Chapter 6 Basic Heat Transfer

(Key Refs: Geankoplis, Ch.4, and McCabe et al., 5th ed, Chts.10-12)

1. Introduction

Physical processes involving the transfer of heat from one point to another are often encountered in the chemical plants and many other process plants. The heating and cooling of liquids or solids, the condensation of vapours, and the removal of heat liberated by chemical reactions are common examples of processes which involve heat transfer. Because of the many applications of heat transfer principles, it is important for chemical and other process engineers to understand the practical aspects as well as the basic laws governing this operation.

Heat transfer as a unit operation is usually only one part of an overall process, and the interrelations among the different operations involved must be recognised. For example, a sodium hydroxide-water mixture may be concentrated by use of an evaporator. In order for the evaporation to proceed at an appreciable rate, heat must be added to the liquid mixture. This heat may be supplied by steam condensing inside pipes immersed in the liquid.

In order for heat to flow, there must be a driving force. This driving force is the temperature difference between the points where heat is received and where heat is originated. Similar to fluid flow from a point of high pressure to a point of low pressure, heat tends to flow in the direction from high temperature to low temperature.

Basic Means of Heat Transfer

There are three basic means of heat transfer, conduction, convection and radiation. In many cases, heat transfer occurs in more than one ways simultaneously.

- **Conduction (Molecular Transport)** of heat in a solid or fluid media results from the vibration of molecules and propagation of the vibration to the adjacent molecules. Although the molecules vibrate in just one spot, their energy is transmitted; the heat flows from the hot end to the cool end of the material without actual material flow. Conduction is the major means of heat transfer in a solid object.

- **Convection** heat transfer occurs through the physical movement of particles in a fluid media. There are two types of convection, one is called natural convection which is caused by difference in the density of the hot and the cold fluid; the other is called forced convection, which is achieved through mechanically mixing the hot and cold fluid.

- **Radiation:** The heat transfer between two objects, which are physically separated, through wave motion in space. Any object with a temperature above absolute zero emits radiant energy in all directions, and the radiation power is a function of temperature.

Usually more than one means of heat transfer are involved in one system. In most cases of chemical processes, conduction and convection are the common means of heat transfer, and
radiation heat becomes important only at very high temperatures or in special processes. In this lecture, we mainly study heat transfer calculations involving conduction and convection.

2. Heat Transfer by Conduction

2.1. Fourier's Law of Heat Conduction

The rate of heat transfer through a homogeneous body by conduction \( q \) is directly proportional to the temperature-difference driving force across the body \( dT \) and to the cross-sectional area \( A \) of the body. The rate of heat transfer is inversely proportional to the thickness of the body (i.e., the length of the path that the heat flows, \( dx \)). The relationship can be expressed mathematically as,

\[
q = -kA \frac{dT}{dx} \quad (1)
\]

where the proportionality constant, \( k \), is thermal conductivity of the material through which heat is conducted. The minus sign signifies that heat flow along the decreasing temperature gradient. Thermal conductivity is a physical property of material and it varies somewhat with temperature. In many heat transfer situations an average value over the temperature range is adequate. Rate of heat transfer \( q \) is measured in watts or Btu/h, and \( dT/dx \) in °C/m or °F/ft. Then the unit for \( k \) is W/m-°C or Btu/ft-hr-°F. Conversion: 1 Btu/ft-hr-°F=4.1365×10^{-3} \text{ cal/s.cm.°C}=1.73073 \text{ W/m.K}.

2.2. Steady-state heat conduction through a flat wall

Consider a flat wall of thickness \( x_w \) and cross-section area \( A \), and temperature \( T_1 \) on one side and \( T_2 \) on the other, and the conductivity of the wall material \( k \) (uniform everywhere in the wall) (Fig. 1). The conduction heat transfer rate may be obtained from Fourier's law by integration of eq. 1, which leads to the following equation,

\[
q = \frac{T_1 - T_2}{x_w/kA} = \frac{T_1 - T_2}{R} \quad (2)
\]

where \( R=x_w/kA \) is the resistance of heat transfer of the wall, while \( (T_1-T_2) \) is the temperature difference, the driving force of heat transfer. Therefore, (heat transfer rate) = (driving force/resistance).

