Selections from Wilhelm, Luther R., Dwayne A. Suter, and Gerald H. Brusewitz. 2004. Physical Properties of Food Materials. Chapter 2 in Food & Process Engineering Technology, 23-52. St. Joseph, Michigan: ASAE. © American Society of Agricultural Engineers. (Rev. Aug. 2005.)

2

Physical Properties of Food Materials

Abstract. *This chapter reviews selected physical properties of food and biological materials. The primary emphasis is upon mechanical and thermal properties, although electromagnetic properties are briefly reviewed.*

Keywords. *Electrical properties, equilibrium moisture content, mechanical properties, non-Newtonian fluids, optical properties, permeability, physical characteristics, thermal properties, viscosity, water activity.*

2.1 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
    a. moisture
    b. thermal
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
3. Light absorptance
4. Color
5. Contrast
6. Intensity

2.2 Physical Properties Applications

The study of food engineering focuses on the analysis of equipment and systems used to process food on a commercial production scale. Engineering of systems for food materials can be more thorough if there is an understanding of the changes that occur in food as it is processed by the system. Raw food materials are biological in nature and as such have certain unique characteristics which distinguish them from other manufactured products. Because food materials are mainly of biological origin they have (a) irregular shapes commonly found in naturally occurring raw materials; (b) properties with a non-normal frequency distribution; (c) heterogeneous composition; (d) composition that varies with variety, growing conditions, maturity and other factors; and they are (e) affected by chemical changes, moisture, respiration, and enzymatic activity. Dealing with materials that have these unique characteristics requires additional consideration, mostly indirectly, in that there are additional sources or causes of variation. People unfamiliar with this natural variability of biological materials may overlook these factors or be frustrated by lack of control over the input parameters. The characteristics of a food material that are independent of the observer, measurable, can be quantified, and define the state of the material (but not how it attained that state) are considered as its physical properties. **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.

It is common for the physical properties of a food to change during processing operations. Not recognizing these changes can lead to potential processing failures. Physical properties are an important aspect of food quality and relate to food safety. They are the basis for instruments and sensors. A few examples of select physical properties of foods are presented in this unit.

2.3 Physical Characteristics

Physical characteristics of raw, unprocessed, as well as processed food materials include particle size and shape, particle and bulk density, porosity, and surface area. The size and shape of a raw food material can vary widely. The variation in shape of a product may require additional parameters to define its size. The size of spherical particles like peas or cantaloupes is easily defined by a single characteristic such as its diameter. The size of non-spherical objects like wheat kernels, bananas, pears, or potatoes may be described by multiple length measurements. The longest diameter (major) and shortest diameter (minor) will adequately describe the size of an ellipsoidal object such as grain kernel or potato. The two dimensions are usually measured perpendicular to one another. The size of pear-shaped objects such as pears, carrots, or beets can be expressed by diameter or circumference of the largest part and an overall length in the direction of the stem. The size of irregular-shaped materials like bananas, okra, or squash requires more extensive considerations.

Particle size is used in sieve separation of foreign materials or grading (i.e., grouping into size categories). Particle size is particularly important in grinding operations to determine the condition of the final product and determines the required power to reduce the particle's size. Small irregular-shaped objects can be sized with sieves by expressing particle size as the smallest sieve opening through which the particle passes. The size of larger objects may be expressed only in terms of its largest diameter or circumference. The size of a banana might be given only in overall length. Precise methods incorporating optical, light, or lasers in machine vision systems exist to define shape and size of irregular-shape objects. These systems are costly; their use is warranted in applications of high value materials more commonly found in highly processed, final products rather than raw, unprocessed materials.

Ultimate use will dictate which physical characteristic properly represents size. Size of a carrot may be expressed only in length or in diameter of its large end. Size may be indicated by weight since it is so easily determined by simply placing on a scale. Thus, the physical property *size* is actually related or correlated to the property *weight*. In practice, there is often a compromise between ease or cost of measurement and usefulness or value of that property in the market channel.

Shape affects the grade given to fresh fruit. To make the highest grade a fruit or vegetable must have the commonly recognized expected shape of that particular fruit/vegetable. Misshapen fruit and vegetables will be down-graded and may sell at a lower price in high volume markets.

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
Ribbed	In cross section, sides are more or less angular
Regular	Horizontal section approaches a circle
Irregular	Horizontal cross section departs materially from a circle

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 (Figure 2.01).

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:

$$Roundness = \frac{A_P}{A_c} \tag{2.01}$$

where: A_p = largest projected area of object in natural rest position
A_c = area of smallest circumscribing circle

$$Roundness = \frac{\Sigma r}{NR} \tag{2.02}$$

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

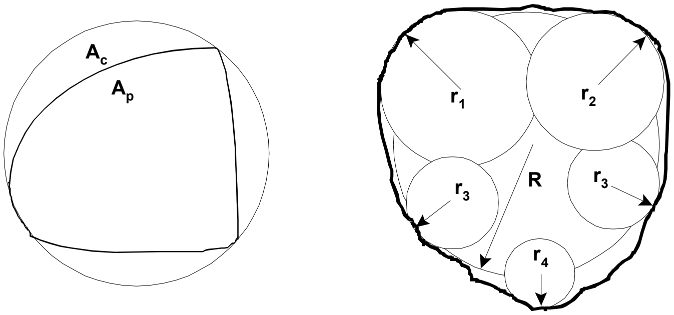
$$Roundness\ \ ratio = \frac{r}{R} \tag{2.03}$$

where R in this case is the mean radius of the object and r is the radius of curvature of the sharpest corner. It should be noted that, in the last definition (2.03), 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.

Sphericity 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:

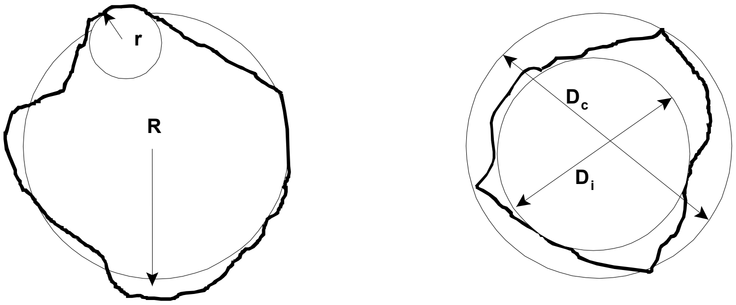
$$Sphericity = \frac{D_i}{D_c} \tag{2.04}$$

where: D_i = diameter of largest inscribed circle
D_c = diameter of smallest circumscribed circle



Roundness $= A_p / A_c$

Roundness $= \Sigma\, r / NR$



Roundness Ratio $= r / R$

Sphericity $= D_i / D_c$

Figure 2.01. Roundness and sphericity as defined by geologists to describe shape of grains and pebbles (Curray, 1951, and Mohsenin, 1970).

Density (ρ) 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. The grain industry determines the amount of agricultural grains by converting the weight to volume (bushels). Even though grain marketing is done in terms of bushels, grain weight, not actual bushels, is the property measured. The density of processed products dictate the characteristics of its container or package. Product density influences the amount and strength of packaging material. Breakfast cereal boxes contain a required weight of cereal. More weight of material can be placed into a box if the cereal density is greater. Also, food density influences its texture or mouth feel. Processing can affect product density by introducing more air, such as is done in the manufacture of butter or ice cream. In products like whipped cream, which are primarily air, control of density is essential.

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:

$$\text{Volume}\,(\text{m}^3) = \frac{\text{mass of displaced water (kg)}}{\text{density of water (kg/m}^3)} \tag{2.05}$$

The **density** of the object can then be determined by dividing the object's mass by the measured volume. The object's mass is measured directly on the scale. The density of foods and food products is used in numerous situations involving heat transfer. Several applications will be demonstrated in the heat transfer chapters.

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:

$$\text{Specific gravity} = \frac{\text{mass in air} \times \text{specific gravity of water}}{\text{mass of displaced water}} \tag{2.06}$$

Another important physical characteristic, **surface area**, is related to size but also depends on particle shape. Surface area is difficult to measure for irregular-shaped objects and thus is often determined indirectly or computed by assuming a specific shape. Several methods have been developed to measure the surface area of items. Surface area is most easily measured for items that very closely resemble common geometric shapes. A frequently used method is the projection method, which uses photographs or projected images to obtain an outline of the object. Once the object outline is obtained, segments can be defined by drawing parallel lines and calculating the area enclosed in each segment. Another method involves tracing an object. The area enclosed in the tracing may be determined by the use of a planimeter, development of segments as defined above, or other methods.

Surface area is useful in estimating the amount of wax applied to fruit, amount of packaging film to wrap fruit, and rate of heating, cooling, freezing, and drying. For granular materials, porosity is closely related to surface area. Particle surface area is important in heating and cooling operations since heat transfer is proportional to surface area.

The physical characteristics of food materials are readily recognized and commonly utilized throughout the marketing channel. Variation in these properties for raw food materials requires the use of statistical measures such as the average or minimum percentage of a particular size. This variation may be affected by seasonal growing conditions.

2.4 Surface Activity

Many foods are a mixture of multi-phase materials (i.e., a mix of solid, liquid, and gas). The boundary between these phases, the interface, plays a significant role in the properties of the food. Examples of a **foam**, a gas in a liquid, are whipped creams and toppings. An **emulsion**, a liquid in a liquid, example is mayonnaise. A **solid foam** example is the meringue on pies. Both oil and water, which do not readily mix, exist in many foods. Milk and cream (oil-in-water) and butter and margarine (water-in-oil) are examples of emulsions. Uniform distribution of oil and water throughout a food material incorporates the use of surface properties. Surface properties are important in unit operations such as spray drying, aeration, hydrogenation, and fermentation. A knowledge of surface properties is also important in cleaning operations. Emulsifying agents and detergents clean because they reduce the surface tension to more readily remove solids (dirt). These liquids wet solid surfaces and dissolve water-soluble and fat-soluble components. Detergents reduce surface tension to break apart large particles and promote spreading over the surface. Detergents allow mechanical force such as sprays or bulk turbulent flow in cleaned-in-place systems to be more effective.

The forces acting on the surface of a liquid tending to minimize its area are known as **surface tension**. The surface tension of water is twice as high as for cooking oils. Thus, water tends to form spherical droplets on clean surfaces. Materials when mixed with water to reduce its surface tension are referred to as surface active, i.e., surfactants. The addition of low concentrations of surfactants decreases the surface tension of water significantly. Wetability and solubility of powders affect their mixing with liquids. The liquid's surface properties control the rate of wetting and dissolution of the powder's particles. Wetting properties of milk powder during spray drying are affected by particle size, surface tension, presence of wetting agents, and the form and location of fat molecules. Although data on the surface properties of food materials are not quantified as extensively as other properties, it is no less important; and empirical, qualitative data are often used as the only information available.

2.5 Moisture in Foods

Foods are composed of nothing in greater amount than water. Fresh fruit, vegetables, and milk contain over 80% water. The amount of water in a food is denoted by its **moisture content**. A food's storability is directly related to moisture content, along with temperature and oxygen availability. High amounts of available moisture lead to mold growth and microbial activity. Fruit must be dried below 30% and agricultural grains below 12% for good long-term storage.

Moisture is present in foods in either solid form (ice), liquid (water), or vapor (humidity in air). The properties of water in each of these forms are significantly different. For example, the dielectric constant of water is 25 times higher than that of ice. Microwave heating is highly affected by a material's dielectric constant. Thus, heating of a frozen food in a microwave takes place significantly more slowly than heating of the same unfrozen food. The change in form or phase of water is accompanied by an exchange in energy. Thus, externally produced thermal energy is required to add sufficient heat to change the form from solid to liquid or liquid to vapor. Similarly, as water turns into ice heat energy is released by the food. These phase changes affect the other food constituents and properties such as density and thermal conductivity. Moisture affects many other physical properties. Since the physical properties of water differ from the other constituents and since water is a major constituent of food, it therefore has a major influence on a food's properties. Moisture content will be considered in more detail in the chapter on drying and dehydration.

Foods, being biological materials, have an affinity for moisture. This interaction of food with water is known as its hygroscopic nature. The moisture content of a hygroscopic material such as food is in direct relation to the humidity of the surrounding air. A hygroscopic material left sufficiently long will eventually reach a unique moisture content known as the **equilibrium moisture content** (*EMC*) for that relative humidity (*rh*) and temperature condition. The *rh-EMC* relationship is non-linear; it is a sigmoid shaped curve. At air relative humidities below 10% and above 90% there is a large change in *EMC* for small relative humidity changes. Each biological material has a unique and different *rh-EMC* relationship. The *EMC* is important in predicting the drying potential of air or storage potential of grain. Materials with moisture contents below their *EMC* will tend to increase in moisture if there is adequate air flow. Materials with moisture contents above their *EMC* will tend to decrease in moisture. The term *EMC* is commonly used in dealing with lower moisture materials, i.e., below 30%, such as agricultural grains and seeds. Agricultural grains, seeds, and nuts need to be kept at low moisture, below 12%, if they are to be stored for long periods in warm temperatures. More details on *EMC* will be given in the drying and dehydration chapter (Chapter 10).

For higher moisture materials such as most food products, the commonly used moisture related property is **water activity** (commonly identified by the symbol a_w), which is the relative humidity of the surrounding air in equilibrium with the moisture in the product. Water activity is a term indicating the amount of free water in a biological material. The free water is the moisture available for microbial and enzymatic activity and for chemical reaction. With water activity above 0.8 there is sufficient water to promote mold growth (Figure 2.02) and water activity above 0.9 allows bacterial growth. Susceptibility to spoilage can be controlled by lowering water activity. Thus, water activity influences a food's storability.

Water activity indicates a product's tendency to dehydrate. Figure 2.03 shows the typical sigmoid shape relationship between water activity and equilibrium moisture content. The curve on the graph shows the lowest moisture content a product can be dried to for a given water activity and temperature. Raising the temperature reduces the equilibrium moisture content, thus allowing for more drying.

The moisture in food has a direct influence on its weight, and weight of material is related to its value in dollars. If the weight of fruit in a packing house decreases by 5% due to moisture lost to the air, the owner has lost 5% of his product, which is 5% of gross income. Moisture in fruit has significant monetary value. Moisture in any food has the same value as the going unit price of the food. For example, if apples are selling for $2.00 per kg and part of the weight is lost in storage due to low humidity air, the lost water has the value of $2.00 per kg! For every 1,000 kg of $2.00/kg product shipped having 5% moisture loss, the owner will be paid $100 less than the cost of the product that was placed into storage. Minimizing weight loss is important in maintaining amount of product as well as its quality.

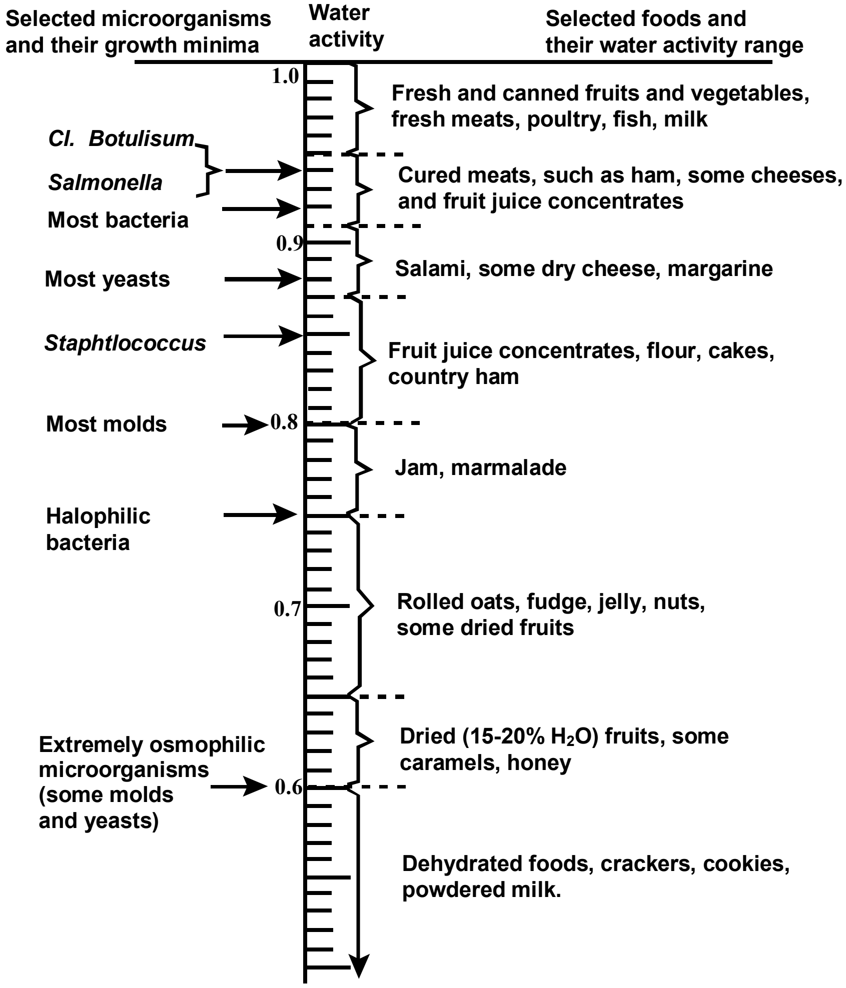


Figure 2.02. Water activities required for growth of organisms. (Based upon Labuza, 1984, and Beuchat, 1981.)

