Physical, Optical and Electrical Properties of Food material

Introduction

Lord Kelvin once said, "When you can measure what you are speaking about, and can express it in numbers, you know something about it; and when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of a science." This chapter covers the basic physical characteristics of foods and food products. Since the physical characteristics of plant and animal food materials affect how they are to be processed, handled, stored, and consumed, knowledge of these characteristics are important to engineers, processors and food scientists, plant and animal breeders, and other scientists. The following provides a list of various properties that will be discussed either in this or following chapters:

Physical Characteristics

1. Shape 2. Size 3. Weight 4. Volume

5. Surface area 6. Density 7. Porosity 8. Color

9. Appearance 10. Drag coefficient 11. Center of gravity

Mechanical Properties

1. Hardness 2. Compressive strength 3. Tensile strength

4. Impact resistance 5. Shear resistance 6. Compressibility

7. Sliding coefficient of friction 8. Static coefficient of friction 9. Coefficient of expansion

10. Elasticity 11. Plasticity 12. Bending strength

13. Aerodynamic properties 14. Hydrodynamic properties

Thermal Properties

1. Specific heat 2. Thermal capacity 3. Thermal diffusivity

4. Thermal conductivity 5. Surface conductance 6. Absorptivity

7.Emmisivity 8. Transmissivity

Electrical Properties

1. Conductance 2. Resistance 3. Capacitance

4. Dielectric properties 5. Reaction to electromagnetic radiation

6. Conductivity—ability of seeds to hold a surface charge

Optical Properties

1. Light transmittance 2. Light reflectance 5. Contrast

3. Light absorptance 4. Color 6. Intensity

Physical properties describe the unique, characteristic way a food material responds to physical treatments involving mechanical, thermal, electrical, optical, sonic, and electromagnetic processes. A better understanding of the way food materials respond to physical and chemical treatments allows for optimum design of food equipment and processes to insure food quality and safety. Knowledge of a food's physical properties is necessary for:

- defining and quantifying a description of the food material,
- providing basic data for food engineering and unit operations, and
- predicting behavior of new food materials

The shape of an irregular object can be described by terms such as the following:

Shape Description

Round -Approaching spheroid

Oblate -Flattened at the stem end and apex

Oblong -Vertical diameter greater than the horizontal diameter

Conic -Tapered toward the apex

Ovate -Egg-shaped and broad at the stem end

Oblate -Inverted oblate

Lopsided -Axis connecting stem and apex slanted

Elliptical -Approaching ellipsoid

Truncate -Having both ends squared or flattened

Unequal -One half larger than the other

Various methods are used to measure or characterize the shape and size characteristics of foods and food products. In several cases, actual measurements are made to estimate the major dimensions and cross sections of the product. Tracings or projections are made to compare the shapes to listed standards. Mohsenin (1970) illustrates the use of standard charts in the describing and defining the shape of a product Various formulas and methods have been devised to estimate cross sections and other characteristics of the materials.

Roundness, as defined by Mohsenin (1970), "is a measure of the sharpness of the corners of the solid." Curray (1951) and Mohsenin (1970) provided the following equations for estimating roundness under different conditions of geometry and application:

Roundness = $\frac{Ap}{Ac}$

where: Ap = largest projected area of object in natural rest position

Ac = area of smallest circumscribing circle

Roundness = $\frac{\sum r}{NR}$

where: r = radius of curvature as defined in figure 2.01

R = radius of maximum inscribed circle

N = total number of corners summed in numerator

Roundness ratio = $\frac{r}{R}$

where *R* in this case is the mean radius of the object and *r* is the radius of curvature of he sharpest corner. It should be noted that, in the last definition (roundness ratio), the use of the radius of curvature of a single corner determines the roundness or flatness of an object. Roundness values will differ for each of the above methods. Thus, the method for roundness determination should always be noted.