2.3. Steady-heat conduction through a cylindrical wall

Consider a tube of inside diameter \( D_i \), outside diameter \( D_o \) and length \( L \), and that heat is flowing radially from the inside surface to the outside (Fig. 2). The inside surface area is \( A_i = \pi D_i L \) and the...
outside surface $A_o = \pi D_o L$. The log-mean heat transfer area of the pipe is defined as,

$$A_{lm} = \frac{A_o - A_i}{\ln(A_o/A_i)} \quad (3)$$

The log-mean area takes account of the variation of the heat transfer area with the pipe radius ($r$),

$$A = 2\pi r L.$$  

The conduction heat transfer rate through the cylindrical wall can then be calculated with the same equation as eq.2 above, while the heat transfer area $A$ is replaced by $A_{lm}$, and the heat transfer resistance is

$$R = \frac{x_w}{k A_{lm}} \quad (4)$$

where the pipe wall thickness $x_w = (D_i - D_o)/2$

### 2.4. Conduction of heat through solid walls in series

Consider the multi-layer wall of more than one material as shown in the diagram (Fig. 3). Assumptions: steady heat transfer, i.e., constant heat transfer rate through each wall, and all the walls have the same cross-section area, $A$, then

$$q = \frac{T_1 - T_4}{R_A + R_B + R_C} \quad (5)$$

where the heat resistance of the walls is given by

$$R_A = \frac{x_A}{k_A A}, \quad R_B = \frac{x_B}{k_B A}, \quad R_C = \frac{x_C}{k_C A} \quad (6)$$

For cylindrical walls in series (Fig. 4), the equation same as (5) applies, but the heat transfer resistance should be replaced by,

$$R_A = \frac{x_A}{k_A A_{lm}}, \quad R_B = \frac{x_B}{k_B A_{lm}}, \quad R_C = \frac{x_C}{k_C A_{lm}} \quad (7)$$

A general equation for heat transfer through composite walls can be written as
3. Heat Transfer by Convection

Heat transfer from a warmer fluid to a cooler fluid, usually through a wall separating the fluids, is common in chemical processes. In this case, heat is transferred from the hot fluid to the wall surface by convection, then through the wall by conduction from hot side to the cold side, and finally from the cold wall surface to the cold fluid by convection. Convection is the principal means of heat transfer in most fluid media. Unlike conduction through solid walls, in convection we deal with fluids, which are constantly in motion. Fortunately, with a few reasonable assumptions, we can use the similar equations to those for conduction to estimate convection heat transfer.

3.1. Estimation of Convection Heat Transfer

When a fluid is flowing past a stationary surface, a thin film is postulated as existing between the flowing fluid and the stationary surface. It is assumed that all the resistance to transmission of heat between the flowing fluid and the stationary surface is due to this film (Fig.). If the film thickness is $x_f$, and the heat conductivity of the fluid is $k_f$, the rate of heat transfer through the film, according to Fourier's law of heat conduction, is given by

$$q = \frac{k_f}{x_f} A_f \Delta T_f$$

where $A_f$= heat transfer area of the film, $\Delta T_f$=mean temperature difference between the bulk fluid and the wall surface ($=T_w-T_b$). In practice, however, the thickness $x_f$ of the imaginary film is hard to define. In engineering, the term $k_f/x_f$ is replaced by a film heat transfer coefficient, $h$, so that

$$q = h A_f \Delta T_f$$

The film coefficient is a function of the flow conditions as well as physical properties of the fluid, and is usually determined through experiments or with empirical equations. It has the units $\text{W/m}^2\cdot\text{K}$ in SI and $\text{Btu/h-ft}^2\cdot\text{F}$ in American Eng unit system ($1 \text{ Btu/h-ft}^2\cdot\text{F}=5.6783 \text{ J/s-m}^2\cdot\text{K}$). Pay attention to the difference in the dimension of $h$ from that of $k$ as well as the fundamental differences between the two.
3.2. Overall Heat Transfer Coefficient (Convection plus Conduction)