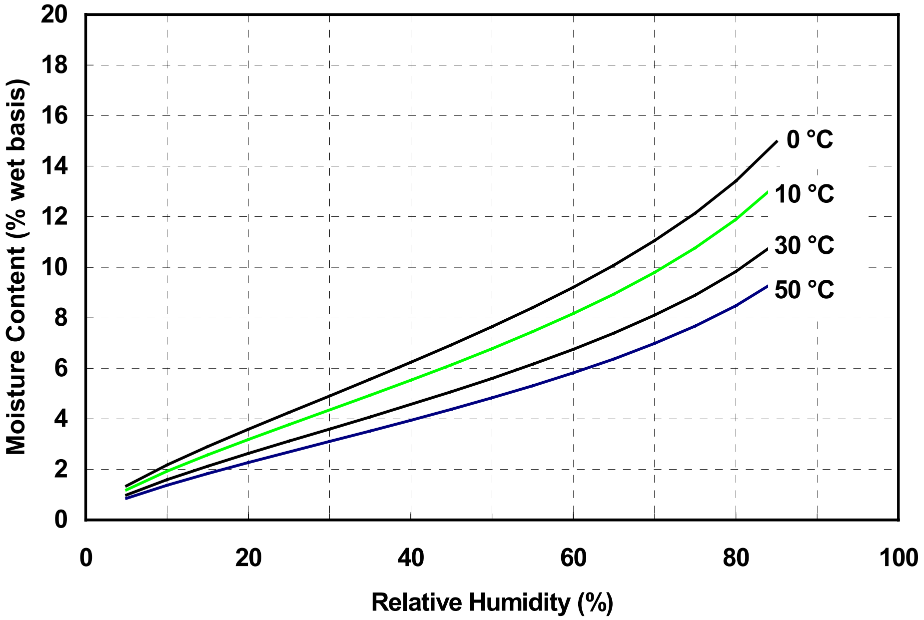


Figure 2.03. Equilibrium moisture content curves for peanut kernels.

Moisture has a tendency to move from a location of higher concentration to a region of lower concentration. More specifically, moisture in the air at a high vapor pressure will go towards a location of lower vapor pressure. This movement of moisture is a natural phenomenon, commonly occurring in foods, and has numerous ramifications. Fruit left open to room air will quickly dry, lose moisture, and eventually become inedible. Preventing or restricting the movement of moisture is a major objective of the wrapping materials business. Foods are wrapped with plastics to prevent the exchange of moisture. Foods are covered with plastic wraps before being heated in the oven to retain moisture in the food. The availability and variety of packaging materials has grown significantly since the 1980's. Materials, primarily plastics, have been developed with unique moisture and gas transmitting properties to meet the defined food requirements (Fellows, 1988).

Permeability (*P*) is defined as $P = [(\text{volume of gas or vapor}) \times (\text{material thickness})] / [(\text{area}) \times (\text{time}) \times (\text{pressure difference across the materials})]$. Wrapping materials have permeability properties unique for each gas or vapor as shown in Table 2.01. Cellophane has an oxygen permeability of 0.0021×10^{10} compared to 2.88×10^{10} cm^3 cm cm^{-2} s^{-1} cm Hg^{-1} for 0.914 gm/cm^3 density polyethylene, while water permeabilities are 1900×10^{10} and 90×10^{10}, respectively. That is, cellophane allows water through faster and oxygen slower than polyethylene. Saran® wrap is 3800 times less permeable to water vapor than cellophane. Plastics are now available to minimize the loss of moisture from fresh fruit while allowing gases like oxygen and carbon dioxide to pass through without accumulating to high levels inside the bag. Without the provision for

Table 2.01. Permeability coefficients and diffusion constants of polymers.[a]

Polymer	Permeant	T (°C)	$P \times 10^{10}$	$D \times 10^{6}$
Poly(ethylene) (density 0.914)	O_2	25	2.88	0.46
	CO_2	25	12.6	0.37
	N_2	25	0.969	0.32
	H_2O	25	90	
Poly(ethylene) (density 0.964)	O_2	25	0.403	0.17
	CO_2	25	1.69	0.116
	CO	25	0.193	0.096
	N_2	25	0.143	0.093
	H_2O	25	12	
Poly(propylene)	H_2	20	41	2.12
	N_2	30	0.44	
	O_2	30	2.3	
	CO_2	30	9.2	
	H_2O	25	51	
Cellulose acetate	N_2	30	0.28	
	O_2	30	0.78	
	CO_2	30	22.7	
	H_2O	25	5500	
Cellulose (Cellophane)	N_2	25	0.003	
	O_2	25	0.002	
	CO_2	25	0.005	
	H_2O	25	1900	
Poly(vinyl acetate)	O_2	30	0.5	0.055
Poly(vinyl alcohol)	H_2	25	0.009	
	N_2	14[b]	<0.001	
	N_2	14	0.33	0.045
	O_2	25	0.009	
	CO_2	25	0.012	
		23[c]	0.001	
		23[d]	11.9	0.0476
	ethylene oxide	0	0.002	
Poly(vinyl chloride)	H_2	25	1.7	0.5
	N_2	25	0.0118	0.004
	O_2	25	0.0453	0.0118
	CO_2	25	0.157	0.003
	H_2O	25	275	0.0238
Poly(vinylidene chloride) (Saran)	N_2	30	0.00094	
	O_2	30	0.0053	
	CO_2	30	0.03	
	H_2O	25	0.50	

Source: Yasuda and Stannett (1989).

[a] Units used are as follows: *P* in [cm^3 (STP) cm cm^{-2} s^{-1} $(cm\ Hg)^{-1}$] and *D* in [cm^2 s^{-1}]

[b] Relative humidity 0% [c] Relative humidity 90% [d] Relative humidity 94%

gaseous exchange, the respiring fresh fruit would eventually produce unacceptable levels of oxygen or carbon dioxide in the surrounding environment. The quality of fresh fruit, and even cut fruit, can now be maintained in refrigerated, modified atmosphere packages for 2-5 times longer than unwrapped products. Oranges and apples have long had wax applied to reduce the loss of moisture and thereby lengthen storage life. The latest moisture reducing materials include newly developed edible films, coatings which reduce moisture loss and are edible, thus eliminating the need for disposal. Edible films are being developed to uniquely match the product's respiration rate to its market requirements.

Moisture in the air affects the food's physical properties and determines the potential for the air to be used in drying operations. Humid air properties are known as the psychometric properties of the air. Psychrometric properties are important in food storage, drying, and adsorption as well as human comfort. Moisture properties are of great economic importance to the food industry. Air with low relative humidity has a greater tendency to withdraw moisture from food materials. Foods in high humidity air will have less tendency to lose moisture to the air. Extremely high humidity, however, can lead to condensation and mold growth. Fruits are solar dried in areas with abundant sunshine and low humidity. At higher humidities, drying occurs at a slower rate. Crop and food dryer design and operation must account for input air temperature and humidity. Operating efficiency, time, and cost depend on the air's moisture and energy content. Air psychometrics will be explained further in the chapter on psychrometrics.

Human comfort is affected primarily by the air temperature but humidity is also a factor. Relative humidities of 30% to 50% are ideal for workers while humidities over 70% add to the discomfort at temperatures above 30°C. To improve comfort in hot weather, air can be cooled with refrigerated air or by evaporative cooling, a low-cost process that lowers temperature but raises humidity.

2.6 Solid-Fluid Behavior

2.6.1 Introduction

Materials exist in either a solid, liquid, or gaseous state. An additional word, ***fluid***, is used to include both gases and liquids, although most fluids involved in food processing are liquids. Food materials, as we know them, commonly exist as some intermediate state, mixture, or composite with gas contained within either the solid or fluid. The usual approach taken by food scientists is to consider foods as one of the two extremes, either solid or liquid, and modify previously developed theories to explain the behavior of one of these two ideal-state materials. Solid-fluid behavior is utilized in food engineering in some of the following:

- design of pumps, mixers, extruders, and piping systems,
- design of instruments and sensors for use in process control,
- determining force to cut or shear, or energy to mill or grind,
- determining strength to withstand puncture, cracking, or failure forces,
- defining tenderness of meat products for quality control, and
- correlating texture measurement with sensory information.

Liquids are defined as materials that flow to take the shape of the container. They commonly are pumped or flow due to gravity. The physical property describing the flowability of a liquid is its viscosity. Ideal fluid flow behavior is Newtonian, i.e., shear stress is proportional to shear rate. "Thicker" fluids have higher viscosity. As viscosity is increased there is a tendency for the flow behavior to become less ideal as it is affected by other parameters. This is described as non-Newtonian flow where shear stress changes with shear rate according to some non-linear relationship. Fluid-like behavior is most often utilized during manufacturing of continuous flow processing. Thus plant engineers and processing operations personnel use fluid properties of foods, usually in bulk or large volumes. Fluid flow characteristics are further discussed in the next section.

Solid-like materials tend to maintain their shape with relatively minor changes so they are recognized as such at later times and after undergoing external loads or stresses. The stress-strain relationship of ideal solids is represented by elasticity theory and described by its elastic modulus. The theory has been extensively developed to explain elastic behavior of non-biological materials, which food engineers can use as a starting point in describing food response to mechanical loads. Non-elastic behavior of solids is exhibited by non-linear stress vs. strain associated with large deformations or variations with time. Solid-like material considerations are often more important to quality control personnel in food plants and then to the consumer. They usually are concerned with individual, sometimes small, pieces of food. Solid-like behavior of foods will be considered further in the texture chapter. **Rheology** is the study of the deformation and flow of materials, either fluid- or solid-like. Rheology is interrelated to other properties such as viscosity, density, porosity, and moisture content. Rheological and these other physical properties are used to quantify texture of foods.

2.6.2 Newtonian and Non-Newtonian Fluids

Solids and fluids differ greatly in their reaction to shearing. (Since the following paragraphs apply to both liquids and gases, the term *fluid* is used here.) Shearing occurs when a material is held between two parallel plates, one of which is moving with respect to the other as shown in Figure 2.04. Under this condition, a solid will deform only a certain amount depending upon the material. If this amount is exceeded, the solid will permanently deform and may even break. If this limit is not exceeded, the solid will return to its original condition when the shearing force is removed—just as a rubber band contracts upon release from stretching.

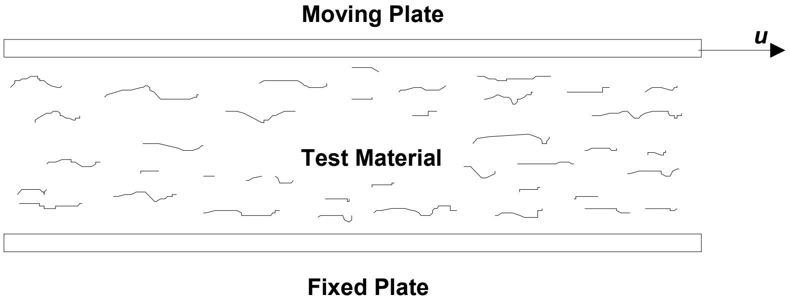


Figure 2.04. Example of shearing.

In contrast to the solid, a fluid deforms continuously with time when exposed to shear. The exact action of fluids under deformation is somewhat complicated; however, certain flow models have been established that describe the actions of the fluid sufficiently for most applications. Before discussing models of interest to us, it is desirable to review certain additional definitions:

Specific weight (w)—Weight of material occupying a unit volume. $w = \rho g$ where g is the gravitation acceleration. Under standard conditions, ρ and w may have the same *numerical* value but different units, i.e., w has units of weight (force) per unit volume ($\mathrm{lb_f/ft^3}$).

Viscosity (μ)—A measure of the resistance of adjacent fluid layers to shearing motion. It has units of $\frac{\text{force} \times \text{time}}{\text{length}^2}$ with common units being $\frac{\mathrm{N\ s}}{\mathrm{m^2}}, \frac{\mathrm{dyne}}{\mathrm{cm^2}}$, and $\frac{\mathrm{lb_f\ s}}{\mathrm{ft^2}}$. Viscosities of both liquids and gases vary significantly with temperature.

Kinematic viscosity $\left(\nu = \frac{\mu}{\rho}\right)$—The form of viscosity commonly used in fluid flow because of the frequent occurrence of the ratio $\frac{\mu}{\rho}$. It commonly has units of $\frac{\mathrm{cm^2}}{\mathrm{s}}$ (stoke), $\frac{\mathrm{m^2}}{\mathrm{s}}$, or $\frac{\mathrm{ft^2}}{\mathrm{s}}$.

Shear rate $\left(\frac{du}{dy}\right)$—Velocity gradient normal to the flow direction, i.e., $\frac{\mathrm{cm/s}}{\mathrm{cm}} = \frac{-}{\mathrm{s}}$ or $\frac{\mathrm{ft/s}}{\mathrm{ft}} = \frac{-}{\mathrm{s}}$. See Figure 2.05.

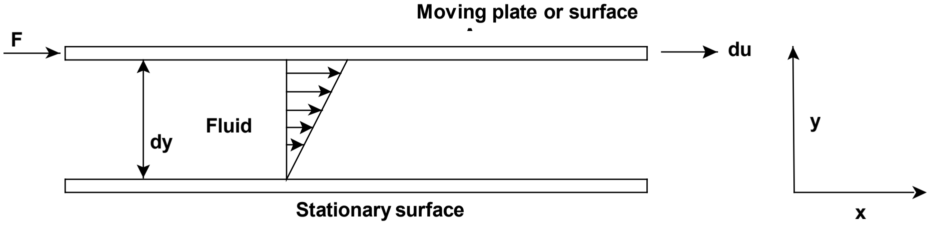


Figure 2.05. Shear rate for a viscous fluid.

Shear stress (τ)—Friction force per unit area on the surfaces restraining the fluid, i.e., $\frac{\mathrm{dynes}}{\mathrm{cm^2}}, \frac{\mathrm{lb_f}}{\mathrm{ft^2}}$, or $\frac{\mathrm{N}}{\mathrm{m^2}}$. For flow through a pipe (or other closed channel), the shear stress is directly related to the pressure gradient in the pipe. The shearing stress on the pipe walls tends to resist flow and must exactly balance the pressure drop in the pipe which tends to cause flow, thus keeping the forces inside the pipe equalized.

Ideal fluid—A fluid model that assumes no viscosity for a fluid and thus no friction effects. It is used widely in aerodynamics for the study of flow over certain body shapes (i.e., aircraft) but it is not suitable for most pipe flow calculations.

Newtonian fluid—Fluids for which the viscosity is not affected by changes in velocity. Water, air, and many other commonly used fluids are Newtonian under almost all conditions.

Non-Newtonian fluids—Fluids for which the viscosity is not constant but changes with velocity and/or pressure gradient. Many food products fall into this category (i.e., applesauce, banana puree, and other materials that contain suspended solids in a liquid).

To examine the relationship between shearing stress (τ), shear rate $\left(\frac{du}{dy}\right)$, and viscosity ($\mu$), we will make use of Figure 2.06. (Remember that you can read shear rate as velocity gradient and shearing stress as friction force per unit area.)

