Heat Transfer

Introduction

The most common processes found in a food processing plant involve heating and cooling of foods. In the modern industrialized food industry, we commonly find unit operations such as refrigeration, freezing, thermal sterilization, drying, and evaporation. These unit operations involve the transfer of heat between a product and some heating or cooling medium. Heating and cooling of food products is necessary to prevent microbial and enzymatic degradation. In addition, desired sensorial properties—color, flavor, texture—are imparted to foods when they are heated or cooled. The study of heat transfer is important because it provides a basis for understanding how various food processes operate.

Modes of Heat Transfer

In Chapter 1, we reviewed various forms of energy, such as thermal, potential, mechanical, kinetic, and electrical. Our focus in this chapter will be on thermal energy, commonly referred to as heat energy or heat content. Heat energy is simply the sensible and latent forms of internal energy. Recall that 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

$$Q = m\, c_p\, \Delta T \qquad \text{----Eq. 1}$$

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 (°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. For example, to thermally sterilize tomato juice, we raise its heat content by transferring heat from some heating medium such as steam into the juice. In order to design the sterilization equipment, we need to know how much heat is necessary to raise the temperature of tomato juice from the initial to the final sterilization temperature using Equation (1). Furthermore, we need to know the rate at which heat will transfer from steam into the juice first passing through the walls of the sterilizer. Therefore, our concerns in heating calculations are twofold: the quantity of heat transferred, Q, expressed in the units of joule (J); and the rate of heat transfer, q, expressed as joule/s (J/s) or watt (W).

1. Conductive Heat Transfer

Conduction is the mode of heat transfer in which the transfer of energy takes place at a molecular level. There are two commonly accepted theories that describe conductive heat transfer. According to one theory, as molecules of a solid material attain additional thermal energy, they become more energetic and vibrate with increased amplitude of vibration while confined in their lattice. These vibrations are transmitted from one molecule to another without actual translatory motion of the molecules. Heat is thus conducted from regions of higher temperature to those at lower temperature. The second theory states that conduction occurs at a molecular level due to the drift of free electrons. These free electrons are prevalent in metals, and they carry thermal and electrical energy. For this reason, good conductors of electricity such as silver and copper are also good conductors of thermal energy. Note that in conductive mode, there is no physical movement of the object undergoing heat transfer.

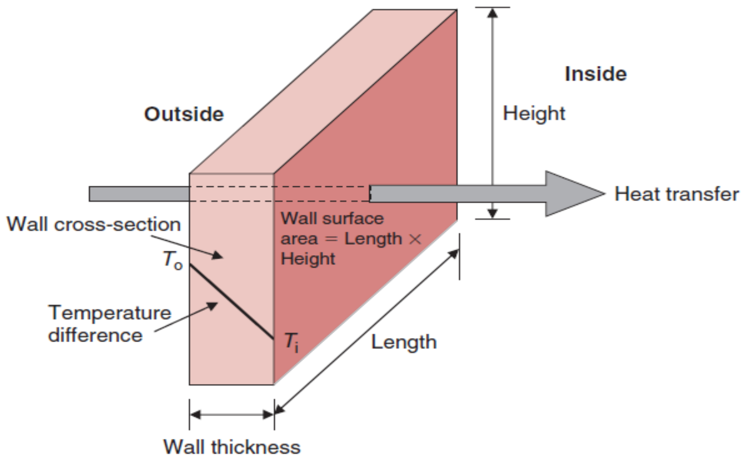

Figure 1. Conductive heat flow in a wall.

Conduction is the common mode of heat transfer in heating/cooling of opaque solid materials. From everyday experience, we know that on a hot day, heat transfer from the outside to the inside through the wall of a room (Fig. 1) depends on the surface area of the wall (a wall with larger surface area will conduct more heat), the thermal properties of construction materials (steel will conduct more heat than brick), wall thickness (more heat transfer through a thin wall than thick), and temperature difference (more heat transfer will occur when the outside temperature is much hotter than the inside room temperature). In other words, the rate of heat transfer through the wall may be expressed as:

$$q \propto \frac{\text{(wall surface area)(temperature difference)}}{\text{(wall thickness)}} \qquad \text{---- (Eq. 2)}$$

Or,

$$q_x \propto \frac{A\,\mathrm{d}T}{\mathrm{d}x} \qquad \text{---- (Eq. 3)}$$

or, by inserting a constant of proportionality,

$$q_x = -kA\frac{\mathrm{d}T}{\mathrm{d}x} \qquad \text{---- (Eq. 4)}$$

where q_x is the rate of heat flow in the direction of heat transfer by conduction (W); k is thermal conductivity (W/[m °C]); A is area (normal to the direction of heat transfer) through which heat flows (m^2); T is temperature (°C); and x is length (m), a variable.

