rate of heat transfer.

1.1. Food Properties during Freezing

The thermophysical properties of foods change dramatically during the freezing process and must be considered. One characteristic of food freezing is that the temperature changes gradually with the phase change, which implies that the fraction of water frozen always changes continuously with temperature below the freezing point (see *Food Freezing*).

1.2. Water Content

Water content (X_w) is not a thermophysical property but significantly influences all thermophysical properties. If the food is a living commodity, such as fruits and vegetables, its water content will change with maturity, cultivars, stage of growth, and harvest and storage conditions. Values of most thermophysical properties can be calculated directly from the water content. X_w is usually expressed as water mass fraction (Kg water; Kg^{-1} food; wet basis) (see *Colligative Properties*).

2. Experimental Data and Prediction Models

Foods show extended variability in composition and structure. This characteristic must be kept in mind when modeling their thermal properties. Foods are generally non-homogeneous, varying in composition and structure not only between products, but also within a single product. Consider for example the thermal conductivity of onions, a typical “laminated” vegetable. The composition and structure (soluble solids, fibers, porosity, etc.) will not only vary between onions with cultivars and growing conditions, but within a given onion with harvest and post harvest conditions (e.g., side of bulb exposed to sun in the case of solar curing). The same situations can also be found in the case of fruit and meat production.

Some thermophysical property models for food systems are only functions of water content. However, the contents of proteins, fats, and carbohydrates differ greatly from one food to another and therefore have variable effects on the properties of a composite food material. Some models include different components of the food, expressing for example a linear combination of the properties of water, fat, protein, carbohydrate, and/or ash.

A large volume of experimental data can be found that has been reviewed by different authors. Thermophysical properties are dependent on the temperature, as well as the materials chemical composition and physical structure. Since foodstuffs are composite materials, it is apparent that the relevant information is the average or effective value. This value is clearly some function of those of the components. Food materials are complex substances. Therefore, the generation of predictive models requires a physical representation of the food under study.

Firstly, foodstuffs are composed of different chemical species, and any model proposed for the prediction of a given property must consider the individual contribution of the "species", namely ash, proteins, carbohydrates, fats, fiber, water, and minor components. This is done by means of some weighing factor accounting for the proportions in which they are present.

Secondly, some food materials can be considered as the described solid continuously dispersed in a gas or liquid phase, usually air or water. This includes porous foods, suspensions, flours, and powders (see Food suspensions, Food Powder Processing). In this case, both the volumetric fraction and the spatial distribution of each phase are considered.

Finally, different foods are processed together to produce a composite foodstuff, as in the case of many canned and packed foods, pastry, confectionery, and a wide variety of prepared foods. Also in this situation, modeling requires information on the effective values of the components, together with the representation of the physical structure.
The value of the thermophysical property will be a function of the temperature, and porosity or water content. Since water can be either liquid or solid, particular attention is paid to frozen foods. This article is oriented, whenever possible, to the presentation of correlating expressions more than to the tabulation of punctual data, in order to provide predictive tools of a more general nature, together with the description of the accepted measuring techniques. Efforts have been made to include the most recent data and correlations whenever possible.

3. Density

3.1. Definition and Units

Density (ρ) is the unit mass per unit volume. The SI unit for density is [Kg m^{-3}]. In particular, when the foodstuff is a porous solid, density plays an important role in heat transfers intrinsically or through the definition of porosity. A few definitions are necessary:

Substance density, ρ_s, (also true density) is the density measured when the substance has been broken, milled, or mashed to guarantee that no pores remain.
Particle density, ρ_p, is the density of a sample that has not been structurally modified. In the case of pores not externally connected to the surrounding atmosphere, particle density will include these closed pores.
Bulk density, ρ_b, (or apparent density) is the density measured, in order to include the volume of the solid and liquid materials, and all pores closed or open to the surrounding atmosphere.

As other authors have used different names for the same condition, it is recommended that the definition of density be verified before using density data.

3.2. Porosity

Porosity indicates the volume fraction of air (or void space). Based on given distinctions among densities, the following definitions of porosity result:

Total porosity (ε_t) is the ratio of air space volume to total volume:

$$\varepsilon = (\rho_s - \rho_b)/\rho_s \tag{4}$$

Open pore porosity (ε_a) is the ratio of the volume of pores connected to the outside to the total volume:

$$\varepsilon_a = (\rho_p - \rho_b)/\rho_p \tag{5}$$

As in the case of density, it is recommended that definitions be verified before using porosity data.

3.3. Density Measurement

Techniques developed for density measurement are methods for measuring volume, weight being easily measured with different types of precision balances. Table 2 lists the principal measurement techniques used for volume (and density) determination in foods.

Method	Description	Governing Equation	Comments	Reference
Hydrometric	The bulk density is calculated from the apparent weight of the sample and the buoyant force E.	$\rho_b = \rho_{liq} (W_{air}/E)$	Soluble foods must be coated to avoid mass loss by dilution.	Lozano et al. (1983)
Geometric	The volume is calculated from the dimensions of the food sample.	$\rho_b = L^3/W$	Not suitable for soft and irregular solid foods.	------------
Pycnometry a.-Liquid pycnometer	The pycnometer is a calibrated flask that allows weighing of an exact, known volume of liquid, which in turn gives the density. The weight is determined by difference in the empty flask.	$\rho_b = W/V$	To set the experiment temperature, the pycnometer is immersed in a constant temperature bath and filled with the sample.	ASTM D369 ASTM D891

b.- Gas pycnometer	By using the perfect gas law, it is possible to determine the volume of open pores (V_{pore}) in a food by determining the gas volume in a chamber (V_{ch}) with or without the sample.	$P_i V_i = m RT$ $V_{pore} = V_{ch}(P_1 - P_2)/P_2$	P_1 and P_2 are the pressure in the empty and filled chamber (with sample), respectively.	Lozano et al. (1983) Mohsenin (1980)

Table 2. Methods for determination of density.

[From:

Lozano J.E., Urbicain M.J., and Rotstein E. (1983). Shrinkage, porosity and bulk density of foodstuffs at changing moisture content. *J. Food Sci*. **48**, 1497. [The effect of drying on the void structure of foods is treated in this paper].

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3.4. Bulk Density of Selected Foods

Table 3 lists measured bulk density values of selected foods and food components.

Food/material	Temperature/range (°C)	Bulk Density (Kg m^{-3})	Reference
Apple (GS; X_w=0.86)	25	837	Lozano et al. (1979)
Cellulose	----------	1550	Kirk & Othmer (1964)
Coffee (Instant)	----------	330	Lewis (1987)
Fat	----------	900/ 950	Lewis (1987)
Glucose (solid)	----------	1560	Kirk & Othmer (1964)
Meat (Beef)	Room	1053	Mascheroni & Calvelo (1980)
Milk	----------	610	Lewis (1987)
Milk, powder	----------	610	Lewis (1987)
Potato (X_w= 0.81)	25	1040	Rao et al. (1975)
Protein	----------	1400	Lewis (1987)
Squash (X_w= 0.81)	22.9	900	Rao et al. (1975)
Water	4	1000	Perry &Green (1984)

From:

Lozano J.E., Urbicain M.J., and Rotstein E. (1979). Thermal conductivity of apples as a function of moisture content. *J. Food Sci***.** 14(1), 198. [Measurement and correlation of density and thermal conductivity of apples as a function of water content is presented]

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Table 3. Bulk density values of selected foods and food components.

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Biographical Sketch

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