UNIT 6 – Heat and Mass Transfer (Part-1)

The most common processes found in a food processing plant involves heating and cooling of foods. Common unit operations such as refrigeration, freezing, thawing, thermal sterilization, drying, frying, and evaporation are carried to achieve these two tasks.

In this module of how heat transfer fundamentals are related to the design and operation of food processing equipment is covered.

Contents

1. Systems for heating and cooling food products

In a food processing plant, heating and cooling of foods is conducted in equipment called heat exchangers. As shown in Figure 1, heat exchangers can be broadly classified into non-contact and contact types.

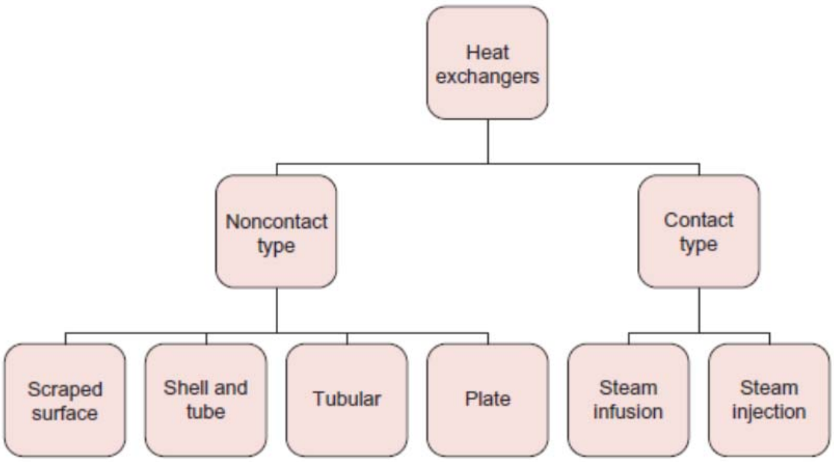

Figure 1: Classification of commonly used heat exchangers.

1.1 Plate Heat Exchanger

The plate heat exchanger invented more than 70 years ago has found wide application in the dairy and food beverage industry. A schematic of a plate heat exchanger is shown in Figure 4.2. This heat exchanger consists of a series of parallel, closely spaced stainless-steel plates pressed in a frame. Gaskets, made of natural or synthetic rubber, seal the plate edges and ports to prevent intermixing of liquids. These gaskets help to direct the heating or cooling and the product streams into the respective alternate gaps. The direction of the product stream versus the heating/cooling stream can be either parallel flow (same direction) or counterflow (opposite direction) to each other.

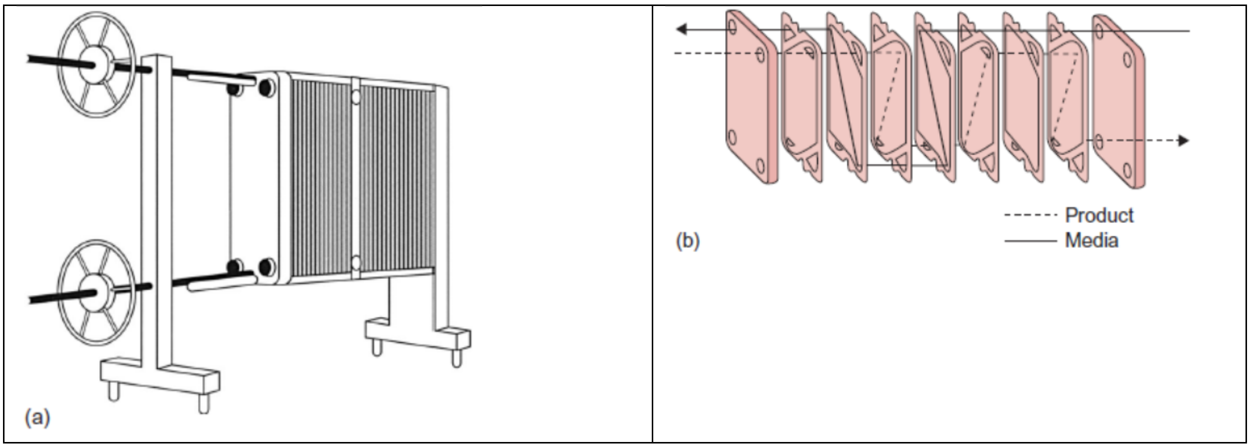

Figure 2: (a) Plate heat exchanger. (b) Schematic view of fluid flow between plates. (Courtesy of Cherry-Burrell Corporation)

