ENGINEERING PROPERTIES OF FOODS

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Summary

The engineering properties of foods are important, if not essential, in the process design and manufacture of food products. They can be classified as thermal (specific heat, thermal conductivity, and diffusivity), optical (color, gloss, and translucency), electrical (conductivity and permittivity), mechanical (structural, geometrical, and strength), and

food powder (primary and secondary) properties. Most of these properties indicate changes in the chemical composition and structural organization of foods ranging from the molecular to the macroscopic level. Both modern and more conventional measurement methods allow computation of these properties, which can provide information about the macrostructural effects of processing conditions in fresh and manufactured foods. Mathematical models have been fitted to data as a function of one or several experimental parameters, such as temperature, water content, porosity, or other food characteristics. Most engineering properties are significantly altered by the structural differences between foods. Several microscopy, scanning, and spectrometric technologies permit close visualization of changes in structure at different levels without intrusion. Microstructure studies have increased understanding of several changes detected in foods resulting from treatment in emerging and conventional unit operations, by relating these changes to engineering property characterization data and models. In the future, structure–property modeling could lead to the synthetic production of natural materials with improved characteristics, provided advances in genetic engineering and biotechnology are incorporated into the food engineering field.

1. Introduction

The word *engine*, derived from the words *engineer* and *engineering*, comes from the Latin word for talent, *ingenium*. From the onset of the Industrial Revolution to the beginning of the twentieth century, the term was used almost exclusively to describe power machines. Those who designed, built, and operated these machines became known as engineers, and their profession, or expertise, as engineering. In today's technological world, the meaning of the term has expanded to include not only such disciplines or activities as chemical, medical, polymer, or food engineering, but also genetic engineering and social engineering. Although these disciplines have little to do with engines, they heavily rely on the ingenuity from which the term was originally conceived.

It is difficult to define what exactly constitutes an engineering property of a certain food. In general, however, any attribute affecting the processing or handling of a food can be defined as an engineering property. Since many properties are related, there is usually an arbitrary element in their classification. Traditionally, they are divided into the following categories:

- *Thermal properties* such as specific heat, conductivity, diffusivity, and boiling point rise, freezing point depression.
- *Optical properties,* primarily color, but also gloss and translucency.
- *Electrical properties*, primarily conductivity and permittivity.
- *Structural and geometrical properties* such as density, particle size, shape, porosity, surface roughness, and cellularity.
- *Mechanical properties* such as textural (including strength, compressibility, and deformability) and rheological properties (such as viscosity).
- Others, including mass transfer related properties (diffusivity, permeability), surface tension, cloud stability, gelling ability, and radiation absorbance.

Nearly all of the above properties are manifestations of a food's chemical composition and structural organization over several orders of length scales—from the molecular to the macroscopic. A change in either composition or structure usually results in a simultaneous change in several properties. Hence it is difficult, if not impossible, to control a single property in isolation. Moreover, properties can be intrinsic, and primarily controlled by the material itself (for example, structural properties like density) and response properties, varying according to the external conditions to which the food is exposed (including colorimetric properties like hue).

Food materials or biological materials in general can display large compositional variations, inhomogeneities, and anisotropic structures. Composition can change due to seasonal variations and/or environmental conditions, or in the case of processed foods, properties can be affected by process conditions and material history. For example, North Atlantic fish show dramatic compositional changes in their protein and moisture contents throughout the seasons. Cereals that are puffed up under different moisture and temperature conditions can vary widely in density and cell-size distribution, and exposure of such products to moist atmospheres, sometimes for short periods only, can have dramatic effects on their crispness. Therefore, in many cases the data found in published lists for engineering properties of foods can only be considered as approximate values. Nevertheless, these tabular values are still very useful since a safety factor is added to almost all calculations or designs of food processes and/or operations. An understanding of what affects the engineering properties of foods is essential for their proper interpretation and successful utilization. Therefore, one should always pay attention to the conditions under which the reported properties were determined, especially when response properties are involved.