Sphericit*y* expresses **the characteristic shape of a solid object relative to that of a sphere of the same volume** (Mohsenin, 1970). Curray (1951) suggested the following equation for estimating the sphericity of an object:

Sphericity = $\frac{\mathrm{Di}}{\mathrm{Dc}}$

where: Di = diameter of largest inscribed circle
Dc = diameter of smallest circumscribed circle

Density (ñ) of a material is the amount of that material occupying a certain space and is expressed in units of mass per unit volume. Materials consisting of particles or grains with interstitial air spaces have different values of particle density and bulk density. Materials without internal air spaces, such as fluids and solids, have equal particle and bulk density. Particle density is the mass divided by the volume of the particle alone. Bulk density is the mass of a group of individual particles divided by the space occupied by the entire mass, including the air space. Density of food materials is useful in mathematical conversion of mass to volume.

Porosity is the percentage of air between the particles compared to a unit volume of particles. Porosity allows gases, such as air, and liquids to flow through a mass of particles referred to as a packed bed in drying and distillation operations. Beds with low porosity (low percentage air space) are more resistant to fluid flow and thus are more difficult to dry, heat, or cool. With high porosity, air flows easily through the bed, drying is fast, and the power required by fans and pumps is low. A frequently used method of measuring the volume of non-porous objects such as vegetables and fruits is the use of platform scales or a top loading balance to determine the volume of a displaced liquid such as water. The liquid volume is computed by determining the mass of the displaced water and dividing by the known density of the water. The mass of the displaced water is the scale's reading with the object submerged minus the mass of the container and water. For objects that float, it is necessary to force the object entirely into the water with a thin stiff rod. If the object is heavier than water, it must be suspended in the water by a rod or other support to insure that the added mass of the object is not measured. The following expression is used to calculate the volume of displaced water:

$$\text{Volume } (m^3) = \frac{mass\ of\ displaced\ water\ (kg)}{Density\ of\ water(kg/m3)}$$

The **specific gravity** is defined as the ratio of the mass of that product to the mass of an equal volume of water at 4°C, the temperature at which water density is greatest. A reference temperature other than 4°C may be used if that temperature is explicitly specified with the specific gravity value. Specific gravity may be calculated from the following expression

$$\text{Specific gravity} = \frac{mass\ in\ air \times Specific\ gravity\ of\ water}{mass\ of\ displaced\ water}$$

SIZE

Size is an important physical attribute of foods used in screening solids to separate foreign materials, grading of fruits and vegetables, and evaluating the quality of food materials. In fluid flow, and heat and mass transfer calculations, it is necessary to know the size of the sample. Size of the particulate foods is also critical. For example, particle size of powdered milk must be large enough to prevent agglomeration, but small enough to allow rapid dissolution during reconstitution. Particle size was found to be inversely proportional to dispersion of powder and water holding capacity of whey protein powders (Resch & Daubert, 2001).

It is easy to specify size for regular particles, but for irregular particles the term size must be arbitrarily specified. Particle sizes are expressed in different units depending on the size range involved. Coarse particles are measured in millimeters, fine particles in terms of screen size, and very fine particles in micrometers or nanometers. Ultrafine particles are sometimes described in terms of their surface area per unit mass, usually in square meters per gram (McCabe, Smith & Harriot, 1993).

Size can be determined using the **projected area method**. In this method, three characteristic dimensions are defined:

1. Major diameter, which is the longest dimension of the maximum projected area;

2. Intermediate diameter, which is the minimum diameter of the maximum projected area or the maximum diameter of the minimum projected area; and

3. Minor diameter, which is the shortest dimension of the minimum projected area.

Optical Properties

Optical properties are those material properties resulting from physical phenomena occurring when any form of light interacts with the material under consideration. In the case of foods, the main optical property considered by consumers in evaluating quality is color, followed by gloss and translucency or turbidity among other properties. “Color” is the general name applied to all sensations arising from the activity of the retina, and is related to visual appearance of food (shape, size, surface and flesh structure, and defects).

Definitions:

Optical properties are related to consumer judgment on food appearance and produce some kind of visual effect. Among these, color, gloss and translucency can be defined as follows.

• Gloss is the name given to light specularly reflected from a plain smooth surface. It can be defined by a goniophotometric curve, which represents the intensity of light reflected at the surface at different angles of incidence and viewing.