In equation form, viscosity is defined by the equation:

$$\tau = \mu\left(\frac{du}{dy}\right) \tag{2.07}$$

for laminar flow in one direction only. Thus:

$$\mu = \frac{\tau}{\frac{du}{dy}} \tag{2.08}$$

and the viscosity of any fluid under given conditions of τ and $\left(\frac{du}{dy}\right)$ is represented by the slope of a curve on a plot such as Figure 2.06. Thus, a Newtonian fluid produces a straight line going through the origin. Non-Newtonian fluids produce a curved line, or do not go through the origin, or both. It has been found that many of these fluids, including some food products, can be represented by a model where the shear stress is described as:

$$\tau = b\left(\frac{du}{dy}\right)^n + c \tag{2.09}$$

This relationship has been widely used in the study of non-Newtonian fluids. Equation 2.09 is called the "power law" equation. Materials which can be described by this equation are called power law fluids. Several food materials obey the power law equation quite well. Some of these are given in Table 2.02.

Example 2.1

A simple method of measuring viscosity is to record the time required for a given amount of fluid to flow through a tube of a given size. Tube systems designed for this purpose are called viscometers. If a food grade oil requires 225 seconds to flow through a viscometer having a constant of 0.035 cSt/s, determine the kinematic (ν) and dynamic (μ) viscosities of the fluid. (The fluid has a density of 875 kg/m^3.)

Solution:

Solve first for the kinematic viscosity, ν, converting from centistokes to m^2/s.

$$\nu = \left(0.035\,\frac{\text{cSt}}{\text{s}}\right)\times(225\,\text{s}) = (7.875\,\text{cSt}) = (0.07875\,\text{St})\times\frac{1\,\frac{\text{m}^2}{\text{s}}}{10^4\,\text{St}} = \left(7.875\times10^{-6}\,\frac{\text{m}^2}{\text{s}}\right)$$

Then solve for $\mu = \rho\nu$.

$$\mu = \rho\nu = \frac{875\,\frac{\text{kg}}{\text{m}^3}\times7.875\times10^{-6}\,\frac{\text{m}^2}{\text{s}}}{1\,\frac{\text{kg m}}{\text{N s}^2}} = \underline{6.891\times10^{-3}\,\frac{\text{N s}}{\text{m}^2}}\qquad \textbf{ANSWER}$$

Table 2.02. Flow constants for various materials.[a]

Material	Temperature (°C)	b, $\left(\frac{\text{N}}{\text{m}^2}\right)\text{s}^n$	n	c, $\left(\frac{\text{N}}{\text{m}^2}\right)$
Applesauce A	24	0.500	0.645	0
Applesauce B	24	0.660	0.408	0
Banana puree A	24	6.50	0.458	0
Banana puree B	24	10.7	0.333	0
Banana puree C	22	107.3	0.283	0
Honey A	24	5.60	1.00	0
Honey B	24	6.18	1.00	0
Minced fish paste	3 - 6	8.55	0.91	1600
Olive Oil	10	0.138	1.00	0
	70	0.0124	1.00	0
Orange juice	0	1.80	0.68	0.7
Tomato paste		15.0	0.475	36.1

[a] Based on data from Charm (1971) and Steffe (1992).

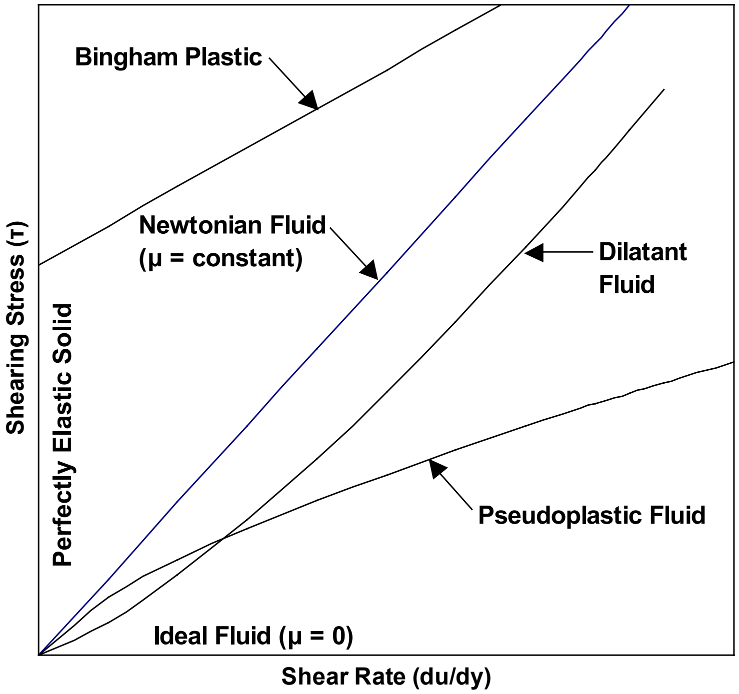


Figure 2.06. Flow characteristics of certain fluids.

2.7 Thermal Properties

Food materials often experience the movement of heat around and through them in various forms and degrees during growth, harvest, handling, processing, transport, storage, and preparation for consumption. Only a few foods such as fresh fruit and some vegetables go from field to the table without any thermal processing. Most foods are thermally processed to extend their shelf life and maintain high quality. Foods are exposed to heat transfer numerous times during heating, cooling, freezing, frying, and/or baking. Thermal operations are also used to insure safe food products for extended periods. A classic example is the pasteurization of milk, a heating process that eliminates bacteria. Pasteurization, followed by proper cooling, provides a safe milk product for weeks. Canned foods, which are good for years, are sterilized with heat processes. Juice, having been heated and aseptically packaged in boxes, is shelf stable without refrigeration for months.

Heat transfer occurs by conduction, convection, and radiation. These mechanisms can occur individually or simultaneously. In food processing, heat transfer is usually a combination of conduction and convection. Conduction is principally involved during heat transfer within solid-like materials, i.e., solids or static liquids. Convection is the transfer between solids (walls of pipes, vats, rooms) and fluids (food materials). In other cases, the food may be the solid and the fluid might be air or water. Radiant heat transfer is less frequently used but is becoming more common in microwave and infrared heating. Having an understanding of the mechanisms of heat transfer allows the food engineer to better design equipment and processes.

The movement of heat to and through a food material depends primarily on the existence of a temperature difference and on physical characteristics such as size, shape, density, and thermal properties. The thermal properties are unique for each food. Each mechanism of heat transfer has an associated thermal property. **Specific heat** (c_p) or heat capacity is the heat required to increase the temperature of one unit of mass by one degree. The subscript (p) is included because specific heat of solids and liquids is determined at constant pressure. In steady state conduction through a solid-like material the important thermal property is **thermal conductivity (k)**. Thermal conductivity is a measure of the ease with which heat flows through a material. Heat is conducted quickly through a metal like copper, hence its thermal conductivity value is high. Heat flows more slowly through materials like wood or fiberglass insulation; their thermal conductivity is low. The thermal conductivity of most food materials is in a relatively narrow range between 0.2 and 0.5 W/m K. Values of specific heat and thermal conductivity for many food materials are published in food engineering textbooks and handbooks (Mohsenin, 1980; Singh and Heldman, 1993; Heldman and Lund, 1992; ASHRAE, 1993; Rao and Rizvi, 1995).

Thermal properties are strongly influenced by a material's water content and to a lesser degree by temperature and pressure. Lacking measured data, thermal properties can be computed from equations using only the material's water content. Siebel's formulas, first proposed over 100 years ago (Siebel, 1892) have been widely used to estimate specific heat values above and below freezing. These formulas, converted to SI units, are:

$$c_P = 3.35X_W + 0.84 \quad \text{(above freezing)} \tag{2.10}$$

$$c_P = 1.26X_W + 0.84 \quad \text{(below freezing)} \tag{2.11}$$

where c_p is specific heat and X_w is the mass ratio of water. These equations assume constant specific heat values of 4.2 and 2.1 kJ/(kg K) for water and ice respectively. Remember, these are only approximations—especially for conditions below freezing, where c_p varies significantly with temperature.

Another relationship for a variety of products above freezing (see figure 2.07) is:

$$c_P = 1.67 + 2.51X_W \tag{2.12}$$

As shown in figure 2.07, this relationship provides an excellent correlation for a variety or products over a wide range of moisture contents.

While water has the greatest effect upon specific heat, other constituents, especially fat content, can also be a factor. Product composition for a variety of products is given in Agriculture Handbook No. 8 (Gebhardt et al., 1982; Haytowitz and Matthews, 1984). Selected values from these publications are shown in Appendix Tables A.6 and A.7. Using these values we can compute c_p using the equation (Heldman and Singh, 1981):

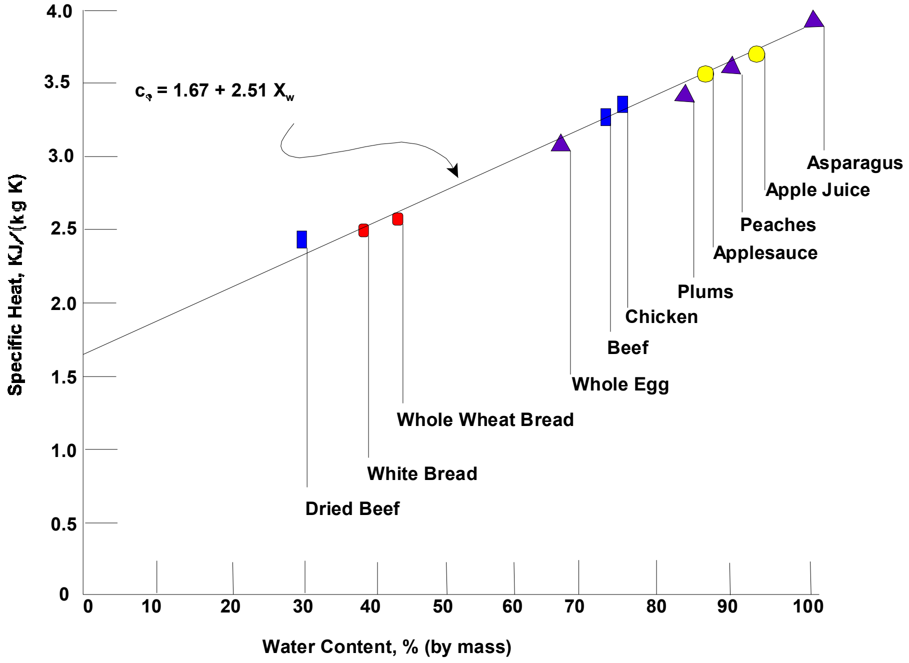


Figure 2.07. Specific heat of food products (at 0° to 20°C for meats, 4° to 32°C all others). Based upon ASHRAE data. (Courtesy of the American Society of Heating, Refrigeration and Air-Conditioning Engineers, 1989.)

$$c_P = 1.42X_c + 1.549X_p + 1.675X_f + 0.837X_a + 4.187X_W \tag{2.13}$$

where X represents the mass fraction of each constituent: carbohydrate (c); protein (p); fat (f); ash (a); and water (w).

Many equations have been proposed for estimating thermal conductivities of food products. Only a few representative equations are shown here. For fruits and vegetables with water content greater than 60%, thermal conductivity can be computed by the equation (Sweat, 1974):

$$k = 0.148 + 0.493X_w \tag{2.14}$$

where: k = thermal conductivity, W/(m K)
X_w = mass fraction of water

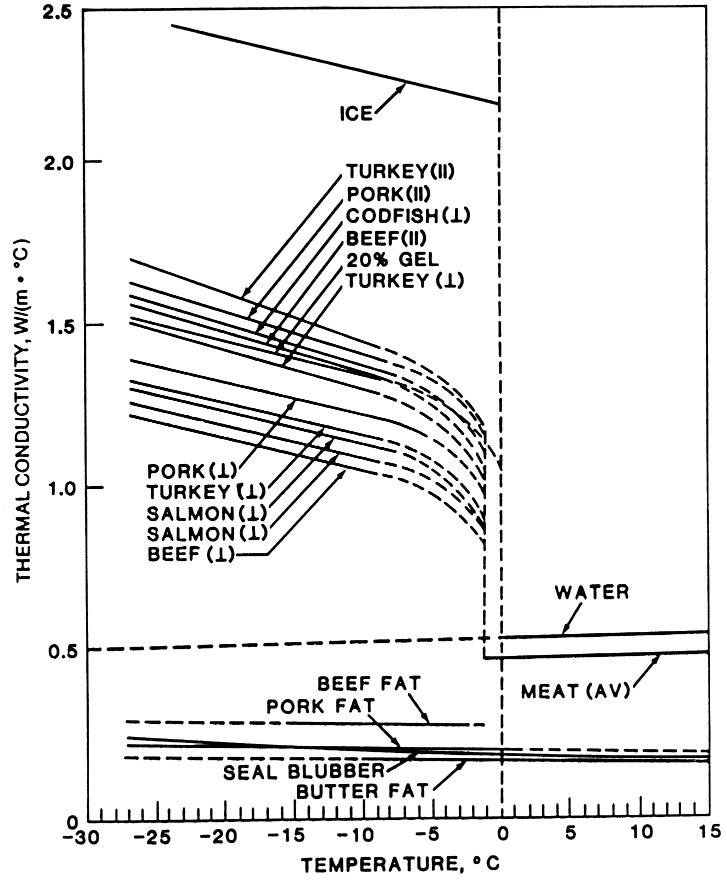
For meat products of 60% to 80% water content, Sweat (1974) suggests:

$$k = 0.08 + 0.52X_w \tag{2.15}$$

An alternate approach is to use an equation based upon the overall food composition to estimate thermal conductivity (Sweat, 1995):

$$k = 0.25X_c + 0.155X_p + 0.16X_f + 0.135X_a + 0.58X_W \tag{2.16}$$

where the parameters of the equations are as defined for equation 2.13.



∥ indicates heat flow parallel to fiber structure
⊥ indicates heat flow perpendicular to fiber structure

Figure 2.08. Effect of freezing upon thermal conductivity of selected products. (Courtesy of the American Society of Heating, Refrigerating and Air-Conditioning Engineers.)

These equations typically predict thermal conductivity to within 15% of measured values. Greater errors commonly occur at low moisture content. Figure 2.08 shows the variation of thermal conductivity with temperature above and below freezing for a variety of products. Note especially the change of thermal conductivity with temperature below 0°C. Only the high fat products, near the bottom of the chart, show little change below 0°C. For other products, thermal conductivity is at least doubled after freezing. A major contributor to this change is the increased thermal conductivity of ice over that of liquid water.

In transient heat transfer, where temperature varies with time and location, the relevant thermal property is thermal diffusivity. **Thermal diffusivity** (α) is a combination of three basic thermal properties, defined as thermal conductivity/(density × specific heat) or $\alpha = k/\rho c_p$. When these three basic properties are known, the diffusivity can be readily computed. Values of thermal diffusivity for food products range from 1×10^{-7} to 2×10^{-7} m^2/s. In the absence of experimental data, Riedel's equation (Riedel, 1969) can be used:

$$\alpha = 0.088 \times 10^{-6} + (\alpha_W - 0.088 \times 10^{-6})X_W \qquad (\alpha \text{ in m}^2\text{/s}) \qquad (2.17)$$

where α is thermal diffusivity, α_w is thermal diffusivity of water, and X_w is mass fraction water.

The use of equations to estimate thermal properties is valuable in the absence if experimental data. Rahman (1995) provides additional data and reference equation for thermal properties.

The thermal property associated with convective heat transfer is the **convective heat transfer coefficient** (h); it also goes by the names *surface heat transfer coefficient*, *local heat transfer coefficient*, or *film coefficient*. Unlike thermal conductivity, which depends only upon the particular material, the convective heat transfer coefficient depends upon fluid velocity, fluid properties, surface characteristics of the solid, and the geometry of each situation. Because the convective heat transfer coefficient is affected by these numerous factors, tables are not available to list values for all foods and situations. The convective heat transfer coefficient varies widely from about 3 W/m^2 °C for still air next to a flat surface to 100,000 W/m^2 °C for steam condensing on a metal pipe. Selecting a proper convective heat transfer coefficient to use in a particular application requires a certain degree of experience.