Plate heat exchangers are suitable for low-viscosity (<5 Pa s) liquid foods. If suspended solids are present, the equivalent diameter of the particulates should be less than 0.3 cm. Larger particulates can bridge across the plate contact points and "burn on" in the heating section.

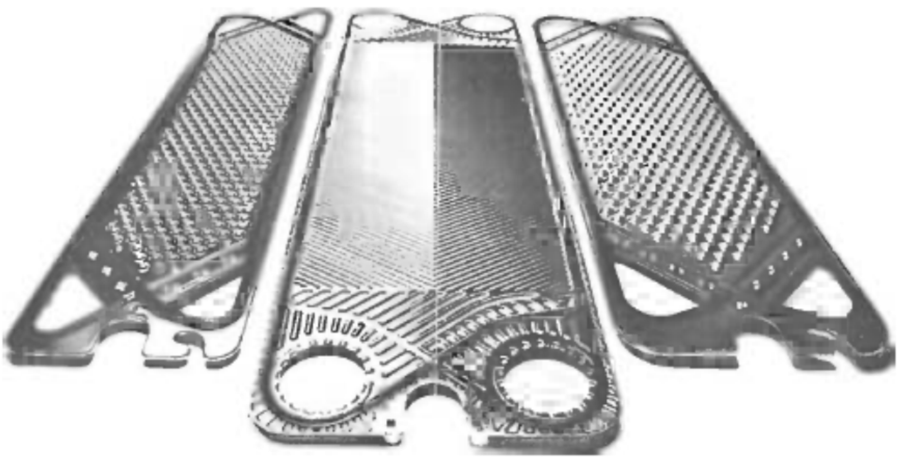

Figure 3: Patterns pressed on plates used on a plate heat exchanger. (Courtesy of Cherry-Burrell Corporation)

In industrial-size plate heat exchangers, product flow rates from 5000 to 20,000 kg/h often are obtained. When using plate heat exchangers, care should be taken to minimize the deposition of solid food material such as milk proteins on the surface of the plates. This deposition, also called fouling, will decrease the heat transfer rate from the heating medium to the product; in addition, the pressure drop will increase over a period of time. Eventually, the process is stopped and the plates are cleaned.

Plate heat exchangers offer the following advantages:

- The maintenance of these heat exchangers is simple, and they can be easily and quickly dismantled for product surface inspection.
- The plate heat exchangers have a sanitary design for food applications.
- Their capacity can easily be increased by adding more plates to the frame.
- With plate heat exchangers, we can heat or cool product to within 1^{o} C of the adjacent media temperature, with less capital investment than other non-contact-type heat exchangers.
- Plate heat exchangers offer opportunities for energy conservation by regeneration.
- These are widely used in food and diary industries due to the cost economics.

As shown in a simple schematic in Figure 4, a liquid food is heated to pasteurization or other desired temperature in the heating section; the heated fluid then surrenders part of its heat to the incoming raw fluid in the regeneration section. The cold stream is heated to a temperature where it requires little additional energy to bring it up to the desired temperature.