Early physical property analyses of food products required constant uniform values and were often oversimplified and inaccurate. Nowadays, computational engineering techniques, such as the finite element method, are much more sophisticated and can be used to evaluate non-uniform properties (for example, thermal properties) that change with time, temperature, and location in food products that are heated or cooled. Improvements measuring the compositions of foods are now allowing predictions of engineering properties that are more accurate than previously, since they can be predicted from existing numerical and empirical models of the food's composition, temperature, and porosity. There has always been a tendency to make general correlations in predicting properties of food materials for use in process design equations. A myriad of mathematical functions have already been fitted to experimental data, and models are bringing order to experience with the goal of clarifying which components or interactions are important in a food system.

The *Engineering Properties of Foods* topic covers different sets of engineering properties that are described in greater detail in specific articles, each with wide applications to food engineering and useful for product characterization and equipment design in food manufacture. Basic definitions, common methods, parameter dependence, modeling, and food engineering applications will dictate the basic pattern followed within most sections. The final section will define how engineering properties and microstructure are related, because foods are complex in both structure and composition, this being the main reason for variability during property determination.

2. Thermal Properties

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.

2.1. 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*, C_p, is the amount of heat needed to raise the temperature of unit mass by unit degree at a given temperature. The SI units for C_p 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, C_p, 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:

$$C_p = (\delta H / \delta T)_P \tag{1}$$

Only with gasses is it necessary to distinguish between C_p and C_v, 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/m^3) to raise the temperature from T_2 to T_1 can be calculated using the following equation:

$$Q = MC_p(T_2\text{-}T_1) \tag{2}$$

(b) *Thermal conductivity*, κ, represents the quantity of heat $\dot{Q}$ 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 $\dot{Q}$ through a material by conduction can be predicted by Fourier's law of heat conduction. A simplified approximation follows:

$$\dot{Q} = \kappa A(T_1 - T_2) / x \tag{3}$$

where A is the surface area of the food, x is its thickness, T_1 is the temperature at the outer surface where heat is absorbed, and T_2 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 [m^2/s], defines the rate at which heat diffuses by conduction through a food composite, and is related to κ and C_p through density ρ [kg/ m^3] as follows:

$$\alpha = \kappa / \rho C_P \tag{4}$$

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 ΔT_f below the expected solidification temperature for pure water. *Freezing point depression* is defined as the temperature reduction ΔT_f. Both the boiling point rise and the freezing point depression of a food are related to its solutes concentration.

2.2. Thermal Variations in Properties and Methods of Determination

Precision and accuracy of measurement are important factors in determining thermal properties variations. In commercial heating or cooling applications, computer techniques nowadays provide accuracies of 2–5 percent for most heat-transfer calculations, which provide much lower relative errors than practical boundary condition determinations (for example, air temperature and velocities).

Several methods are known for measuring specific heat and C_p and thermal conductivity κ experimentally. C_p measurement of foods can be determined by methods of mixtures and differential scanning calorimetry (DSC). For methods of mixtures, a calorimeter of known specific heat is used and C_p is determined from a heat exchange balance. In the DSC method, the sample is put in a special cell where the temperature is increased at a constant heating rate. The specific heat of the food is obtained from a single heat thermogram, which relates heat flow as a function of time or temperature. Two experimental methods to determine κ are the Fitch method and the line source method. In the Fitch method, a solid slab of a certain food receives heat from one layer and conducts it to a copper plug. Conductivity k is obtained from the food's temperature as a function of heat conduction time. The line source method is based on the use of a thermal conductivity probe to measure a temperature–time relation on a thin cylindrical food piece to which constant heat is applied.

Thermal diffusivity α is usually either determined by direct experimental methods or estimated through Eq. (4). Several direct methods for α determination can be based on a one-dimensional heat conduction equation where geometrical boundary conditions are defined. For instance, an apparatus can be used where the sample is located in a special cylinder and immersed in a water bath at constant temperature. Thermocouples located at the center of the sample (axis) and surface of cylinder measure temperature at different heating times. Transient temperature variations are used for the analytical solution. Indirect methods, although they might yield more accurate diffusivity values, require more time and instrumentation for the three-parameter determination (ρ, κ, and C_p).