Heat transfer may involve either sensible energy or latent energy. If the temperature of an object is changed due to the heat transfer, then the heat transfer involves a transfer of sensible heat. The exchange of energy that occurs during a change in phase is called the latent heat. **Latent heat** involves heat exchange without a temperature change. The heat exchange during the phase change from liquid to solid is the **heat of fusion** (h_{sf}) or heat of solidification. Freezing water into ice or the opposite, thawing, is a common example of heat of fusion. The energy to change a liquid to vapor is the latent heat of vaporization. **Latent heat of vaporization** (h_{fg}) is useful in applications involving drying or evaporation where a liquid is vaporized for ease of separation from the mixture. Vaporizing water is commonly done to dry food materials. Drying is a fast method to remove moisture but is more energy intensive than mechanical methods. The heat of vaporization is about seven times more than the heat of fusion, which is five times more than raising the temperature (sensible heating) by 100°C.

Pure water freezes at 0°C, while food products freeze at lower temperatures. This lower freezing temperature phenomenon is called the **freezing point depression**. The freezing point is lowered due to the presence of solutes, solids, in the water. The change in the freezing point temperature is primarily dependent on the concentration or amount of solids. Knowing the exact freezing point temperature is useful in operations involving freezing and thawing. Similarly, the boiling point is elevated by the presence of solute in the liquid phase as found in most foods. The boiling point is useful in evaporation and drying operations. Examples would be the depression of the freezing point for high salt products i.e., processed meats, and the boiling point rise with sugar content in candy making.

Fruit and vegetable products are living organisms. To maintain their life processes, they must consume energy. They do this by a “combustion” process that “burns” sugar to produce CO_2 and heat. The heat produced by this process is commonly called the **heat of respiration (Q_R)**. While small for any single item such as an apple or an ear of sweet corn, the heat of respiration can become a significant source of heat when large quantities of material are present. High respiration rates also cause rapid deterioration in food quality. Heats of respiration vary greatly among products and increase exponentially with temperature. Appendix Table A.8 lists heats of respiration of selected products at different temperatures. The following equations provide approximate values for heats of respiration for sweet corn with husk and apples. They are based upon data from Hardenburg et al. (1986).

$$\text{Log}_{10}\, Q_R = 0.0379\, t + 1.028 \quad \text{(Sweet corn with husk)} \tag{2.18}$$

$$\text{Log}_{10}\, Q_R = 0.0456\, t - 0.047 \quad \text{(Apples)} \tag{2.19}$$

where: Q_R = heat of respiration, kJ/kg day
t = temperature in °C

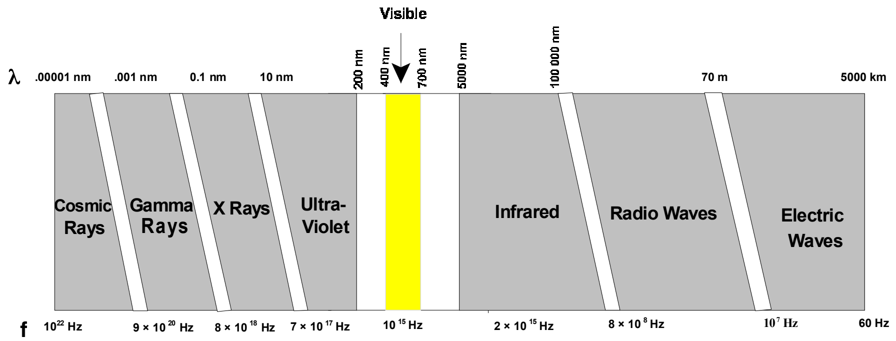
Heats of respiration are also affected by maturity and storage time. Information regarding changes with storage time for a limited number of products is provided by ASHRAE (1998). The data show that heats of respiration can change greatly with storage time. This change may be either an increase or a decrease, depending upon the product and the storage temperature. For example, broccoli stored at 5°C showed a decrease from 217 mW/kg to 98 mW/kg over eight days of storage. Plums, on the other hand, showed an increase from 12 to 27 mW/kg over 18 days of storage at the same temperature. Strawberries stored for 5 days showed a decrease in respiration at 0°C while respiration increased when strawberries were stored at 5°C for 5 days.

These are the primary thermal properties that, together with other physical properties, are involved during thermal processing of food materials. These thermal properties are not constant but vary with moisture content, temperature, and food constituents. Choosing the best value of the thermal property is important to predicting and describing thermal operations.

2.8 Electromagnetic Properties

Electromagnetic radiation encompasses a wide variety of phenomena as represented by the various regions along its broad spectrum (Figure 2.09). Utilizing selective parts of the electromagnetic spectrum is the basis for our modern electrical power distribution system and the many forms of transmitted communication including radar, radio, television, and satellite. Short wavelength energy is used for medical purposes including X-rays and radiography. The intermediate range includes the infrared, visible, and ultraviolet portions of the spectrum. Only a few specialized, narrow regions are utilized in food applications. These include light, infrared, and microwave frequencies.

The interaction of visible light and matter is referred to as color. The color of an object is affected by the surrounding lighting intensity and wavelength. Thus, the color one perceives of an object can be influenced by changing the ambient light. The color of a food material is therefore not only dependent on its own characteristic properties but also is affected by the surrounding light. For this reason optical properties of food materials are considered as they interact with light. The human perception of color is important in marketing most products including foods. Color printing and television advertising regularly use color to deliver their message. The visible portion of the electromagnetic spectrum is that part which lies approximately in the wavelength range of 4 to 8 $\times 10^{-7}$ m. Light energy in this range incident on biological materials is either transmitted, absorbed, or reflected. Most foods are opaque: they do not allow energy to be transmitted through them, thus most energy is absorbed or reflected. Energy is reflected at various wavelengths each representing a different color to the human eye (Table 2.03). Electromagnetic energy in the 622-780 nm range is recognized as red while the 492-577 nm range is green, etc. Color is the basis of optical sensors used in high speed sorting machines to separate and grade raw nuts, fresh fruit, processed vegetables, etc. Optical sensors are extremely fast and allow sorting decisions to be made in less than 0.1 sec. Color sorting machines are able to sense and remove off-color objects to provide a similar colored acceptable product that is clear of foreign matter. The capability of color sorting equipment has improved in the last 30 years with more intense, consistent light sources, narrower wavelength filters, and faster



λ = wavelength f = frequency

$f \times \lambda = c$ (speed of light = 3.00×10^8 m/s)

Figure 2.09. Electromagnetic spectrum.

Table 2.03. Wavelengths and frequencies of colors in the visible spectrum.

Color	Wavelength, nm	Frequency, 10^{14} Hz
Violet	390 - 455	7.69 - 6.59
Blue	455 - 492	6.59 - 6.10
Green	492 - 577	6.10 - 5.20
Yellow	577 - 597	5.20 - 5.03
Orange	597 - 622	5.03 - 4.82
Red	622 - 780	4.82 - 3.84

signal processing components. Machine vision has advanced from the use of non-color, i.e., grey- level, to use of three-component RGB color. The combination of optical sensors, machine vision, high-speed signal processing, and decision making with fuzzy logic provide opportunities for new applications in the food industry.

The electrical properties of biological materials have long been utilized for rapid, non-destructive measurement of moisture content. The moisture in agricultural grains is routinely sampled for making decisions about drying, storing, and marketing. Moisture content can be measured rapidly, with low cost electronic sensors, as food products flow through processing operations. For these reasons, moisture is the primary quality factor used in the agricultural grain trade. Electrical conductance and resistance of water differs significantly from dry matter so that property can be utilized in determining moisture in food materials (Figure 2.10). Knowledge of these properties provides for rapid assessment of current quality and storage potential in a modern marketing system.

Dielectric properties of food materials are utilized in microwave heating. Home microwave ovens became so popular in the 1980s that now most U.S. homes use them for thawing, heating, and cooking food. Home microwave ovens use the 2450 MHZ frequency. Industrial usage of microwave ovens has not been as widespread. Microwave heating results from absorption of electromagnetic waves. Absorption of microwave energy depends primarily on the composition of the material. Water and high moisture foods are excellent absorbers of microwave energy while dry materials and ice are poor absorbers. Microwave heating, therefore, works best to heat unfrozen foods of high moisture. Microwave differs from convection heating where heat must move from the outside inward. Microwave energy can penetrate deeply into the product, although the intensity of this energy decreases with depth. For example, when heating raw potatoes at 2450 MHz, half the total energy is absorbed by the first 0.93 cm of depth (Table 2.04). Despite this depletion of energy, heating occurs rapidly at

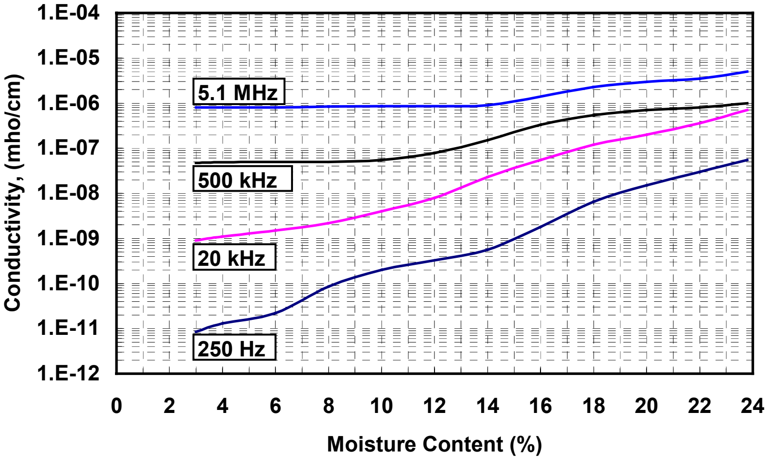


Figure 2.10. Example of the dependence of dielectric properties upon moisture content. Based on data of Nelson and Stetson (1976).

Table 2.04. Dielectric properties of foods and materials at 2450 MHz.[a]

	Dielectric Constant	Loss Factor	Penetration Depth
	$\in'$	$\in''$	d_p (cm)
Water, distilled	77.4	9.2	1.7
Water + 5% NaCl	67.5	71.1	0.25
Ice	3.2	0.003	1162
Potatoes, raw	62.0	16.7	0.93
Banana	61.8	16.7	0.93
Beef, raw	50.8	16.0	0.87
Beef, cooked	32.1	10.6	1.10
Ham	57.4	33.2	0.46
Bread	4.0	2.0	2.00
Glass ceramic	6.0	0.03	160
Paper	3 - 4	0.05 - 0.10	50

[a] Selected data from Buffler (1993).

all locations in a product exposed to microwave energy. This heating may not be uniform throughout due to spatial variation in material properties and in the microwave radiation. The interaction of the food material and the microwave heat source makes it even more important to know the dielectric properties of the food. Table 2.04 lists dielectric properties of selected food products and related materials.

Near infrared properties of foods are utilized in component analysis, particularly moisture, protein, and oil. Laboratory instruments based on near infrared wavelengths of 1 to 10×10^{-7} m are available to determine composition of samples in a few minutes. These instruments are considerably more expensive ($15,000 - $30,000) than dielectric-based moisture meters. As researchers find the unique wavelengths for a particular food constituent, new instruments will be developed for laboratory analysis of off-line samples, lower-cost portable units, and as on-line sensors in production control systems.

High energy radiation, very short wavelengths such as 10^{-11} to 10^{-12} m, can be utilized in sterilization of foods. The exposure of foods to gamma or X-rays has produced products that can be stored for long periods without refrigeration or other processing methods. Irradiated foods are more available in European stores than in the U.S. where irradiated fruit is currently found only at a few locations. Research continues to investigate the safe processing, handling, and consumption of irradiated foods.

Food materials react to and interact with electromagnetic radiation in ways which depend on their unique properties. Having an awareness of their existence and knowledge of these effects provide scientists and engineers with powerful alternatives to process food materials.

2.9 Sources of Physical Properties Data

Physical properties have been identified for various food materials and in many processing applications. The recognition and importance of these properties leads to the need for physical properties data for specific food materials. Physical properties data have been obtained over the years and are currently being collected at an increasing rate with advances in instrumentation and data acquisition. The number of food materials for which physical properties data are determined increases daily, but the number of unknown products is also increasing. New foods are constantly being formulated and raw materials are changing over the years as new varieties are developed and growing conditions change.

When the need arises, how can one obtain physical properties data? Data can be obtained directly from published sources, such as textbooks and handbooks, for certain materials, computed by formula for unknown but similar materials, or measured experimentally. Data listed in tables in published sources must be used with caution. Take note of any limitations or conditions for which the values may or may not apply. Publishers usually do not have sufficient space to give the entire explanation of conditions under which the data were obtained. If the exact food material is not given in a published table, a formula from a food engineering textbook or other source can be used to compute some physical properties, i.e., thermal properties, based on the constituents. These mixture formulae are based on the linear combination of the constituent components. Another approach is to interpolate or extrapolate a “best guess” number from values listed for similar materials. This is often the quickest way for an immediate answer. The best approach seems to be to actually measure the physical property of the exact material in question. This is the most costly and time consuming and may not be the most accurate if measured values are obtained incorrectly. A by-product of making your own measurements is that you develop an appreciation for the technique of determining physical properties and thereby can better use published values. Unless the economics dictates the need for a property value with high accuracy or for a substantially different material, using published values wisely may be the most efficient use of resources.

List of Symbols

a_w	water activity, dimensionless ratio
A	area, m^2
b	coefficient in power law equation. If fluid is Newtonian, $b = \mu$.
c	intercept term for power law equation
c	speed of light, m/s
c_p	specific heat capacity at constant pressure, J/(kg K) or KJ/(kg K)
d_p	penetration depth (microwave energy), cm
D	diameter, m
D	diffusivity, m^2/s
EMC	equilibrium moisture content, decimal or percent
f	frequency, Hz
h	convective (surface) heat transfer coefficient, $W/(m^2 K)$
h_{fg}	$(h_g - h_f)$, latent heat of vaporization, kJ/kg
h_{sf}	$(h_f - h_s)$, latent heat of fusion, kJ/kg
k	thermal conductivity, W/(m K)
P	permeability, cm^3 (STP) cm cm^{-2} s^{-1} $(cm\ Hg)^{-1}$
Q_R	heat of respiration, kJ/kg day
r	radius, m
t	temperature, °C
u	velocity, m/s
w	specific weight , force/unit volume
X	mass ratio (mass fraction) of a specified material
α	thermal diffusivity, m^2/s
$\in'$	dielectric constant
$\in''$	dielectric loss factor
λ	wavelength, m
μ	dynamic (or absolute) viscosity, Pa s or $(N\ s)/m^2$
ρ	density, kg/m^3
τ	shear stress, N/m^2 or Pa
ν	kinematic viscosity (μ/ρ), m^2/s

Subscripts

a	ash
c	carbohydrates
f	fat
p	protein
w	water

Superscript

n	exponent in power law equation

Selections from Wilhelm, Luther R., Dwayne A. Suter, and Gerald H. Brusewitz. 2004. Texture of Food Materials. Chapter 3 in Food & Process Engineering Technology, 53-64. St. Joseph, Michigan: ASAE. © American Society of Agricultural Engineers. (Rev. Aug. 2005.)

Texture of Food Materials

3

Abstract. *This chapter provides a brief coverage of selected food texture parameters. Emphasis is placed upon instrumental measurements.*

Keywords. *Bending, compression, sensory, shear, stress, strain, tension, texture instruments.*

3.1 Introduction to Texture

Texture of food materials plays a key role in consumer acceptance and market value. Texture characteristics are important factors for raw products and for processing, preparation, and consumption. Texture features are also important considerations in quality assurance, including hazard analysis critical control program (HACCP) and food safety issues. Additionally, flavor, juiciness, color, and other appearance characteristics are important factors in food selection and contribute to texture.

Some of the descriptive terms utilized to characterize food properties include toughness vs. tenderness, hard vs. soft, dry vs. moist, brittle vs. elastic, roughness vs. smoothness, crispness vs. sogginess, firmness, stickiness, ripeness, springiness, blandness, flakiness, grittiness, aroma, etc. Many of the methods utilized by food scientists and engineers to classify characteristics of food products represent attempts to develop techniques that will reasonably predict how consumers will perceive the item and, therefore, purchase it.

The two main methods for evaluation of texture characteristics are instrumental and sensory (Bourne, 1982; Rosenthal, 1999). Humans are especially sensitive at identifying differences between two samples, whereas instruments can quickly provide a quantitative measurement on an absolute scale.