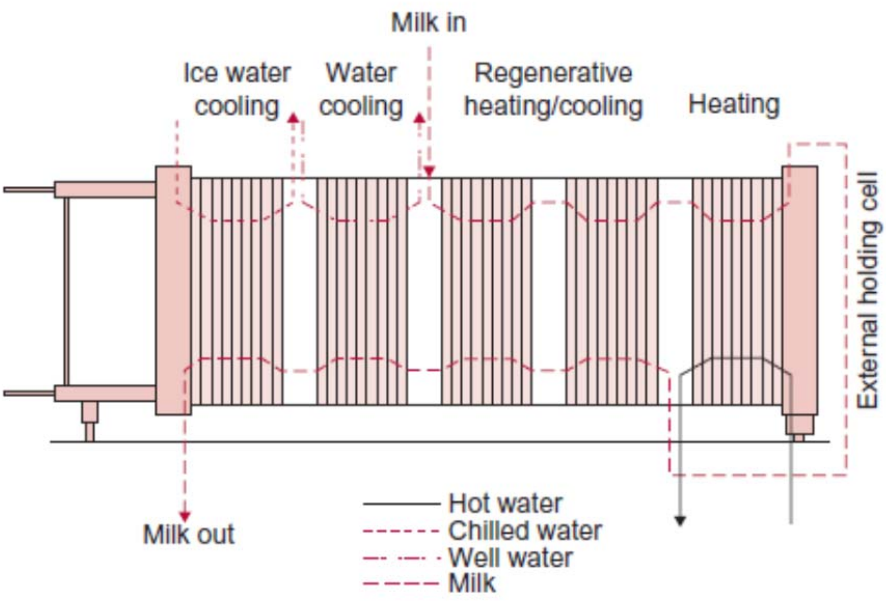

Figure 4: A five-stage plate pasteurizer for processing milk. (Reprinted with permission of Alfa-Laval AB, Tumba, Sweden, and Alfa-Laval, Inc., Fort Lee, New Jersey)

1.2 Tubular Heat Exchanger

The simplest noncontact-type heat exchanger is a double-pipe heat exchanger, consisting of a pipe located concentrically inside another pipe. The two fluid streams flow in the annular space and in the inner pipe, respectively. The streams may flow in the same direction (parallel flow) or in the opposite direction (counterflow). Figure 5A is a schematic diagram of a counterflow double-pipe heat exchanger.

A slight variation of a double-pipe heat exchanger is a triple-tube heat exchanger, shown in Figure 5B. In this type of heat exchanger, product flows in the inner annular space, whereas the heating/cooling medium flows in the inner tube and outer annular space.

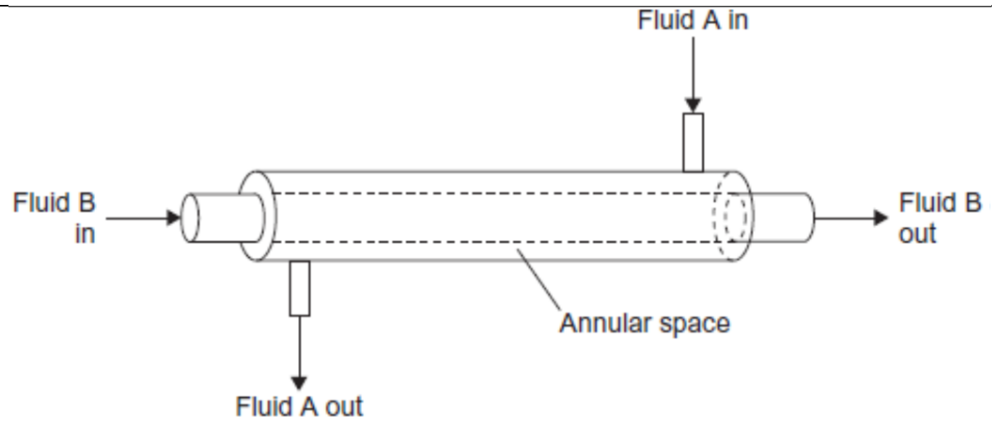

Figure 5A: Schematic illustration of a tubular heat exchanger.