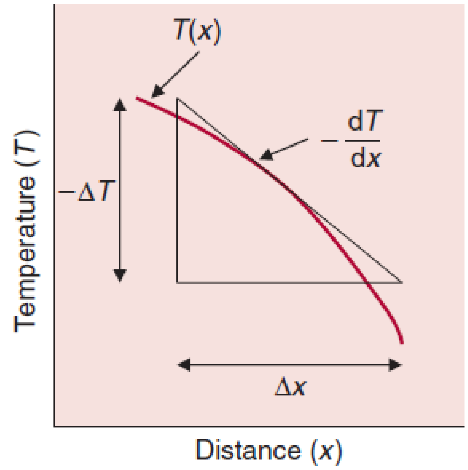

Figure 2. Sign convention for conductive heat flow.

Equation (3) is also called the 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. As shown in Figure 2, the gradient dT/dx is negative, because temperature decreases with increasing values of x. Therefore, in Equation (3), a negative sign is used to obtain a positive value for heat flow in the direction of decreasing temperature.

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. The complex behavior of fluid flow next to a solid surface, as seen in velocity profiles for laminar and turbulent flow conditions, make the determination of convective heat transfer a complicated topic.

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. Both of these mechanisms may result in either laminar or turbulent flow of the fluid, although turbulence occurs more often in forced convection heat transfer.

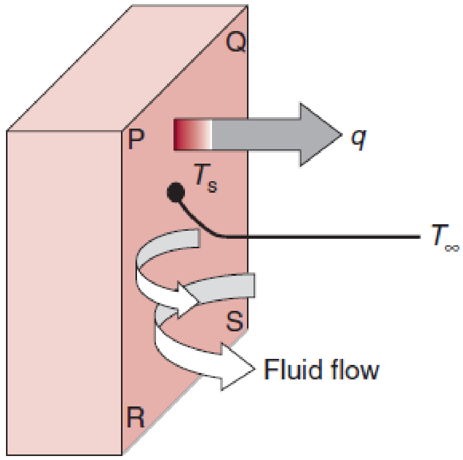

Figure 3. Convective heat flow from the surface of a l at plate.

Consider heat transfer from a heated fl at plate, PQRS, exposed to a flowing fluid, as shown in Figure 3. The surface temperature of the plate is T_s, and the temperature of the fluid far away from the plate surface is T_∞ . Because of the viscous properties of the fluid, a velocity profile is set up within the flowing fluid, with the fluid velocity decreasing to zero at the solid surface. 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_∞.

$$q \propto A(T_s - T_\infty) \qquad \text{---- (Eq. 5)}$$

Or,

$$q = hA(T_s - T_\infty) \qquad \text{---- (Eq. 6)}$$

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 °C). This equation is also called Newton's law of cooling.

Table 1. Some Approximate Values of Convective Heat-Transfer Coefficient

Fluid	**Convective heat-transfer coefficient (W/[m^2 K])**
Air	
Free convection	5–25
Forced convection	10–200
Water	
Free convection	20–100
Forced convection	50–10,000
Boiling water	3000–100,000
Condensing water vapor	5000–100,000

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. Table 1 gives some approximate values of h. A high value of h reflects a high rate of heat transfer. Forced convection offers a higher value of h than free convection. For example, you feel cooler sitting in a room with a fan blowing air than in a room with stagnant air.

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. This is in contrast to microwave and radio frequency radiation, where the wave penetration into a solid object is significant.

All objects at a temperature above 0 Absolute emit thermal radiation. 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:

$$q = \sigma \varepsilon A T_{\mathrm{A}}^4 \qquad \text{---- (Eq. 7)}$$

where σ is the Stefan–Boltzmann constant, equal to 5.669×10^{-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.