3.2 Sensory or Subjective Measurements

Sensory measurements can be classified into two general categories. Consumer acceptance taste tests are frequently conducted in shopping malls, supermarkets, and other areas having large numbers of consumers. The purpose of these tests is to obtain a general profile of consumer acceptance or rejection of the product. Since the consumers are not trained panelists, the results of the tests are essentially qualitative. The information gathered provides consumer reaction, which includes numerous characteristics of which texture is but one factor. The test results are not normally very helpful in identifying methods to improve the product.

The second category of measurements includes those tests conducted by professionals with experience in sensory evaluation techniques. The panelists are trained to detect, with a high degree of replication, specific food characteristics such as tenderness/toughness, flavor, juiciness, brittleness/softness, sponginess, odor, etc. In highly controlled sensory evaluation laboratories, the panelists are periodically blind tested to evaluate scientific standards. A sensory panel commonly consists of 6 to 12 people who can evaluate up to 10 characteristics on a 1 to 10 scale in one session of 1 to 3 hours. There is a wide variation between people in their ability to detect individual food characteristics. Results from the sensory evaluation tests are often correlated with those obtained from instrumental or objective measurement methods as a means to determine the use of the non-sensory tests.

3.3 Instrumental or Objective Measurement Methods

Various instruments have been developed and tested for measuring selected characteristics of raw and manufactured food products. Here we present only a sampling of the instrumental methods. Instrumental measurements are conducted with equipment that provides precise control of all important conditions that may affect the results. In many cases, data gathered from tests conducted with instruments are compared with sensory evaluation results.

3.3.1 Fundamental Concepts and Definitions

Mechanical properties are those characteristics having to do with the change in shape and size of a material when forces are applied (Mohsenin, 1986). Mechanical properties are expressed in terms of force, deformation, and modulus of elasticity. Rheology is the study of deformation and flow of materials having a consistency intermediate between solid and liquid. Examples of rheological properties are time-dependent stress and strain, creep, and stress relaxation.

The terms *mechanical* and *rheological* properties are sometimes used interchangeably in cases involving force vs. deformation or stress vs. strain when time effects are considered.

Mechanical properties of materials have a strong scientific base for which engineers have agreed upon commonly used terms. Some of that terminology is appropriately used in the application to foods. For a more extensive list of terms see a standard strength of materials textbook. Refer to Figure 3.01 for diagrams of the loading types discussed in the following definitions.

Stress (σ) is the applied force per unit area and may be expressed as Newtons per square meter (Pascals), pounds force per square inch, kilograms force per square meter, etc. The force may produce tension, shear, or compression within the sample. Bending involves both tension and compression. Torque involves only shear forces.

Tensile stress is a stress resulting from forces directed away from the sample. Stretching a rubber band produces tensile stress in the band.

Compressive stress is a stress resulting from forces directed at the sample and acting to push on, or compress, it.

Shear stress is the stress that is tangential to the plane on which the forces act tending to change the sample’s shape. Shear stress is produced like a tensile (or compressive) stress but the two pulling (or pushing) forces are offset from each other.

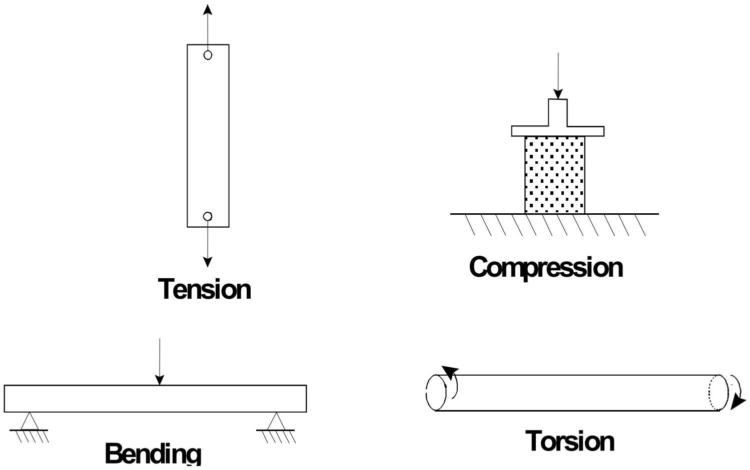


Figure 3.01. Examples of tension, compression, bending, and torsion loading.

Torsional stress is that shear stress exerted on the sample resulting from a twisting action.

Strain (ϵ) is the change, due to the applied force, in the size or shape of a body referred to its original size or shape. Strain is a dimensionless quantity, but it is frequently expressed in meters per meter, inches per inch, or percent. Strain in most objects is relatively small, but strain in a rubber band can be quite large.

Modulus of elasticity (E) is calculated as the ratio of the stress to the corresponding strain in the linear portion of the stress vs. strain or force vs. deformation curve (Figure 3.02). In cases where the stress vs. strain relation is not linear (the case with many biological materials), various apparent moduli are computed for use in select conditions.

Poisson's ratio is the ratio of transverse strain to the corresponding axial strain. It provides a measure of the change in length vs. change in width of the sample during loading.

Tensile strength is the maximum stress a material is capable of sustaining without failure. The tensional strength is calculated utilizing the maximum load during a tension test and is based on the sample's original cross-sectional area.

Bioyield point is the first stress in a material, less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress. The bioyield point is typically identified by a dip in the stress-strain curve as shown in Figure 3.02. Materials exhibiting a bioyield point commonly are composites made of more than one uniform homogeneous substance. This is common in whole fruit and vegetables having a stronger outer layer.

Plasticity is the capacity of a material to take permanent, nonrecoverable deformation.

Viscoelasticity describes the combined solid-like and liquid-like behavior in which the stress-strain relationship is time dependent. Analysis of viscoelastic materials is very complex and will not be considered here.

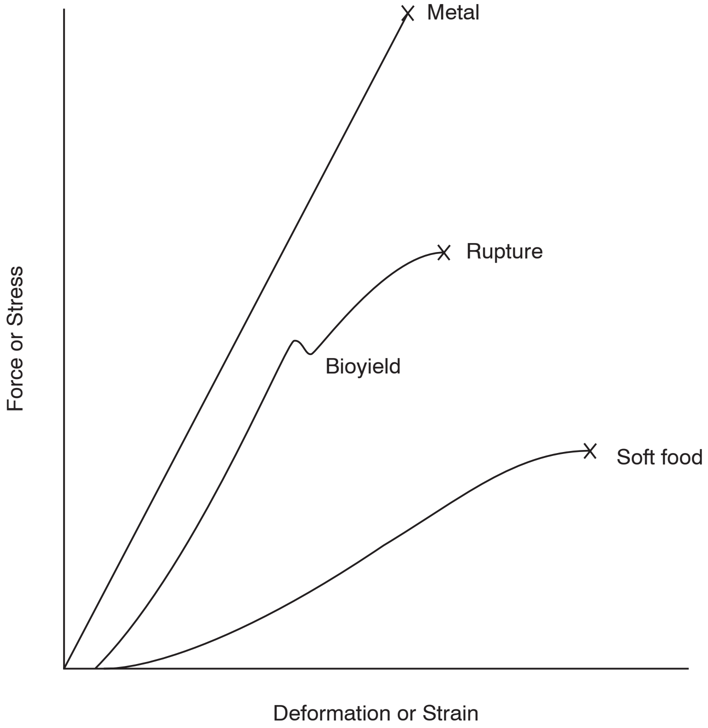


Figure 3.02. Stress-strain relationships for metal, curvilinear, and bioyield materials.

3.3.2 Stress-Strain Behavior

Mechanical properties of agricultural and food products can be measured by uniaxial compression, uniaxial tension, shear, and bending. Various instruments used in these tests will be illustrated and discussed. The type of loading, preparation of the specimen, loading rate, strain (deformation) rate, and other factors are dependent upon the material and desired use of the data. The value of the modulus of elasticity is usually calculated and utilized for comparison with known and desired properties.

3.3.2.1 Uniaxial Compression

One of the very important requirements for uniaxial compression tests of biological materials is that of applying a true axial load in a manner to ensure that the force is applied uniformly over the cross section of the specimen. Specimens having large length-to-diameter ratios, i.e., slender specimens, will buckle or bend when sufficiently loaded, rather than compress axially. This buckling condition occurs before and instead of uniaxial compression. To prevent buckling and insure uniaxial compression, specimen length should be less than five times the diameter, or equivalent if noncircular in cross-section. The length-to-diameter ratio of the specimen must be selected to prevent buckling during loading. A special device is frequently utilized to cut a cylindrical core sample from the material being tested. The device minimizes irregularities in the specimen and permits proper preparation of the ends, which will come in contact with the loading and support plates. The diameter of the cored specimen is measured prior to loading and recorded for later computations of stress and strain.

One of the major properties calculated is the modulus of elasticity (E) according to the following formula:

$$E = \frac{F / A}{\Delta L / L} \tag{3.01}$$

where: F = force in Newton, N
A = cross-sectional area of the specimen, m^2
ΔL = change in length due to application of the force F, m
L = initial length of the specimen, m

Example 3.1

Compute the modulus of elasticity when a 50 mm long by 20 mm (0.020 m) diameter sample compresses 0.50 mm upon loading by a 20 N force.

Solution:

The modulus of elasticity (E) is defined as stress/strain. Thus:

$$\text{Stress} = \text{Force / area} = 20\ \text{N}/[3.14\times(0.020)^2/4)\ \text{m}^2 = 0.06366 \times 10^6\ \text{N/m}^2$$

$$\text{Strain} = \Delta L/L = 0.50\ \text{mm}/50\ \text{mm} = 0.01$$

$$E = \frac{\text{stress}}{\text{strain}} = \frac{0.06366\times10^6\ (\text{N/m}^2)}{0.01} = 6.366\times10^6\ \frac{\text{N}}{\text{m}^2} = \underline{6366\ \text{kPa}} \quad \textbf{ANSWER}$$

Selections from Wilhelm, Luther R., Dwayne A. Suter, and Gerald H. Brusewitz. 2004. Thermal Processing. Chapter 7 in Food & Process Engineering Technology, 163-192. St. Joseph, Michigan: ASAE. © American Society of Agricultural Engineers. (Rev. Aug. 2005.)

Thermal Processing

7

Abstract. *This unit introduces the concepts relative to thermal processing. The concept of thermal death of microorganisms is presented. Procedures for determining adequacy of thermal death at constant temperature and for changing temperatures are discussed. Additional topics include heat penetration analyses for retort processing and the relationship between experimental and theoretical heat penetration data.*

Keywords. *Aseptic processing, heat penetration curves, microorganisms, retorts, sterilization, thermal death.*

7.1 Introduction

Food spoilage has been a serious problem since food was first collected for preservation. The lack of a good quality food supply contributed significantly to human diseases, many of them nutritional in origin. Eventually, primitive societies learned a form of preservation—drying and salting of fish, meat, and other products. Other preservation methods including cooking and fermentation also developed over time. The modern era of food preservation began in 1810 when Nicholas Appert, of France, invented the art of canning. He heat-treated perishable food in glass jars and bottles, thus making one of the most important advances in the history of food processing. Shortly thereafter, two Englishmen, Donkin and Hall, began to can food using tin plate instead of glass. By 1839, American canneries had adopted this English practice.

We now know that food products contain many microorganisms that can cause spoilage of food, and illness and death. For our health, and to store food for extended periods, some type of food preservation is necessary. The most practical method of preservation for many foods is the thermal processing (sterilization) technique developed by Appert. This processing typically involves sealing the food inside a container and placing that container into a retort for a specified time period. **Retorts** are containers that can be sealed and filled with steam under pressure. (For some special applications, water, or a mixture of steam and air, may be used.) The high temperature condensing steam provides the heat energy needed for sterilization. The canner traditionally used for canning foods in the home is a small-scale retort. Aseptic processing, a different sterilization method, is discussed later in this chapter. For additional thermal processing information, consult Stumbo (1965), Larousse and Brown (1997), and similar publications.

Modern food processing utilizes knowledge about microorganisms and biochemical reactions to enhance food products. The use of heat allows the food industry to create safe, lasting, and enjoyable foodstuffs. This unit emphasizes the heat transfer aspects of thermal processing; however, a brief coverage of microbiology is needed to understand the sterilization process.

7.2 Microorganisms

The food industry is quite familiar with microorganisms, for they play a large role in the production of food products such as cheese, alcoholic beverages, and yogurt. However helpful a few of these organisms may be, others are troublesome because their metabolic activities result in the spoilage of foodstuffs.

Microorganisms are subdivided into many classes. **Yeasts** and **molds,** which are types of **fungi,** and **bacteria** pose the greatest spoilage threats to food. The category of bacteria is further broken down into three types based upon the oxygen requirements of the organisms:

1. **Obligate aerobes**. Obligate aerobes are those that require the presence of molecular oxygen to grow and to survive.
2. **Facultative anaerobes**. Facultative anaerobes are the group of bacteria that normally grow best in the presence of oxygen but can also survive in its absence.
3. **Obligate anaerobes**. Obligate anaerobes are the group of bacteria that live in the absence of oxygen.

The capability of bacteria to survive without oxygen is a key factor in food spoilage, especially of canned foods. Canned foods have very low levels of molecular oxygen, thus making facultative and obligate anaerobes the likely culprits of food spoilage. Bacteria pose another dilemma to the food processing industry in that some of these organisms produce spores that are resistant to heat treatment. Spores are the result of reproduction and remain dormant until favorable conditions arise for growth.

Fungi also produce spores. Both yeasts (which are unicellular fungi) and molds are important spoilage agents in foods with a high acidity level and low water activity. However, the survival of bacteria, especially in low acid foods, is usually the greatest concern in food processing.

Microorganisms are also classified according to the temperature ranges in which they optimally grow (Figure 7.01). Bacteria possess an amazing ability for adaptation as demonstrated by their ability to thrive in hostile environments from the arctic tundra to the great depths of the oceans. The three main temperature categories of microorganisms are psychrophilic, mesophilic, and thermophilic. **Psychrophilic microorganisms** grow in temperature ranges of –10° to 10°C (14° to 50°F). These organisms are responsible for spoilage of food in refrigerators. **Mesophilic microorganisms** optimally grow within the temperature range of 10° to 40°C (50° to 104°F). The majority of microorganisms fall into this category. The final category of temperature classifications is the thermophilic microorganisms. **Thermophilic microorganisms** survive and often thrive at high temperatures ranging from 40° to 80°C (104° to 176°F). The food industry is quite concerned with these microorganisms because of their ability to survive at high temperatures. Proper thermal processing is necessary to ensure the destruction of thermophilic microorganisms and spores.

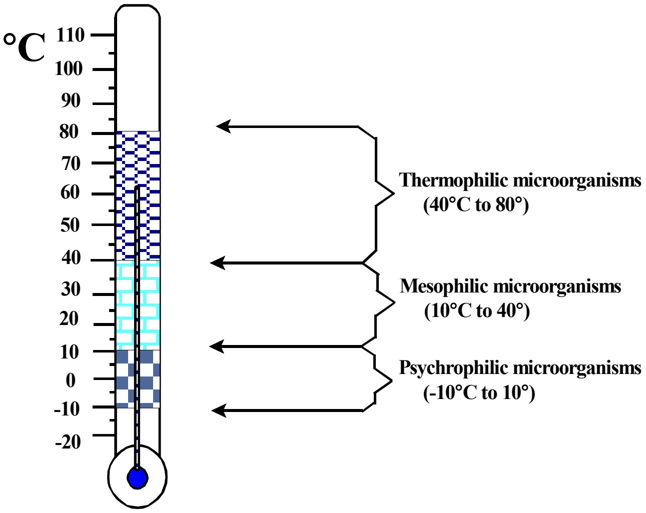


Figure 7.01. Optimum temperature range for microorganisms.

Many different spoilage organisms exist in our environment. A few of the major spoilage organisms are:

- *Clostridium botulinum*: *C. botulinum*, a food spoilage organism whose toxin is labeled the deadliest in the world, is responsible for botulism food poisoning. This organism normally exists in soil and water as non-harmful vegetative cells; however, in the absence of air, it becomes deadly. In only a few days, with suitable conditions, *C. botulinum* can produce the toxin. It is found mainly in canned and bottled products that have received an inadequate heat process.
- *Salmonella* spp.: *Salmonella* is an organism that is commonly associated with seafood, poultry, and uncooked eggs. Great care is taken in the food industry to place strict standards on the testing of foods for this organism.
- *Shigella* spp.: *Shigella* is often found with water and fresh fruit and vegetables that have been exposed to fecal contamination.
- Enteropathogenic *Escherichia coli*: *E. coli* is one of the most widely known bacterial species. Many strains of *E. coli* exist. The species resides in the intestines of animals. The food industry is primarily concerned with the contamination of ground beef and other undercooked or raw foods (FAO, 1976). Such contamination has received considerable media attention in recent years, with the evolution of strains that can cause serious illness and death.