• Color is essentially a beam of light composed of irregularly distributed energy emitted at different wavelengths. Depending on the type of illumination, the same material can show different light qualities and produce different sensations. Foods, along with other materials, have color properties, which depend exclusively on their composition and structure.

• Translucency of foods is defined using an opaque-to-transparent scale. In liquid foods, light passing through changes its path randomly (in other words, is scattered) when interacting with suspended particles. Although light can be transmitted or reflected, the human eye only experiences translucency as a sensory attribute distinct from color. Many food products (such as cloudy fruit and vegetable juices) are neither fully opaque nor fully transparent, but are translucent.

Methods and Applications

The color perceived when the eye views a food is related to the following three factors: the spectral composition of the light source, the chemical and physical characteristics of the food, and the spectral sensitivity properties of the eye. To evaluate the colorimetric properties of a food, two of these factors must be standardized. Although the human eye can give fairly uniform results, it can be replaced by some instrumental sensor or photocell to provide even more consistent determinations. Visual colorimeters facilitate visual comparisons and eliminate differences in interpretation between operators.

In practice, visual measurement of color entails comparing the color problem with reference colors available in printed charts under well-defined and favorable conditions for good, reproducible comparisons. Light source, geometry of viewing, and color of background are the most important factors to control. Description of color for purchase specifications of food commodities or packaging materials involves color tolerances, which are defined in one, two, or three dimensions in color space to avoid variability of the human eye. Several systems of color analysis have been created. The most used are the CIE, Munsell, Hunter, and Lovibond systems.

• In the CIE system, spectral curves indicate how the eyes of normal observers respond to various spectral light types in the visible portion of the spectrum. The system is based on the fact that any color can be matched as a suitable mixture of red, green, and blue. These primary combinations are called tristimulus values of color. A certain color can be defined by chromacity coordinates x and y, and by the luminous transmittance or lightness. A chromacity diagram defines different color points that define the standard color of a food. The US Department of Agriculture uses chromacity coordinates to define specifications of color standards for a variety of products.

• In the Munsell system, all colors are described by three attributes: hue (or type of color), lightness (relative to the proportion of light emitted), and saturation or purity (associated with clear to dark perception). The hue scale is based on ten hues distributed on a circumference (scaled 1 to 10); the lightness ranges from black to white (0 to 10) and is distributed on a perpendicular line; the purity is of irregular length beginning with 0 for the central gray to the limit of purity obtainable by available pigments in the Munsell book of color. The

• The Lovibond system is a standard method generally used to determine the color of vegetable oils. It involves visual comparisons of light transmitted through a glass couvette using color filters. Vegetable oils are usually expressed in terms of red to yellow. The Lovibond index can also be used to measure color in wines and juices. Computer software packages have been

developed that easily convert light transition spectra into CIE, Munsell, Hunter, and Lovibond color indices.

Color can be measured instrumentally with colorimeters, which may be broadly classified as tristimulus colorimeters and spectrophotometers. The difference between spectrophotometers and colorimeters is that the former measures intensity of light through the completely visible spectrum, and colorimeters are designed to measure only some parameters related to sensory colors. Colorimeters are very useful in the quality control of foods, and give results normally correlated with visual measurements.

A Munsell colorimeter consists of a circular rotating platform where several colored disks are mixed in different proportions to provide a range of shades to match the color of a certain food product. It is widely used in the food industry for quality control of a number of solid products like tomatoes, fruits, and peanut butter.

Tristimulus colorimeters measure both related scales of Munster, Hunter, or CIE systems, which are numerically related. The quality of output for this type of instrument mainly depends on the correct combination of light source, filter, and photocell to obtain a good reproduction of visual response. Glossmeters measure intensity of light reflected at three angles of incidence and reflection, and normally give results in the form of indices, obtained by comparing the sample reflectance to that of a highly reflective flat glass, used as a calibration standard. These indices are easy to interpret, in contrast to more difficult goniophotometric curves used in the past for classification. Translucency can be the measurement of the reflection of a thin sample against both a white and black background. From these measurements, the value of reflection from an opaque layer is calculated as a ratio between absorption and scattering to measure scattered light.