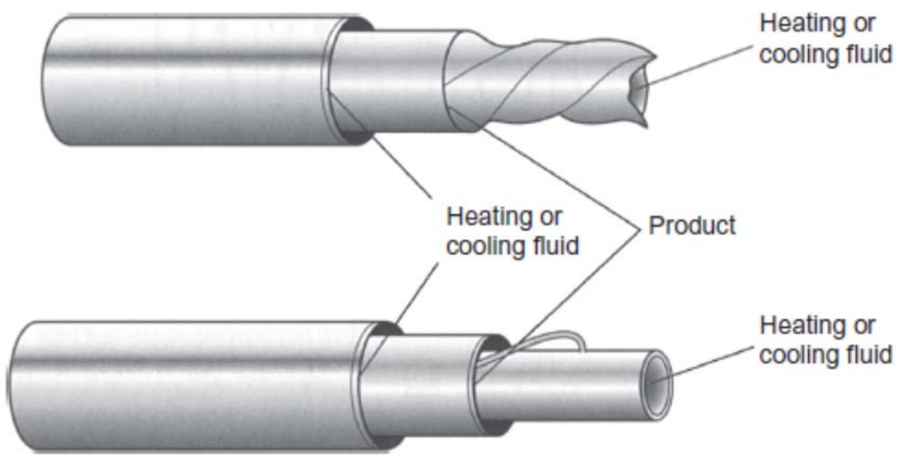

Figure 5B: Schematic illustration of a tripletube heat exchanger.

The innermost tube may contain specially designed obstructions to create turbulence and better heat transfer. Some specific industrial applications of triple-tube heat exchangers include heating single-strength orange juice from 4 to 93°C and then cooling to 4°C; cooling cottage cheese wash water from 46 to 18°C with chilled water; and cooling ice cream mix from 12 to 0.5°C with ammonia.

Another common type of heat exchanger used in the food industry is a shell-and-tube heat exchanger for such applications as heating liquid foods in evaporation systems. As shown in Figure 6, one of the fluid streams flows inside the tube while the other fluid stream is pumped over the tubes through the shell. By maintaining the fluid stream in the shell side to flow over the tubes, rather than parallel to the tubes, we can achieve higher rates of heat transfer. Baffles located in the shell side allow the cross-flow pattern.