7.3 Thermal Processing

Thermal processing uses heat to produce desired changes in food. These changes may include improved food quality and additional ease in further processing; however, the primary desired result is food preservation. Microorganisms pose the greatest threat in the spoilage of food products. To ensure safe food, we must know the appropriate temperature and duration of heating to achieve sterilization. For simplicity, the word organism (or microorganism) will be used to represent both vegetative cells and spores in the remainder of this discussion.

Microorganisms are resistant to heat for a number of reasons. The three most important variables contributing to the heat resistance of microorganisms are the type of microorganism, the incubation conditions in which the microorganisms are growing, and the conditions that are present during heat treatment. Just as microorganisms vary in size and shape, they differ in their ability to resist heat, even among different strains of the same species. Spores have a greater level of resistance than their parents, making spores the most difficult form of microorganism to destroy. The conditions in which the microorganisms and spores have grown are a second determining factor in thermal processing. An incubation condition in which spores are formed at high temperatures enables the organism to better resist processing at high temperatures. Additionally, the age of the microorganisms and the medium in which they are present affect their heat resistance. These characteristics are not unique to microorganisms. Animals exhibit similar responses to thermal stress.

The condition of the food in which the microorganisms and spores are present has a major effect upon their heat resistance. The pH of the medium is an important indicator of the resistance of spoilage bacteria, yeasts, and fungi. Bacteria prefer an acidity level near neutral while yeasts and fungi are more resistant to heat at mildly acidic conditions. Spores are more resistant to moist heat than to dry heat while bacteria prefer the opposite. Also, microorganisms have a greater heat resistance in foods high in fats, proteins, and sucrose.

7.3.1 Sterilization

The purpose of sterilization is to insure that spoilage organisms are inactivated and that pathogenic microorganisms and spores are destroyed. The spores of *C. botulinum* are quite resistant to heat processing and, therefore, are a common target of the sterilization process. Some nonpathogenic spoilage microorganisms have a heat resistance higher than *C. botulinum*, thus preventing a food product from achieving complete sterility. A completely sterile food item would have no surviving microorganisms or spores remaining after thermal processing. Complete sterilization is not practical, however, because sterilization time increases greatly as the number of organisms approaches zero. Thus, sterilization, as used here, is actually commercial sterilization—a degree of sterilization that is sufficient to achieve an acceptable reduction in microorganisms.

The degree of sterilization is measured by the **sterilization value** (*SV*). A sterilization value of 12*D* means a 12 decimal reduction in the number of spores of a specific strain of microorganism present. For example, assume a process designed to reduce the number of spores of a specific microorganism by 6 decimal reductions (6*D*) is applied to pears containing 10^2 of these spores per container. Thermal processing would reduce the number of spores of this microorganism in the pears to 10^{-4} spores per container, which is the equivalent of one spore per 10,000 containers. A sterilization value of 12*D* reduces the number of the specified microorganism to 10^{-10} organisms per container with the likelihood of a surviving microorganism reduced to one in 10^{10} containers. The value of 12*D*, based on the destruction of *Clostridium botulinum*, has been a long-time industry standard.

Example 7.1

A food process engineer is using thermal processing to sterilize a can of green beans. The engineer feels that sterilization will be achieved once 99.9999% of the *C. Botulinum* organisms are inactivated. What is the sterilization value of this process?

Solution:

The percentage of organisms remaining after processing is:

$$100\% - 99.9999\% = 0.0001\%$$

The ratio of initial organisms to final organisms is:

$$100\% \,/\, 0.0001\% = 1{,}000{,}000$$

The number of decimal reductions is then:

$$\log 1{,}000{,}000 = 6$$

The sterilization value of the process is <u>6*D*</u>. **ANSWER**

7.3.2 Thermal Death Calculations

Knowledge about microorganisms and their relationship with various foodstuffs gives us the ability to calculate the processing times required to achieve a commercially sterile product. To examine this concept, we will first look at an idealized constant-temperature sterilization process. At constant temperature, the death rate of spores for a specific organism is a function of heating time. Figure 7.02 is a typical graph of such a death rate. This graph shows the typical logarithmic death curve—a straight line on a semi-logarithmic plot. This straight line relationship results from the fact that the rate of decrease in viable organisms is proportional to the number of organisms present. This can be represented as shown in Equation 7.01 where k is simply a constant for a particular organism, and N is the number of organisms at any time θ:

$$\frac{dN}{d\theta} = -kN \tag{7.01}$$

We can find the total change in N over any time period, θ, by rearranging (separating the variables) and integrating (note that at $\theta = 0$, $N = N_0$ and at any other time, θ, $N = N$):

$$\int_{N_0}^{N} \frac{dN}{N} = -k\int_{0}^{\theta} d\theta$$

The result of this integration is:

$$\ln\frac{N}{N_0} = -k_1\theta \tag{7.02}$$

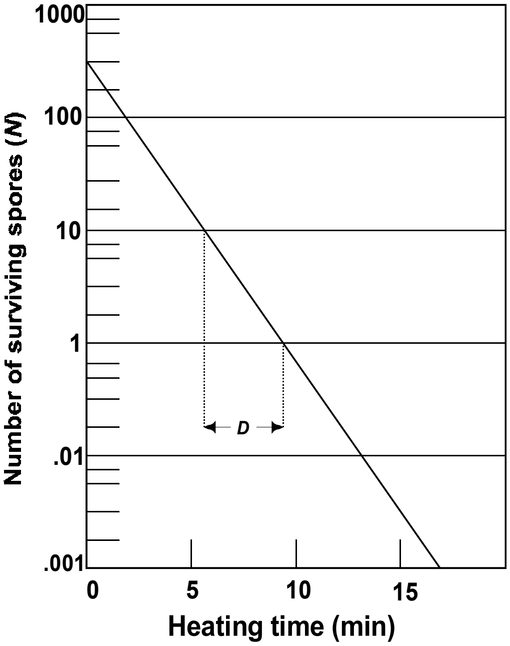
To express the relationship of Equation 7.02 on a semi logarithmic chart such as Figure 7.02, we must first convert from natural logarithms to common (base 10) logarithms. This is easily done by noting that:

$$\ln x = 2.3026 \log x$$

Thus:

$$\ln\frac{N}{N_0} = 2.3026 \log\frac{N}{N_0} - k_1\theta \quad \text{or} \quad \log\frac{N}{N_0} = -\frac{k_1}{2.3026}\theta = k_2\theta$$

where $k_2 = k_1/2.3026$.



7.02. Death rate curve at constant temperature.

Thus, we see that Equation 7.02 represents the straight line of Figure 7.02. Remember that *D* represents the heating time required for one log reduction in the number of microorganisms. Note also that one log cycle reduction represents a 90% decrease (100 to 10, 10 to 1, 1 to 0.1, etc.). Thus, a 2*D* reduction is a 99% reduction; a 3*D* reduction is a 99.9% reduction, etc.

We now look at the effect of both time and temperature upon sterilization. To do this, we will define a relationship between the time and the temperature required to achieve sterilization. We first define F_0 as the time required at a reference temperature of 121.1°C (250°F) to achieve a desired sterilization value. However, we also need a method to calculate the time required for the desired sterilization at other temperatures. If we select a specific sterilization value (e.g., 12*D*) as that needed for thermal death of a particular organism, we can then graph the time required for thermal death as a function of temperature. Figure 7.03 shows such a graph for a hypothetical organism. We will develop the equation for this straight line in the following paragraphs. This development helps provide a review of algebra, and the use of logarithms in equations.

We begin with the general equation for a straight line: $y = mx + b$. The Y axis is logarithmic, thus $Y = \log\,\theta$. The slope m is $\Delta y/\Delta x$, and, for any full cycle, $\Delta y = -\log 10 = -1$. The corresponding value of Δx is the change in temperature corresponding to one full log cycle. We will define this value as z. Substituting into the straight line equation, we have:

$$\log\theta = -\frac{\log 10}{z}\times t + b = -\frac{1}{z}\times t + b = -\frac{t}{z} + b \qquad (7.03)$$

We now know that the slope of this line is $-1/z$. This slope and an intercept (coordinates of any point on the line) fully define the straight line. The point selected is the location where the line crosses the 121.1°C (250°F) temperature line. The value of time (θ) at this temperature of 121.1°C is defined as F_0. Substituting into Equation 7.03 and solving for b:

$$\log F_0 = -\frac{121.1}{z} + b$$

$$b = \log F_0 + \frac{121.1}{z} \qquad (7.04)$$

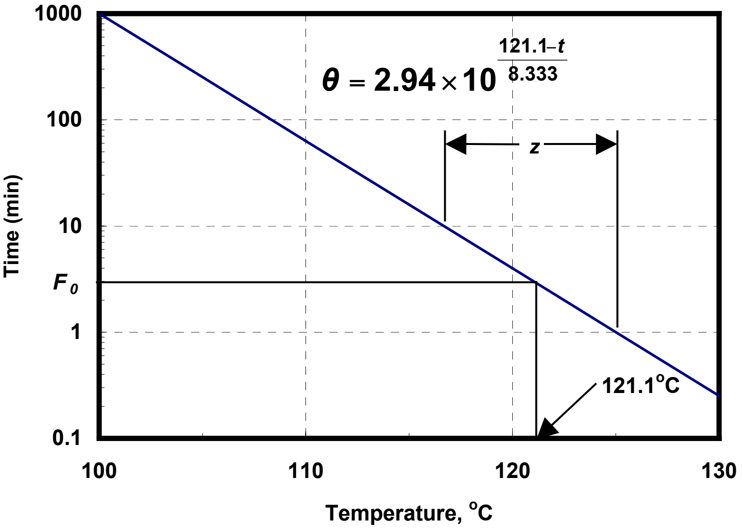


Figure 7.03. Plot of thermal death time for hypothetical organism XZYZX.

Substituting for b in Equation 7.03, we obtain:

$$\log\theta = -\frac{t}{z} + \log F_0 + \frac{121.1}{z}$$

Combining terms, we obtain the common form of the equation relating θ and F_0:

$$\log\frac{\theta}{F_0} = \frac{121.1 - t}{z} \qquad (t \text{ in °C}) \qquad (7.05)$$

or, converting to exponential form:

$$\frac{\theta}{F_0} = 10^{\frac{121.1-t}{z}} \qquad (t \text{ in°C}) \qquad (7.06)$$

For Figure 7.03, F_0 is 2.94 minutes, corresponding to the thermal death time at 121.1°C. The thermal death line traverses one full log cycle in a temperature increment of 8.333°. Thus, $z = 8.333°$.

If we know F_0 and z for any microorganism in a food product (see Table 7.01 for typical examples), we can compute the thermal death time, for that organism and food product, at any temperature. Recall that the sterilization value (SV) of a process (i.e., 12D or 18D) is defined as the number of decimal reductions in the spores. Using this information, and noting that D represents one decimal reduction, we can relate F_0 and D, for any given temperature by:

$$F_0\,(\text{min}) = D\left(\frac{\text{min}}{\text{cycle}}\right) \times SV\,(\text{cycles}) \qquad \text{or} \qquad SV = \frac{F_0}{D} \qquad (7.07)$$

Example 7.2

A can of chicken noodle soup was processed at a constant soup temperature until a 99.999% reduction in *C. botulinum* was obtained. *C. botulinum* has a D value of 0.6 min for conditions of this process. How long must the soup be held at this constant temperature to achieve the result?

The same can of soup also originally contained 10 spores of a second spoilage organism with a D value of 2.1 minutes. What percent of this second spoilage organism remains in the can?

Solution:

The D value for a 99.999% reduction can be calculated. The reduction ratio is:

$$\frac{100\%}{(100-99.999)}=\frac{100}{0.001}=10^{5}$$

Thus, the sterilization value of the process is 5D. The time required to destroy 99.999% of *C. botulinum* can now be calculated. This is the total time of the process.

$$SV_{C.bot.}=\frac{F}{D_{C.bot.}}=5 \quad \text{or} \quad \frac{F}{0.6}=5 \quad \text{and} \quad F=\underline{3\text{ minutes}}$$ **ANSWER**

This time is then used to determine the sterilization value of the second spoilage organism.

$$SV_{new}=\frac{3\text{ min}}{D_{new}}=\frac{3\text{ min}}{2.1\text{ min}}=1.429$$

Thus, we only have a 1.429 reduction in the second spoilage organism, and the percent remaining is:

$$\text{Percent remaining}=\frac{1}{10^{1.429}}=0.037\times 100\%=\underline{3.7\%}$$ **ANSWER**

Example 7.3

A manufacturer of canned corn desires to reduce the sterilization time by raising the corn temperature to 135°C. Previously, the cans of corn had been processed at a corn temperature of 121°C. Assume F_0 = 2.5 minutes and z = 10°C. Determine F_{135}.

Solution:
Use Equation 7.05:

$$\log\left(\frac{\theta_{135}}{F_0}\right)=\log\theta_{135}-\log F_0=\frac{121.1-135}{10}=-1.4$$

$$\log\theta_{135}=\log 2.5-1.4=0.3979-1.4=1.0021$$

$$\theta_{135}=\frac{1}{10^{1.0021}}=0.09953=\underline{0.10\text{ minutes}}$$ **ANSWER**

The constant temperature exposure time required for equivalent thermal death is substantially reduced (from 2.5 minutes at 121°C. to 0.1 minutes at 135°C). Note that both Example 7.2 and 7.3 assume a constant temperature of the processed material. Actual product temperatures vary with time, and this must be taken into account.

Table 7.01. Thermal processing data for selected microorganisms.

Microorganism	Z value(°C)	D_{121} value (min)	Typical foods
Thermophilic (35° to 55°C)			
Bacillus stearothermophilus	10	4.0	Vegetables, milk
Clostridium thermosaccharolyticum	7.2-10	3.0-4.0	Vegetables
Mesophilic (10° to 40°C)			
Clostridium sporogenes	8.88-11.1	0.8-1.5	Meats
Bacillus subtilis	4.1-7.2	0.5-0.76	Milk products
C. botulinum toxins A and B	5.5	0.1-1.3	Low-acid foods
Psychrophilic (–5° to 1.5°C)			
C. botulinum toxin E	10	3.0 (60°C)	Low-acid foods

From Fellows (1988).

7.3.3 Sterilization Equipment (Retorts)

The information presented in the previous section is based upon constant temperature sterilization. In actual processing operations, temperatures change with time. It is not possible, for example, to immediately change the temperature of an entire can of corn from 30°C to 70°C. Instead, the can must be heated from the outside, with the contents near the center being the last to reach the desired temperature. Since bacteria live longest at the lowest temperature in a container, we will always be interested in the "cold spot" during thermal processing. In the absence of convective circulation of liquids, the cold spot is the geometric center of the can. If circulation is present, the cold spot will be a function of can orientation. For vertical cans, it should be along the center axis of the can, but below the geometric center.

The physical device used to achieve this sterilization process is commonly called a **retort**. Since retorts play such an important role in the processing of foods, we will examine some commonly used types of retorts.

7.3.3.1 Still Vertical and Horizontal Steam Retorts

These retorts are cylindrical vessels positioned in either a vertical or horizontal orientation. They operate in a batch mode. While retort designs differ, the common feature is a chamber that can be filled, sealed, pressurized with steam for the desired time, depressurized, and emptied. These batch systems can be adapted for different products and container sizes by adjusting the steam pressure and/or holding time.

With older (and still widely used) retort models, prefilled cans are placed into crates or baskets that are then placed into the retort. In **vertical retorts** (Figure 7.04), the crates are raised and lowered by a hoist. In **horizontal retorts** (Figure 7.05) the crates are placed on a wheeled carrier that rolls on metal tracks into the retort. These systems are very labor intensive since the crates are filled, placed into the retort, removed from the retort, and emptied—all operations requiring human labor.