Boiling point elevation ΔT_r at a certain external pressure can be determined from a thermodynamic equation using the latent heat of vaporization and molar fraction of the food. However, the use of these equations requires knowledge of the proportions of specific components of the foods that cause changes in the boiling points. In many cases, estimates for specific components present in higher concentrations can be used. Sometimes reference liquids under the same vapor pressure conditions can be compared with the food, and charts can be used to determining boiling points at different saturation concentrations. On the other hand, freezing points T_f in foods can be directly determined from the freezing curve (or cryoscope) method without using component concentrations. ΔT_f value can be derived from the temperature plateau after initial temperature depression (or supercooling) on a time-temperature plot. Furthermore, DSC can also be used to determine the onset, peak, and end of freezing.

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 C_p, 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 C_p 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 C_p. 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 C_p of each individual component in a food differs from the C_p 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 C_p 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 C_p than bulk-frozen water, and ice has a C_p of about one-half that of liquid water. Thus, C_p below freezing is approximately half that of C_p 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. C_p 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 C_p 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, most are 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.

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Biographical Sketches

Gustavo V. Barbosa-Cánovas received his B.S. in Mechanical Engineering at the University of Uruguay and his M.S. and Ph.D. in Food Engineering at the University of Massachusetts, Amherst, MA. He then worked as an Assistant Professor at the University of Puerto Rico from 1985–90, during which he was granted two National Science Foundation (NSF) awards for research productivity. Following this he went to Washington State University (WSU), where he is now Professor of Food Engineering and Director of the Center for Nonthermal Processing of Food (CNPF). Dr. Barbosa-Cánovas chaired the Organizing Committee for the 1997 and 1999 Conference of Food Engineering (CoFE). In addition, he is an Editor of the journal *Food Science and Technology International* published by Sage, the journal *Innovative Food Science and Emerging Technologies* published by Elsevier Science, and the Food Engineering theme in the *Encyclopedia of Life Support Systems* (EOLSS) to be published by UNESCO.

Dr. Barbosa-Cánovas is the Editor-in-Chief of the Food Engineering Book Series published by Kluwer Academic and Plenum Publishers (KAPP) as well as of the Food Preservation Technology Book Series published by CRC Press. He has chaired and organized several technical sessions at the American Institute of Chemical Engineers (AIChE) and Institute of Food Technologists (IFT) annual meetings, edited twelve books on Food Engineering topics, and authored, among others, *Dehydration of Foods* (Chapman & Hall), *Nonthermal Preservation of Foods* (Marcel Dekker), *Food Engineering Laboratory Manual* (Technomic), and *Engineering Properties of Biological Materials* (ASAE). Dr. Barbosa-Cánovas is also a member of the editorial board for four technical journals, including the *Journal of Food Engineering*, *Journal of Food Process Engineering*, *Journal of Food Science and Technology* (LWT), and the *International Journal of Physical Properties of Foods.* He is International Consultant for the United Nations' Food Agriculture Organization (FAO), Associate Researcher for the United Nations' PEDECIBA (a special program to develop basic sciences), and a consultant for several major food companies in the United States.

Pablo Juliano received a B.S. in Chemistry from the University of Uruguay in 1999. In 2000, he was awarded a scholarship from the Organization of American States to pursue graduate studies at Washington State University toward an M.S. in Food Engineering, where he received his Ph.D. in 2006. He also worked in quality assurance at Nestle (Uruguay) between 1996 and 2000, where he applied his ISO 9000 Quality Specialist Degree. Dr. Juliano specialized in food powder technology and high pressure processing of food.

Micha Peleg is Professor of Food Engineering at the University of Massachusetts, Amherst, MA in the Department of Food Science (since 1990). He first obtained his B.Sc. (Chemical Engineering) at Technion, Israel Institute of Technology in 1963, his M.Sc. (Food Engineering and Biotechnology) at Technion in 1967, and his D.Sc. (Food Engineering and Biotechnology) at Technion in 1971. Dr. Peleg's current research areas are mathematical and computer-aided modeling and analysis of rheological behaviors of solid foods, mechanical testing of food materials, viscosimetry, powders, particle size distributions, and microbial populations dynamics.

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