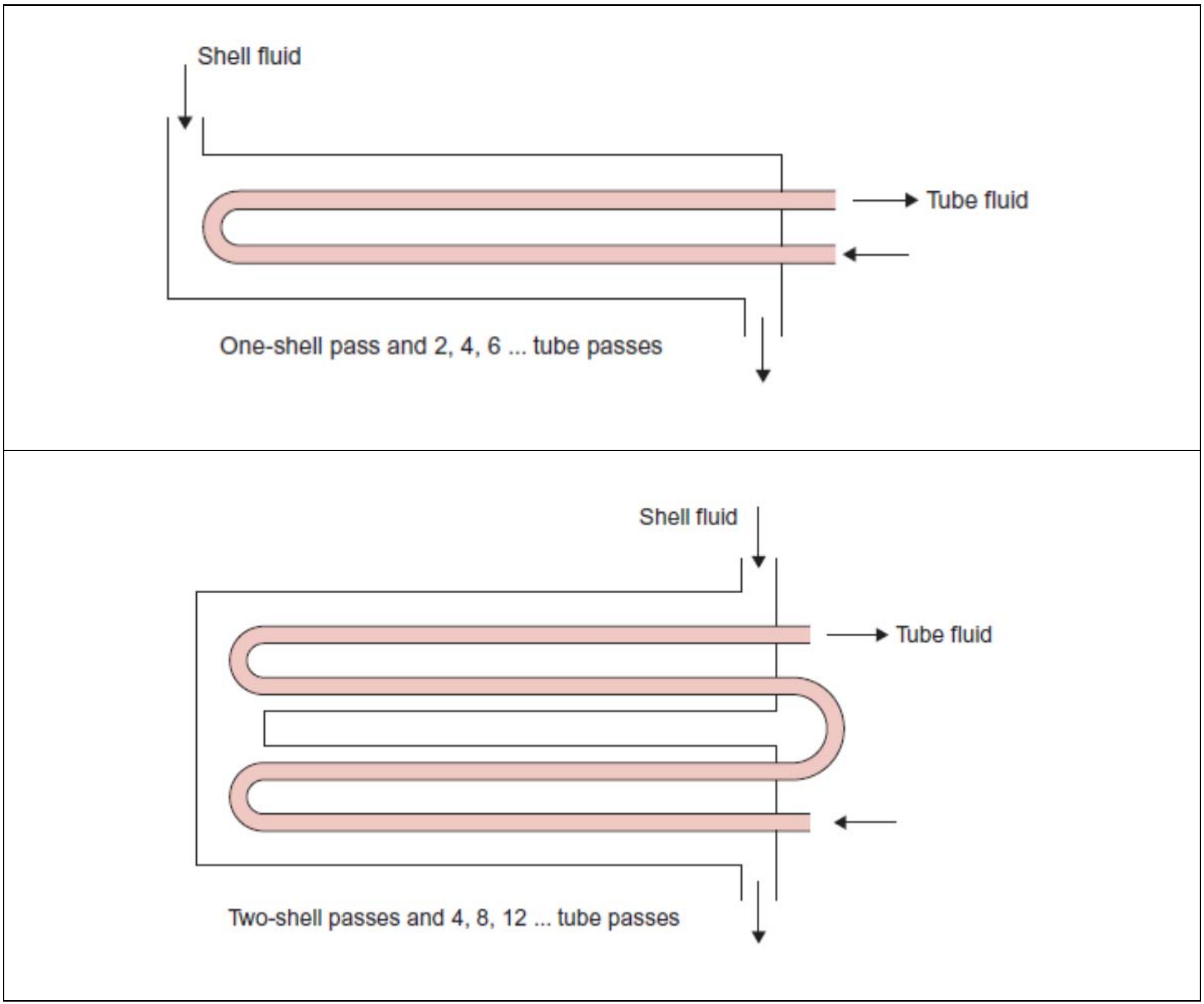

Figure 6: A shell-and-tube heat exchanger. One or more tube passes can be accomplished, depending on the design. The shell-and tube heat exchangers shown in this Figure are one shell pass with two tube passes, and two shell passes with four tube passes.

A wide variety of food products is processed using heat exchangers. These products present unique and often complex problems related to heat transfer. In the following sections, we will develop quantitative descriptions emphasizing the following:

- Thermal properties. Properties such as specific heat, thermal conductivity, and thermal diffusivity of food and equipment materials (such as metals) play an important role in determining the rate of heat transfer.

- Mode of heat transfer. A mathematical description of the actual mode of heat transfer, such as conduction, convection, and/or radiation is necessary to determine quantities, such as total amount of heat transferred from heating or cooling medium to the product.

- Steady-state and unsteady-state heat transfer. Calculation procedures are needed to examine both the unsteady-state and steady-state phases of heat transfer.

  Some of these topics are dealt in following sections

2. Thermal Properties of Food

2.1 Specific Heat

Specific heat is the quantity of heat that is gained or lost by a unit mass of product to accomplish a unit change in temperature, without a change in state:

$$c_p = \frac{Q}{m(\Delta T)} \qquad \text{Eq. (1)}$$

where Q is heat gained or lost (kJ), m is mass (kg), ΔT is temperature change in the material (^oC), and c_p is specific heat (kJ/[kg ^oC]).

Specific heat is an essential part of the thermal analysis of food processing or of the equipment used in heating or cooling of foods. With food materials, this property is a function of the various components that constitute a food, its moisture content, temperature, and pressure. The specific heat of a food increases as the product moisture content increases. For a gas, the specific heat at constant pressure, c_p, is greater than its specific heat at constant volume, c_v.

In most food processing applications, we use specific heat at constant pressure c_p, since pressure is generally kept constant except in high-pressure processing.

For processes where a change of state takes place, such as freezing or thawing, an apparent specific heat is used. Apparent specific heat incorporates the heat involved in the change of state in addition to the sensible heat.

In designing food processes and processing equipment, we need numerical values for the specific heat of the food and materials to be used.

(1) Published information
(2) Calculation of specific heats using predictive equations

The predictive equations are empirical expressions, obtained by fitting experimental data into mathematical models. Typically these mathematical models are based on one or more constituents of the food. Since water is a major component of many foods, a number of models are expressed as a function of water content.