Selections from Wilhelm, Luther R., Dwayne A. Suter, and Gerald H. Brusewitz. 2004. Refrigeration. Chapter 8 in Food & Process Engineering Technology, 193-212. St. Joseph, Michigan: ASAE. © American Society of Agricultural Engineers. (Rev. Aug. 2005.)

Refrigeration Systems

8

Abstract. *This chapter provides a brief coverage of refrigerants and vapor compression refrigeration systems. Refrigeration loads and freezing/thawing times are also reviewed.*

Keywords. *Coefficient of performance, cooling, freezing, refrigerants, refrigeration cycles, refrigeration systems.*

8.1 Introduction

The Romans used ice for cooling over 2000 years ago. Collecting ice and storing it in insulated buildings for later use was a common method of cooling for centuries. Commercial ice production became widespread in the United States in the late 1800's. By 1900 commercial production and sale of ice for use in home iceboxes was common. In some households, "kerosene refrigerators" soon replaced the iceboxes. The availability of electricity and "electric refrigerators" made home refrigeration available to almost everyone in the United States by the mid-1900's.

The cooling methods noted above make use of latent heat to accomplish the cooling. The latent heat of fusion for ice (heat required to melt it) provided the cooling effect for the icebox. For every kilogram of ice melted, approximately 335 kJ of heat is removed. (Actually somewhat more cooling is obtained because the actual initial ice temperature is almost certainly below 0°C.) Now, imagine that the ice is replaced by a container of liquid Refrigerant 134a (R-134a). At atmospheric pressure, R-134a boils at –26.1°C (Table 8.01). Thus it will immediately begin to boil, removing 216.8 kJ of energy for each kilogram of refrigerant evaporated. This is an effective cooling method, but the loss of evaporating refrigerant is a potential pollution problem. In addition, the cost of refrigerant for this process would be quite high. These problems are removed by keeping the refrigerant inside a closed system and taking advantage of the fact that the boiling temperatures of refrigerants vary with pressure. This pressure effect is clearly shown in Table 8.01. We know that, at atmospheric pressure, water boils at 100°C. For those conditions, 2257 kJ of energy is needed to evaporate one kilogram of water. If we increase the pressure to 1.0 MPa, the boiling point increases to 179.9°C and the latent heat of vaporization decreases to 2013.6 kJ/kg. Further increase in pressure to the critical point produces a condition where the latent heat of vaporization is zero. This occurs at the top of the vapor dome (refer to pages 234 to 237 of Chapter 9 for additional details).

Table 8.01. Boiling point and latent heat of vaporization as a function of pressure for selected materials.[a]

	Absolute Pressure		Boiling Point		Latent Heat of Vaporization	
Material	MPa	psi	°C	°F	kJ/kg	Btu/lb
Water	0.10132	14.7	100.0	212.0	2256.6	970.2
Water	1.0	145.0	179.9	355.8	2013.6	865.7
Water	22.064	3200	374.0	7505.2	0	0
Ammonia	0.10132	14.7	–33.3	–28.0	1369.6	588.8
Ammonia	1.0	145.0	24.9	76.8	1165.7	501.1
Ammonia	2.0	290.1	50.7	123.2	1053.2	452.8
Refrigerant 12	0.10132	14.7	–29.8	–21.6	165.9	71.3
Refrigerant 12	1.0	145.0	41.7	107.1	128.6	55.3
Refrigerant 22	0.10132	14.7	–40.8	–41.4	233.8	100.5
Refrigerant 22	1.0	145.0	23.4	74.1	184.0	79.1
Refrigerant 23	0.10132	14.7	–82.0	–115.7	238.8	102.7
Refrigerant 23	1.0	145.0	–30.4	–22.7	186.6	80.2
Refrigerant 134a	0.10132	14.7	–26.1	–14.9	216.8	93.2
Refrigerant 134a	1.0	145.0	39.4	102.9	163.9	70.5
Nitrous Oxide	0.10132	14.7	–88.3	–127.0	377.5	162.3
Nitrous Oxide	1.0	145.0	–37.6	–35.7	321.1	138.1

[a] Computed from data in ASHRAE (1997) and (for Nitrous Oxide) ASHRAE (1959).

Most refrigerants have temperature enthalpy charts similar in form to that for water. Two such charts are shown at the end of this chapter. Temperatures, pressures, and latent heats of vaporization differ, but the form of response does not. Pressure-enthalpy and temperature-enthalpy charts have a liquid area, a superheated vapor area, and a transition area beneath a vapor dome that consists of a combination of liquid and vapor. This region beneath the vapor dome is very important for analysis of the widely used vapor compression refrigeration cycle.

8.2 Refrigeration Cycles

The food industry makes use of two types of refrigeration cycles. Both cycles use the pressure-temperature effect noted in Table 8.01. Many large systems use an absorption cycle while other systems (including home refrigeration appliances) use a vapor compression cycle.

A vapor-compression refrigeration cycle is shown in Figure 8.01. A refrigerant with a low boiling point (e.g., Refrigerant 134a) is compressed. The compressed gas, now with a much higher boiling point, moves to the condenser. The boiling point of the refrigerant is now higher than the temperature of the surrounding air. Therefore, the gas will give up heat and condense (the latent heat of vaporization is given up to the surroundings). The high-pressure liquid refrigerant then flows to the evaporator. As it enters the evaporator, it flows through a restriction (expansion valve or capillary tube), which produces a substantial pressure drop. This lowers the boiling point of the

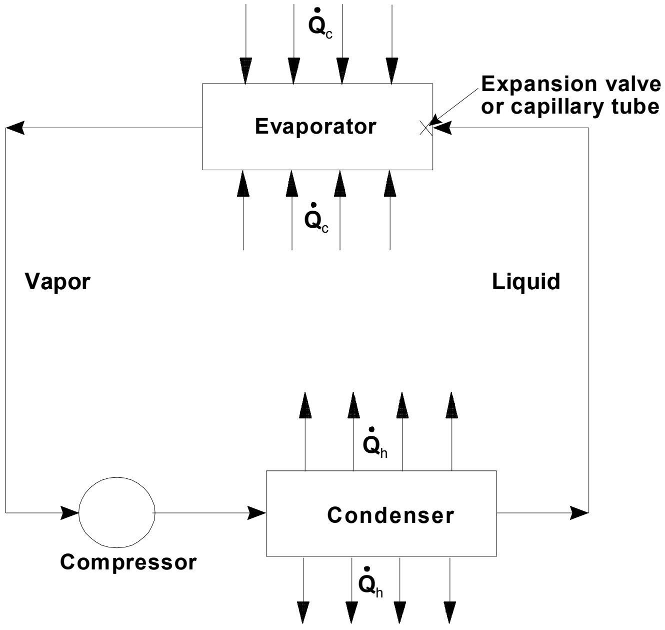


Figure 8.01. Vapor compression refrigeration cycle.

liquid to a very low value—well below the temperature around the evaporator coils. Heat gained by the evaporator coils causes the liquid to boil. The low pressure vapor then flows to the compressor where it is compressed to continue the cycle.

This vapor compression refrigeration cycle is commonly used in the refrigerators, freezers, and air conditioners used in the home and in many commercial applications. The "standard" for refrigerants used in the compression refrigeration cycle was Refrigerant 12 (commonly called Freon 12) until the early 1990's. Refrigerant 12 possesses the desirable properties for a refrigerant: low boiling point, non-poisonous, non-explosive, non-corrosive, and it mixes with oil. The last property is needed to permit internal lubrication of the compressor during operation. Refrigerant 12, however, possesses one very undesirable property. It is a chlorofluorocarbon (CFC) that, when released to the upper atmosphere, degrades to produce chlorine (Rowland, 1997). This chlorine has a powerful ability to destroy ozone in the upper atmosphere. New refrigeration systems no longer use Refrigerant 12 and other CFC's that are major chlorine producers. One of the replacement refrigerants is Refrigerant 134a.

The other cycle commonly used in refrigeration employs heat to produce cold! It is commonly called the ammonia absorption cycle. This cycle makes use of the ability of water to absorb ammonia. Heat is then used to "drive" the ammonia from the water. An ammonia absorption cycle is shown in Figure 8.02. The cycle uses a pump to produce the high pressure in the generator and condenser. Note that, even with the absorption cycle, a pressure difference must be present between the condenser and the evaporator.

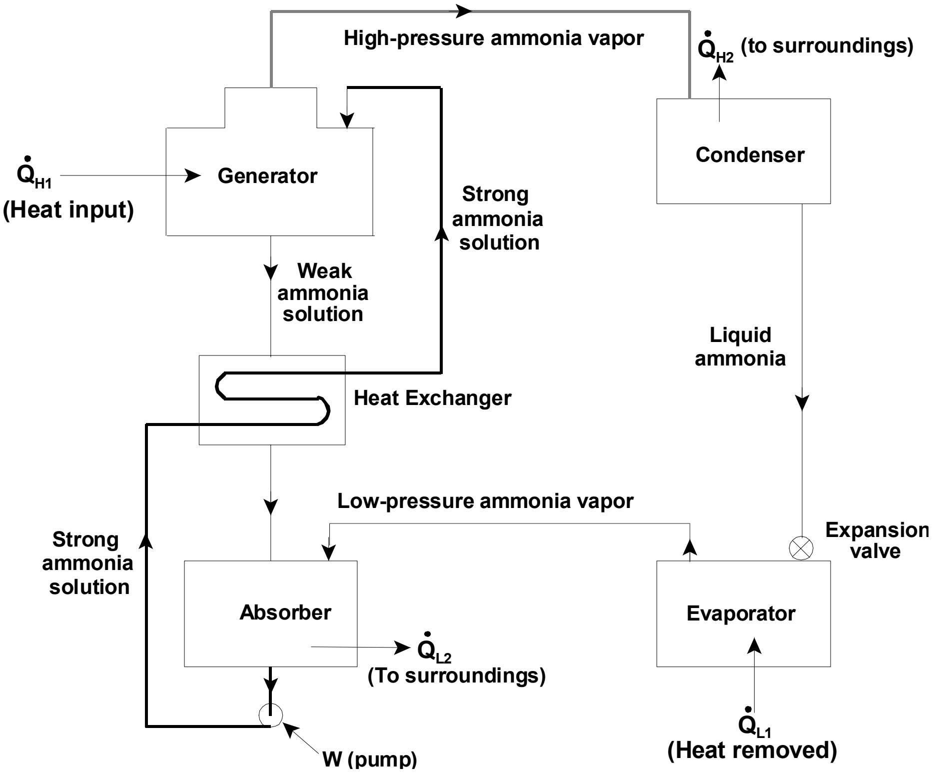


Figure 8.02. Sketch of an ammonia absorption cycle.

8.3 Analysis of the Vapor-Compression Refrigeration Cycle

To analyze refrigeration cycles, we must use charts (Figures 8.04 and 8.05, pages 209 and 211) or thermodynamic tables of properties (Tables 8.02 and 8.03, pages 210 and 212). The full refrigeration cycle is best represented on a pressure-enthalpy diagram for the refrigerant used. Figure 8.03 represents such an ideal cycle for a typical refrigerant. The high-pressure vapor (at point D) is usually cooled at the specified pressure until it becomes a saturated liquid. That defines state point A on the curve. The refrigerant flows through the expansion valve with no change in energy content (constant enthalpy) and begins to evaporate at the lower pressure. The process B–C represents constant pressure evaporation (boiling at a very low temperature). At point C, the refrigerant is 100% vapor. It is then compressed reversibly (constant entropy) to the high-pressure value (point D). Our analysis will consider only this **ideal** cycle. However, you should be aware that real cycles deviate from the cycle shown. In real cycles, pressure drops in the system plumbing prevent constant pressure operations for processes B–C and D–A. In addition, there are no abrupt changes in processes at points A, B, C, and D. Real processes do not permit the sharp changes in direction shown on the chart. Each change is gradual, producing rounded corners rather than the sharp changes noted.

As we analyze the ideal vapor compression refrigeration cycle we must note the following energy changes:

1. The amount of cooling provided by process B–C is the energy required for evaporation ($h_g - h_L$).
2. The work of compression, process C–D, is given by ($h_H - h_g$).
3. The heat rejected by the system (condenser heat transfer, process D–A) is ($h_H - h_L$).

The efficiency of this cycle is the ratio of output to input. It is called coefficient of performance (*COP*):

$$COP = \frac{\text{Cooling Produced}}{\text{Work Input}} = \frac{h_g - h_L}{h_H - h_g} \tag{8.01}$$

The coefficient of performance is usually greater than one.

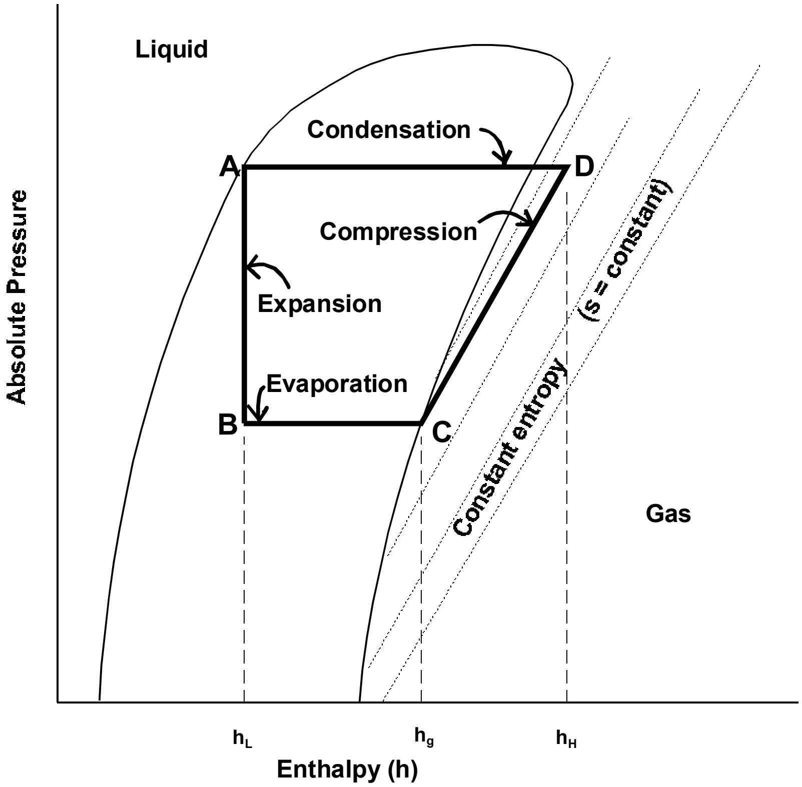


Figure 8.03. An ideal vapor-compression refrigeration cycle.

Example 8.1

An ideal refrigerant cycle using Refrigerant 12 operates between refrigerant temperatures of –30°C and 50°C. Find the operating pressures and the coefficient of performance.

Solution:

Use Figure 8.04 to locate the state points A, B, C and D as identified in Figure 8.03. The input parameters are: $t_H = 50°C$, $t_L = -30°C$. Temperatures are shown as small tic marks on the saturated liquid curve. Since 50°C and –30°C are not shown, we must interpolate along the curve. Doing so, we find the corresponding pressures to be: P_h = 1.2 MPa and P_L = 0.10 MPa. Following the cycle as sketched in Figure 8.03, we find h_L = 250 kJ/kg. Moving along P = 0.10 MPa to the saturated vapor line, we find h_g = 339 kJ/kg. Following a constant entropy line of 1.58 (by interpolation) to its intersection with the constant pressure line (P = 1.2 MPa, Point D), we find h_H = 388.

We can now solve for the coefficient of performance:

$$COP = \frac{h_g - h_L}{h_H - h_g} = \frac{339 - 250}{388 - 339} = \frac{89}{49} = \underline{1.82} \qquad \textbf{ANSWER}$$

Note: We can also use tabulated values for the refrigerants to more accurately determine most of the properties. Using Table 8.02 (the data for Refrigerant 12), we find that at 50°C, P_h = 1.2171 kPa and h_L = 249.51 kJ/kg. Similarly, for –30°C, P_L = 0.10044 kPa and the enthalpy of saturated vapor is h_g = 338.81 kJ/kg. We cannot determine h_H since it is in the superheated vapor region and the table only covers saturation values.

Note also that the highest temperature for the cycle, in the superheat region, is actually about 75°C. However that temperature drops quickly as the superheated refrigerant condenses. Once the saturated vapor line is reached, the heat rejection continues at a constant temperature of 50°C. Most of the heat removal occurs at this temperature. Thus, we typically identify the high temperature as 50°C even though it exceeds that value for a short time.