Additional information on the visual appearance of turbid products such as orange juice can be obtained. Processing can affect food product color through changes in its physical state and/orpigment content. Color measurement techniques can improve the understanding on processing changes and reaction kinetics in foods. Applications of color measurement for food processing research are many and varied. For instance, color measurement techniques are used for recording desirable color changes in canning salmon with higher oil content, defining translucency of the tissues and green pigment degradation after blanching treatment of green peas, studying browning kinetics, or determining the influence of particle sizes in the final color of powders. Characterization of the color of ingredients can also help to predict the color of the final product—for example, control of raw strawberries for processing into jam. In red wine, the percentage of brown component and the relative loss of anthocyanin can be followed by reflectance measurement during storage.

Glossiness of a product is a property of the smoothness of its surface. When this characteristic is desired, manufacturers try to improve it, as in the case of fruits covered with wax to make them more visually appealing. Translucency is also worth consideration in some liquid foods, such as fruit juices. Its measurement can be determined by considering the contributions of both absorbed and scattered light when traversing these products. For a few clear liquid foods, such as oils and beverages, color is mainly a matter of transmission of light. Other foods are opaque and derive their color mostly from reflection. Optical properties can be used to perform quality control and continuous inspection during processing operations. Major requirements for a quality control system are ease of calibration and use, stability, precision, speed, cheapness, and industry-wide applicability. A complete color description requires the use of three dimensions, and a control automatic system may be based on this complete specification. Specifications may be set to provide an idea of fruit ripeness, milk or cream discoloration during sterilization, degree of roasting of coffee grains, or browning of apples slices during storage. Continuous color measurements are used in tasks involving color sorting (or "electronic sorting") by using in-line systems. Color sorting is used for a very wide range of food materials in screening defects. Visible, infrared, and ultraviolet laser beams can provide continuous inspection through scanning of product size, symmetry, damage, irregular shape, fill level, and label placement by adding automatic software in connection with mechanical devices. For example, during conveying of pre-fried potato chips, optical devices detect any with defects (for example, black spots), and automatically deploy an air nozzle to deflect their path from the conveyor belt.

Electrical Properties

There are two main electrical properties in food engineering: electrical conductivity and electrical permittivity. Electrical properties are important when processing foods involving electric fields, electric current conduction, or heating through electromagnetic waves. These properties are also useful in the detection of processing conditions or the quality of foods.

Electrical Conductivity and Permittivity

Electrical conductivity is a measure of how well electric current flows through a food of unit cross-sectional area A, unit length L, and resistance R. It is the inverse value of electrical resistivity (measure of resistance to electric flow) and is expressed in SI units S/m in the following relation:

ƒÐ = L /(AR) (5)

Electrical permittivity is a dielectric property used to explain interactions of foods with electric fields. It determines the interaction of electromagnetic waves with matter and defines the charge density under an electric field. In solids, liquid, and gases the permittivity depends on two values:

1. The dielectric constant ƒÃ • f, related to the capacitance of a substance and its ability to store electrical energy.

2. The dielectric loss factor ƒÃ • h, related to energy losses when the food is subjected to an alternating electrical field (i.e., dielectric relaxation and ionic conduction).

The electrical conductivity of foods has been found to increase with temperature (linearly), and with water and ionic content. Mathematical relationships have been developed to predict the electrical conductivity of food materials: for example, for modeling heating rates through electrical conductivity measurements, or for probability distribution of conductivity through liquid-particle mixtures. Electrical conductivity shows different behaviors during ohmic and conventional heating. At freezing temperatures, electrical conductivity increases with temperature, as ice conducts less well than water. Starch transitions and cell structural changes affect electrical conductivity, and fat content decreases conductivity. As in thermal properties, the porosity of the food plays an important role in the conduction of electrons through the food.