One of the earliest models to calculate specific heat was proposed by Siebel (1892) as,

$$c_p = 0.837 + 3.349 X_W \qquad \text{Eq. (2)}$$

where X_w is the water content expressed as a fraction. This model does not show the effect of temperature or other components of a food product.

The influence of product components was expressed in an empirical equation proposed by Charm (1978) as

$$c_p = 2.093 X_{\mathrm{f}} + 1.256 X_{\mathrm{s}} + 4.187 X_W \qquad \text{Eq. (3)}$$

where X is the mass fraction; and subscripts f is fat, s is nonfat solids, and w is water. Note that in above equation, the coefficients of each term on the right-hand side are specific heat values of the respective food constituents. For example, 4.187 is the specific heat of water at 70^{o} C, and 2.093 is the specific heat of liquid fat.

Heldman and Singh (1981) proposed the following expression based on the components of a food product

$$c_p = 1.424 X_{\mathrm{h}} + 1.549 X_{\mathrm{p}} + 1.675 X_{\mathrm{f}} + 0.837 X_{\mathrm{a}} + 4.187 X_{\mathrm{W}} \qquad \text{Eq. (4)}$$

where X is the mass fraction; the subscripts on the right-hand side are h, carbohydrate; p, protein; f, fat; a, ash; and w, moisture.

Choi and Okos (1986) presented a comprehensive model to predict specific heat based on composition and temperature. Their model is as follows:

$$c_p = \sum_{i=1}^{n} c_{\mathrm{p}i} X_i \qquad \text{Eq. (5)}$$

where X_i is the fraction of the ith component, n is the total number of components in a food, and c_{pi} is the specific heat of the ith component.

2.2 Thermal Conductivity

The thermal conductivity of a food is an important property used in calculations involving rate of heat transfer. In quantitative terms, this property gives the amount of heat that will be conducted per unit time through a unit thickness of the material if a unit temperature gradient exists across that thickness. In SI units, thermal conductivity is

$$k = \frac{\text{J}}{\text{s m }^{\circ}\text{C}} = \frac{\text{W}}{\text{m }^{\circ}\text{C}} \qquad \text{Eq. (6)}$$

Note that W/(m ^{o}C) is same as W/(m K).

Most high-moisture foods have thermal conductivity values closer to that of water (0.597 W/(m ^{o}C) (at 20 ^{o}C)) . On the other hand, the thermal conductivity of dried, porous foods is influenced by the presence of air with its low value (0.0251 W/(m ^{o}C) (at 20 ^{o}C).

For fruits and vegetables with a water content greater than 60%, the following equation has been proposed (Sweat, 1974):

$$k = 0.148 + 0.493X_W \qquad \text{Eq. (7)}$$

X_w is water content expressed as a fraction. For meats and fish, temperature 0-60 ^{o}C, water content 60-80%, wet basis, Sweat (1975) proposed the following equation:

$$k = 0.08 + 0.52X_W \qquad \text{Eq. (8)}$$

Choi and Okos (1986) gave the following expression that includes the influence of product composition and temperature:

$$k = \sum_{i=1}^{n} k_i Y_i \qquad \text{Eq. (9)}$$

where a food material has n components, k_i is the thermal conductivity of the i^{th} component, Y_i is the volume fraction of the i^{th} component, obtained as follows:

$$Y_i = \frac{X_i / \rho_i}{\sum_{i=1}^{n} (X_i / \rho_i)} \qquad \text{Eq. (10)}$$

where X_i is the weight fraction and ρ_i is the density (kg/m^3) of the i^{th} component.

2.3 Thermal Diffusivity

Thermal diffusivity, a ratio involving thermal conductivity, density, and specific heat, is given as,

$$\alpha = \frac{k}{\rho c_p} \qquad \text{Eq. (11)}$$

The units of thermal diffusivity are $\alpha = \frac{m^2}{s}$

Thermal diffusivity may be calculated by substituting values of thermal conductivity, density, and specific heat in Equation (11).