Example 8.2

Repeat Example 8.1 using Refrigerant 134a.

Solution:

Figure 8.05, for Refrigerant 134a, is read in the same manner as Figure 8.04, used for the previous example. We find the following results:

$P_L = 0.084$ MPa $P_H = 1.3$ MPa
$h_L = 272$ kJ/kg $h_g = 380$ kJ/kg $h_H = 440$ kJ/kg

$$COP = \frac{h_g - h_L}{h_H - h_g} = \frac{380 - 272}{440 - 380} = \frac{108}{60} = \underline{1.80} \qquad \textbf{ANSWER}$$

The coefficient of performance for Refrigerant 134a is quite close to that for Refrigerant 12 operating under the same conditions. In general, the coefficients of performance will be different for systems using different refrigerants but operating at the same pressures.

8.3.1 Heat Pumps

The refrigeration cycle is actually a cycle that “pumps” thermal energy from a region of lower temperature to a region of higher temperature. The examples we have looked at involve using this pumping cycle to cool. Refrigeration systems are also used to provide heat. When used for this purpose they are called heat pumps. This is most easily visualized by imagining a window air conditioner installed in reverse, such that the condenser coils (hot air) are inside the room and the evaporator coils (cold air) are outside the room. The exact mechanism used for an actual air conditioner/heat pump is more complicated since changes from heating to cooling are implemented by changing the direction of refrigerant flow.

If a system is being used as a heat pump, then the useful output is heat rejected at the condenser—not heat absorbed in the evaporator. Thus, the coefficient of performance for a heat pump is higher than for a cooling system operating between the same pressures. The equation for COP is then:

$$COP_{HP} = \frac{\text{Heat rejected}}{\text{Work input}} = \frac{h_H - h_L}{h_H - h_g}$$

For Example 8.2, using R-134a, the heat pump coefficient of performance is:

$$COP_{HP} = \frac{440 - 272}{440 - 380} = \frac{168}{60} = 2.80$$

Example 8.3

An ideal refrigerant cycle using Refrigerant 134a operates between pressures of 0.3 and 1.5 MPa. Determine the evaporator and condenser temperatures and calculate the coefficient of performance.

Solution:

We will use Figure 8.05 to obtain the required information. However, most points can also be found using Table 8.03. Where available, interpolated values from this table are also shown (in parenthesis) as a check of the chart results.

The temperatures corresponding to the specified pressures are:

condenser temperature: $t_H = 55$ºC (55.23ºC)
evaporator temperature: $t_L = 1$ ºC (0.6ºC)

The enthalpy and entropy values corresponding to the saturated liquid (*L*) and saturated vapor (*g*) points on the cycle are:

$h_L = 280$ kJ/kg (279.8 kJ/kg)
$h_g = 400$ kJ/kg (399.0 kJ/kg)
$s = 1.74$ kJ/kg K (1.73 kJ/kg K)

Following the constant entropy line (s = 1.74) to the high pressure of 1.5 MPa, we find:

$h_H = 435$ kJ/kg
$t \approx 63$ºC (this temperature quickly drops to 55ºC as condensation begins)

Knowing the enthalpy values, we can now calculate the coefficient of performance:

$$COP = \frac{400-280}{435-400} = \frac{120}{35} = \underline{3.43} \qquad \textbf{ANSWER}$$

8.4 Refrigeration Capacity

The capacity of a refrigeration system is a function of the refrigerant, the operating pressures, and the mass of refrigerant circulated $\left[\dot{Q} = \dot{m}(h_g - h_L)\right]$. In Example 8.1, we calculated a heat removal of 89 kJ for one kg of refrigerant ($h_g - h_L$). The cooling capacity will depend upon both this heat removal and the circulation (evaporation) rate of the refrigerant. If the circulation rate is 2 kg/min, then the cooling capacity for the system is:

$$\dot{Q} = 2\ \frac{\text{kg}}{\text{min}} \times \frac{1\ \text{min}}{60\ \text{s}} \times 89\ \frac{\text{kJ}}{\text{kg}} = 2.97\ \text{kW}$$

Refrigeration capacity of cooling systems is sometimes given in "tons." This rating is based upon the cooling capacity of one ton of ice melted over a 24-hour period [(2000 lb × 144 BTU/lb)/24 hr = 12,000 BTU/hr = 3.5 kW]. While the use of "ton" to indicate cooling capacity does have a logical basis this is another example of using one unit (mass) to represent something completely different (rate of energy transfer, or power).

8.5 Refrigeration Loads

Refrigeration systems are widely used for cooling, freezing, and refrigerated storage of food and other products. Refrigeration units used for these applications must be sized to overcome heat gain through the walls of the system and also perform the desired functional operation. For example, freezing a food product may be considered as a three-step operation: (1) the product is cooled to its freezing point, (2) it is frozen at constant temperature, and (3) the frozen product is further cooled to the desired final temperature. The energy required to do this can be computed as:

$$Q = \dot{m} c_P (t_1 - t_f) + \dot{m} h_{sf} + \dot{m} c'_P (t_f - t_2) \tag{8.02}$$

where: c_p, c'_p = specific heat values above and below freezing, respectively, kJ/(kg K)

h_{sf} = the latent heat of fusion, kJ/kg

$\dot{m}$ = the mass of product being frozen, kg

Q = the total energy removed in the cooling operation, (kJ) and

t_1, t_2, t_f = the initial, final and freezing point temperatures, respectively, ºC or K.

Appendix Table A.5 lists the necessary thermal properties to make the above calculation for selected food products.

Example 8.4

Twenty kilograms of strawberries at 22°C are to be frozen to –24°C. What amount of energy must be removed from the strawberries?

Solution:

We can use Equation 8.02 to solve for Q.

From Table A.5, $c_p = 3.89$, $c'_p = 1.94$, and $h_{sf} = 307$. Thus:

Q = 20 kg [3.89 kJ/kg K(22– –0.8)K + 307 kJ/kg + 1.94.kJ/kg K(–0.8– –24)K]

= 20 [3.89 (22.8) + 307 + 1.94 (23.2)] kJ

= 20 [88.69 + 307 + 45.01] = 20 (440.7) kJ

= <u>8814 kJ</u> **ANSWER**

Considerable refrigeration may also be required for refrigerated storage. Fresh products must be cooled to the desired storage temperature and held at that temperature. These products are living organisms and produce heat as a part of their life processes. This heat of respiration, while small on a unit mass basis, is a major source of heat where large masses of products are handled (e.g., apple storage warehouses). Heat of respiration varies with products and increases with temperature for all products (Appendix, Table A.8).

8.6 Food Freezing

Consumption of frozen foods has increased because of demand for high quality products and increased use of home microwave ovens for rapid meal preparation. Proper freezing retains food color, texture, and nutrient quality for long time periods provided storage temperatures are maintained sufficiently low. The storage life of foods is extended by lowering temperature and greatly extended by freezing the product. Lowering temperature reduces the microbial growth rate which is temperature dependent. Freezing foods reduces the amount of water in liquid form that is available for microbial activity. Production volume freezing is done quickly but requires significant energy. The amount of energy to freeze food materials has been determined and is fairly predictable in most cases. The time required to accomplish freezing is less predictable, depending on properties of the food, physical characteristics of the particular equipment, and operation of the system.

Removing sufficient energy from a food product to change its state from "liquid-like" to "solid-like" is a process known as freezing. The temperature at which a food freezes depends on its constituents. Although foods contain a substantial amount of water, they behave differently from pure water. The freezing point of foods is lowered below that of water by an amount known as the freezing point depression. The presence of a solute in water lowers its freezing point. Depressions are typically 1° to 5°C for many foods, i.e., they freeze at –1°C and lower (Appendix, Table A.5). Also, the freezing process for a food material occurs over a range in temperatures rather than at a single temperature like pure water. For example, ice cream products begin to freeze at –2°C and 50% of the water is frozen at –5°C. When 80% of the water is frozen, the remaining unfrozen portion has a freezing point of –15°C. The last 5% to 15% of the water in foods may never be frozen. (data from ASHRAE [1998] *Handbook of Refrigeration*, Table 9, Chapter 19).

Freezing foods involves the removal of energy from the food. The energy removed to freeze foods is partially the sensible cooling required to lower the temperature to the freezing point, but the primary energy removed is the latent energy for phase change. The latent heat of freezing for water, 335 kJ/kg, is many times larger than the sensible energy removed to lower the temperature by one degree. Latent heat values are used to compute the amount of energy removed for freezing. The thermal conductivity of water and food materials increases greatly at below freezing temperatures; the increase is fourfold for water (Figure 2.08). Other thermal properties change, but to a lesser degree, during freezing.

Freezing time, *FT*, for foods and other products can be computed by an equation known as Plank's formula:

$$FT = \rho h_{sf} \frac{\left(\frac{Pd}{h} + \frac{Rd^2}{k} \right)}{t_f - t_a} \tag{8.03}$$

where: d = product thickness (smallest dimension), m
FT = freezing time, s
h = convective heat transfer coefficient, W/(m^2 K)
h_{sf} = latent heat of fusion, kJ/kg
k = thermal conductivity of frozen product, W/(m K)
t_f = initial freezing temperature of product, from Table A.5, °C or K
t_a = temperature of refrigerated air, °C or K
ρ = density of frozen product, kg/m^3
P and R are constants depending on product shape

The constants for "standard" shapes are $P = 1/2$ and $R = 1/8$ for an infinite plate (slab); $P = 1/4$ and $R = 1/16$ for a long cylinder; and $P = 1/6$ and $R = 1/24$ for a sphere. The equation includes a term, $\Delta h_{sf} Rd^2/k$, for heat flow from the inside to the surface, i.e., heat transfer controlled by food properties, and a term $\Delta h_{sf} Pd/h$ for heat flow from the food's surface, i.e., heat transfer controlled by the equipment and its operation. The temperature difference, $t_f - t_a$, is the usual temperature difference term found in heat transfer equations. This equation estimates the time only for phase change, excluding time to lower temperature either above or below the freezing point. Plank's equation can be used to estimate freezing time, or graphs are available based on the equation. ASHRAE's *Handbook of Refrigeration* (1998) has freezing time graphs for meat (Chapter 16), poultry (Chapter 17), and fishery products (Chapter 18). Plank's equation has numerous assumptions and limitations; but it is simple, includes the pertinent factors, and is sufficiently accurate for most applications. The equation tends to under-estimate freezing times of food products of non-ideal, irregular shape. There are other, more complicated, equations to predict freezing time for specific products and for particular situations. However, it is more common to use Plank's simpler equation recognizing that it predicts times 10% to 30% less than actual freezing times.

Example 8.5

Beef patties for hamburgers are being frozen in an air-blast freezer having air at –22°C and a convective heat transfer coefficient of 50 W/(m^2 K). A patty averages 1 cm thick and is circular with a diameter of 8 cm. Frozen ground beef has a density of 1050 kg/m^3, a thermal conductivity of 1.4 W/(m K), a latent heat of fusion of 250 kJ/kg, and begins to freeze at –2°C. Compute the time to freeze the product using Plank's equation.

Solution:

Assume the shape of the patty is a slab (thickness is small compared to other dimensions). Thus, P and R are 1/2 and 1/8, respectively.

Using Plank's equation:

$$FT = \rho\, h_{sf}\, \frac{\left(\dfrac{Pd}{h} + \dfrac{Rd^2}{k}\right)}{t_f - t_a}$$

$$FT = 1050\,\frac{\text{kg}}{\text{m}^3} \times 250\,\frac{\text{kJ}}{\text{kg}}\,\frac{\left[\dfrac{0.01\ \text{m}}{2\times 50\,\dfrac{\text{W}}{\text{m}^2\ \text{K}}} + \dfrac{(0.01\ \text{m})^2}{8\times 1.4\,\dfrac{\text{W}}{\text{m K}}}\right]}{(-2)-(-22)\ \text{K}}$$

FT = 262 500 kJ/m^3 [0.000 100 m^3 K/W + 0.000 008 9 m^3 K/W] / 20 K

FT = 1 429 J/W = 1 429 J/ (J/s) = 1 429 s = 23.8 min **ANSWER**

Notice that no consideration was given to the initial temperature of the product in the above example. The computed time starts with the unfrozen product, at a temperature of –2°C. Starting at higher temperatures will require allowance for time to lower the product temperature to –2°C.

How do product dimensions affect freezing time? For example, how long will it take to freeze a patty of twice the thickness? Consider the previous problem with all the parameters the same except that *d* is changed from 0.01 m to 0.02 m. Plank's equation now becomes:

FT = 262,500 kJ/ m^3 K ([0.000 200 m^3 K/W + 0.000 035 7 m^3 K/W) / 20 K

FT = 3.094 kJ/W = 3094 sec = 51.6 min.

We see that doubling the product's thickness will require slightly more than doubling of the freezing time, i.e., 2.17 times longer to freeze. The assumed value of *h* (50 W/m^2 K) for the equipment was for high velocity air blast freezing. With less efficient cooling (values of *h* are 5 to 10 for still-air freezing systems, 100 for plate freezing, and 600 W/(m^2 K) for liquid-immersion systems), freezing time (*FT*) would increase. With thin products like the patty of this example, *h* is the controlling factor. With thicker products like a side of beef carcass, *d* is larger and the second term in the parenthesis in Plank's equation contributes more to the total freezing time. Also, increases in thickness in this situation will have a non-linear (d^2) effect on freezing time. Thus, a small reduction in *d* of a thick product will cause a relatively large reduction in freezing time for low efficiency equipment systems.

Freezing time is important in determining the capacity of equipment and quality of product. The freezing rate establishes the type of ice crystal formation. Slow heat removal from a food causes a few large crystals to form while rapid heat removal causes formation of many small crystals. The smaller the size of the ice crystals in the frozen product, the better the texture of the subsequent food product.

Analogous to the often-used freezing time computation is the occasional need to predict the thawing time. Plank's formula can be used for computing the thawing time by substituting the food property values for density and conductivity of the unfrozen material. Since the thermal conductivity of unfrozen material is less than for frozen material, thawing time is longer than freezing time for the same food material and same operating conditions, i.e., temperature difference and convective heat transfer coefficient.

Example 8.6

The frozen beef patties of Example 8.5 are being thawed in open air with the same convective heat transfer coefficient and temperature difference. Compute the time to thaw the product and compare with the freezing time.

Solution:

The numbers to be used in Plank's equation are the same as for freezing except that the thermal conductivity now is 0.4 W/m K (unfrozen meat). The resulting equation then becomes:

$$TT = 1050\,\frac{\text{kg}}{\text{m}^3} \times 250\,\frac{\text{kJ}}{\text{kg}} \left[\frac{\dfrac{0.01\,\text{m}}{2 \times 50\,\dfrac{\text{W}}{\text{m}^2\text{K}}} + \dfrac{(0.01\,\text{m})^2}{8 \times 0.4\,\dfrac{\text{W}}{\text{m K}}}}{20\,\text{K}} \right]$$

$TT = 1.723$ kJ/W = 1723 s = <u>28.7 min</u> **ANSWER**

Note that, assuming all factors are the same, thawing of these relatively thin patties takes 20% longer than freezing. This is due to the difference in thermal conductivity of frozen and unfrozen material.

List of Symbols

c_p	specific heat capacity at constant pressure, J/(kg K) or kJ/(kg K)
c'_p	specific heat capacity below freezing at constant pressure, J/(kg K) or kJ/(kg K)
COP	coefficient of performance, dimensionless
d	product thickness, m
FT	freezing time, s
h	enthalpy, kJ/kg
h	surface heat transfer coefficient, W/(m^2 K)
h_{sf}	($h_f - h_s$) latent heat of fusion, kJ/kg
k	thermal conductivity, W/(m K)
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
P	Plank Equation constant, a function of product shape
Q	energy, J
$\dot{Q}$	heat transfer rate, W
R	Plank Equation constant, a function of product shape
s	entropy, kJ/(kg K)
t	temperature, °C
TT	thawing time, s
ρ	density, kg/m^3

Subscripts

$1,2$	initial and final temperatures
a	air (or dry air)
f	frozen product
f	freezing point
g	gaseous state
H	highest enthalpy value of refrigeration cycle
HP	heat pump operation
L	liquid