In foods, permittivity can be related to chemical composition, physical structure, frequency, and temperature, with moisture content being the dominant factor. Dielectric properties (ƒÃ • f, ƒÃ • h) are primarily determined by their chemical composition (presence of mobile ions and permanent dipole moments associated with water and other molecules) and, to a much lesser extent, by their physical structure. The influence of water and salt (or ash) content largely depends on the manner in which they are bound or restricted in movement by other food components. Free water and dissociated salts have a high dielectric activity, while bound water-associated salts and colloidal solids have low activity. Power dissipation is directly related to the dielectric loss factor ƒÃ • h and depends on the specific heat of the food, density of the material, and changes in moisture content (for example, because of vaporization). Permittivity also depends on the frequency of the applied alternating electric field. Frequency contributes to the polarization of molecules such as water. In general, dielectric constant increases with temperature, whereas loss factor may either increase or decrease depending on the operating frequency. Both the dielectric constant ƒÃ□f and loss factor ƒÃ□h decrease significantly as more water freezes. Reasonable comprehensive tabulations of electrical properties data are available for foods in electronic and printed form.

Methods and Applications

The conductivity of a material is generally measured by passing a known current at constant voltage through a known volume of the material and by determining resistance. The total conductivity is then calculated simply by taking the inverse of the total resistivity. Basic measurements involve bridge networks (such as the Wheatstone bridge circuit) or a galvanometer. There are other devices that measure electrical conductivity of foods under ohmic or conventional heating conditions, using thermocouples and voltage and current transducers to measure voltage across and current through the samples.

Known methods for measuring dielectric properties are the cavity perturbation, open-ended coaxial probe, and transmission line methods. Since modern microwave network analyzers have become available, the methods of obtaining dielectric properties over with frequency ranges have become more efficient. Computer control of impedance analyzers and network analyzers has facilitated the automatic measurement of dielectric properties over wide frequency ranges, and special calibration methods have also been developed to eliminate errors caused by unknown reflections in the coaxial-line systems.

Distribution functions can be used in expressing the temperature dependence of dielectric properties. Electrical properties are important in processing foods with pulsed electric fields, ohmic heating, induction heating, radio frequency, and microwave heating. Conductivity plays a fundamental role in ohmic heating, in which electricity is transformed to thermal energy when an alternating current (a.c.) flows through food. As it has potential use in fluid pasteurization, it is important to know the effective conductivity or the overall resistance of liquid-particle mixtures. Furthermore, liquid-particle mixtures can be pasteurized using pulsed electric field technology, where products with low electrical conductivity are better and more energy-efficient to process. Electrical conductivity can be used for acidity studies, therefore, and for monitoring processes where acidity increases, as in fermentations. Crystallization processes (for example, in sugar solutions) can also be monitored with conductivity measurements, as conductivity has been found inversely proportional to viscosity, which in turn follows supersaturation closely.

Conductivity measurements have also been used to measure moisture contents in materials, particularly grain products. The electrical field inside the food is determined by the dielectric properties and the geometry of the load, and by the oven configuration. These properties are also useful in detection processing conditions, or the quality of foods. The major uses for dielectric properties are measuring and heating applications. Permittivity and moisture are closely correlated when the water content is high. Properly designed electrical instruments can be used to determined moisture content or water activity. Knowledge of dielectric properties in partially frozen material is critical in determining the rates and uniformity of heating in microwave thawing. As the ice in the material melts, absorption of energy increases tremendously. Thus, the portions of material that thaw first absorb significantly more energy and heat at increasing rates, which can lead to localized boiling temperatures while other areas are still frozen. Salt affects the situation through freezing point depression, leaving more water unfrozen at a given temperature.

Dielectric properties are also important in the selection of proper packaging material sand cooking utensils, and in the design of microwave and radio frequency heating equipment, because they describe how the material interacts with electromagnetic radiation. Studies of heating uniformity and temperature elevation rate involve dielectric properties. Typical features of power density patterns of a load are large internal hot and cold areas, internal focusing effects, and the edge-heating phenomenon. For example, when a raw egg is heated it may explode because the power density near its center is much higher than in other parts, causing violent shattering as the interior becomes superheated.

Reference

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