Choi and Okos (1986) provided the following predictive equation, obtained by substituting the values of k, ρ, and c_p in Equation (12):

$$\alpha = \sum_{i=1}^{n} \alpha_i X_i \qquad \text{Eq. (12)}$$

where *n* is the number of components, α_i is the thermal diffusivity of the i^{th} component, and X_i is the mass fraction of each component.

3. Modes of Heat Transfer

Heat energy is simply the sensible and latent forms of internal energy. The heat content of an object such as a tomato is determined by its mass, specific heat, and temperature. The equation for calculating heat content is

$$Q = mc_p \Delta T \qquad \text{Eq. (13)}$$

where m is mass (kg), c_p is specific heat at constant pressure (kJ/[kg K]), and ΔT is the temperature difference between the object and a reference temperature (^{o}C). Heat content is always expressed relative to some other temperature (called a datum or reference temperature).

Although determining heat content is an important calculation, the knowledge of how heat may transfer from one object to another or within an object is of even greater practical value. The three common modes of heat transfer—conduction, convection, and radiation

3.1 Conductive Heat Transfer

Conduction is the mode of heat transfer in which the transfer of energy takes place at a molecular level. Note that in conductive mode, there is no physical movement of the object undergoing heat transfer. Conduction is the common mode of heat transfer in heating/cooling of opaque solid materials.

Consider the heat transfer across a room wall as depicted in figure 7. The rate of heat transfer through the wall may be expressed as

$$q \ \alpha \ \frac{\text{(wall surface area)(temperature difference)}}{\text{(wall thickness)}}$$

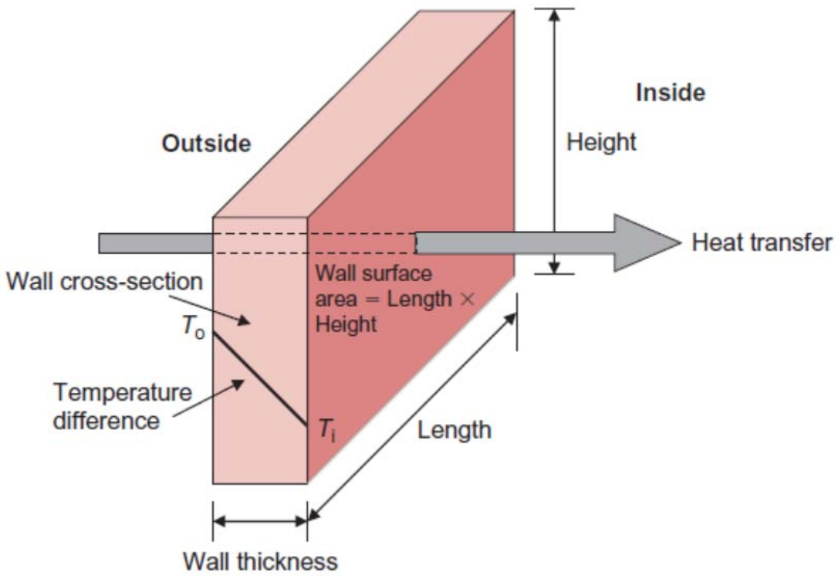

Figure 7: Conductive heat flow in a wall.

$$q_x \ \alpha \ \frac{AdT}{dx}$$

or, by inserting a constant of proportionality,

$$q_x = -k\frac{AdT}{dx} \qquad \text{Eq. (14)}$$

where q_x is the rate of heat flow in the direction of heat transfer by conduction (W); k is thermal conductivity (W/[m ^oC]); A is area (normal to the direction of heat transfer) through which heat flows (m2); T is temperature (^oC); and x is length (m), a variable. Equation 14 is also called Fourier's law for heat conduction, after Joseph Fourier, a French mathematical physicist. According to the second law of thermodynamics, heat will always conduct from higher temperature to lower temperature.

3.2 Convective Heat Transfer

When a fluid (liquid or gas) comes into contact with a solid body such as the surface of a wall, heat exchange will occur between the solid and the fluid whenever there is a temperature difference between the two. During heating and cooling of gases and liquids the fluid streams exchange heat with solid surfaces by convection.

The magnitude of the fluid motion plays an important role in convective heat transfer. For example, if air is flowing at a high velocity past a hot baked potato, the latter will cool down much faster than if the air velocity was much lower.

Depending on whether the flow of the fluid is artificially induced or natural, there are two types of convective heat transfer: forced convection and free (also called natural) convection. Forced convection involves the use of some mechanical means, such as a pump or a fan, to induce movement of the fluid. In contrast, free convection occurs due to density differences caused by temperature gradients within the system.

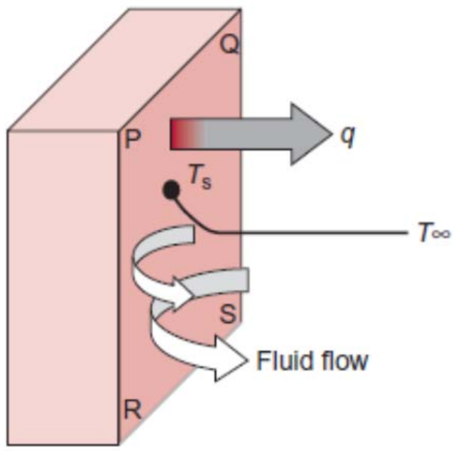

Figure 8: Convective heat flow from the surface of a flat plate.

Consider heat transfer from a heated flat plate, PQRS, exposed to a flowing fluid, as shown in Figure 8. The surface temperature of the plate is T_S, and the temperature of the fluid far away from the plate surface is T_∞.

Overall, we see that the rate of heat transfer from the solid surface to the flowing fluid is proportional to the surface area of solid, A, in contact with the fluid, and the difference between the temperatures T_S and T_∞.

$$q \ \alpha \ A(T_S - T_\infty) \text{ , or}$$

$$q = hA(T_S - T_\infty)$$

The area is A (m^2), and h is the convective heat-transfer coefficient (sometimes called surface heat-transfer coefficient), expressed as W/(m^2 ^oC). This equation is also called Newton's law of cooling. Note that the convective heat transfer coefficient, h, is not a property of the solid material. This coefficient, however, depends on a number of properties of fluid (density, specific heat, viscosity, thermal conductivity), the velocity of fluid, geometry, and roughness of the surface of the solid object in contact with the fluid.

3.3 Radiation Heat Transfer

Radiation heat transfer occurs between two surfaces by the emission and later absorption of electromagnetic waves (or photons). In contrast to conduction and convection, radiation requires no physical medium for its propagation—it can even occur in a perfect vacuum, moving at the speed of light, as we experience everyday solar radiation. Liquids are strong absorbers of radiation. Gases are transparent to radiation, except that some gases absorb radiation of a particular wavelength (for example, ozone absorbs ultraviolet radiation). Solids are opaque to thermal radiation. Therefore, in problems involving thermal radiation with solid materials, such as with solid foods, our analysis is concerned primarily with the surface of the material.

Thermal radiation emitted from an object's surface is proportional to the absolute temperature raised to the fourth power and the surface characteristics. More specifically, the rate of heat emission (or radiation) from an object of a surface area A is expressed by the following equation:

$$q = \sigma \varepsilon A T_A^4$$

where σ is the Stefan-Boltzmann constant, equal to 5.669 x 10^{-8} W/(m^2 K^4); T_A is temperature, Absolute; A is the area (m^2); and ε is emissivity, which describes the extent to which a surface is similar to a blackbody. For a blackbody, the value of emissivity is 1.

Conclusions

In this module we have studied fundamentals of systems for heating and cooling food products. A heat exchanger is a device used to transfer heat between one or more fluids. Plate and Tubular type heat exchangers were detailed in the present module. Thermal properties of foods and beverages must be known to perform the various heat transfer calculations involved in designing equipment and estimating process times for processing foods and beverages. In the present module thermal properties such as specific heat, thermal conductivity and thermal diffusivity were detailed. Finally three different modes of heat transfer, viz., convection, conduction and radiation has been discussed with their governing equations.