Heat flow from one fluid through a solid wall into another fluid must overcome several resistances in series, including the resistances of the fluid films and that of the solid wall (Fig. 5). The total flow of heat is proportional to the heat transfer area, and to the overall temperature difference, i.e.,

\[ q = U A \Delta T_{\text{overall}} = \frac{T_h - T_c}{1/UA} \]  \hspace{1cm} (10)

where \( \Delta T_{\text{overall}} \) is the overall temperature difference between the hot (\( T_h \)) and the cold fluid (\( T_c \)), the proportionality constant \( U \) is termed as the overall heat-transfer coefficient (\( h \) as the individual heat-transfer coefficient), and \( 1/UA \) may be considered as the total heat resistance.

In the case of heat transfer from a liquid through a solid wall and into another fluid (the two fluids are separated by the wall), the following relationship applies,

\[ R = \frac{1}{UA} = \frac{1}{h_i A_i} + \frac{x_w}{k_w A_w} + \frac{1}{h_o A_o} \]  \hspace{1cm} (11)

where \( A = \) the base area chosen for the evaluation of \( U, A_i, A_o = \) inner and outer wall surface area, respectively, \( A_w = \) mean wall area, \( x_w = \) wall thickness, \( k_w = \) wall thermal conductivity. Therefore, the total heat transfer resistance here is the sum of resistance of the two fluid films (\( R_i = 1/h_i A_i \) and \( R_o = 1/h_o A_o \)) and that of the wall (\( R_w = x_w/k_w A_w \)). The heat transfer areas:

- For flat walls, all the areas are the same \( A = A_i = A_o = A_w \)
- For cylindrical (pipe) walls, \( A_i = \pi D_i L, A_o = \pi D_o L, A_w = A_{lm} \)

For a cylindrical (pipe) wall, the base area may be either \( A_i \) or \( A_o \), and correspondingly, the overall coef. may be either \( U_i \) or \( U_o \). No matter which area is chosen as the basis, the heat transfer rate obtained from eq.(10) should be equal, i.e.,

\[ q = U A \Delta T_{\text{overall}} = U_i A_i \Delta T_{\text{overall}} = U_o A_o \Delta T_{\text{overall}} \]  \hspace{1cm} (12)

Obviously, \( UA = U_i A_i = U_o A_o \).

3.3. The Log-Mean Temperature Difference

For heat transfer between two flowing fluids with one inside and the other outside a tube (e.g., double-pipe heat exchanger as shown in Fig. 6), the temperature difference between the two fluids varies from the inlet to the outlet. In this case calculation of heat transfer rate (with the previous eqs.) should use the log-mean temperature difference (LMTD) as given by,

\[ \Delta T_{\text{lm}} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} \]  \hspace{1cm} (13)

The \( \Delta T \)'s are represented by (see diagram in the last page),

- Counter-current flow: \( \Delta T_1 = T_{hi} - T_{co} \) \hspace{1cm} \( \Delta T_2 = T_{ho} - T_{ci} \)
Parallel/Co-current flow: $\Delta T_1 = T_{hi} - T_{ci}$  \hspace{1cm} $\Delta T_2 = T_{ho} - T_{co}$

The subnote $i$ is for inlet, $o$ for outlet, and, $c$ is for cold fluid, $h$ for hot.

4. Shell-and-Tube Heat Exchangers

Such tubular exchangers are made up of bundles of tubes in parallel and series which are enclosed in a shell (Fig. 8). In a shell-and-tube exchanger, one fluid (tube-side fluid) flows through the tubes and the other (shell-side fluid) flows outside the tubes. Shell-and-tube exchangers are the most commonly used industrial heat exchangers (high capacity with a large area to volume ratio).

Double-pipe heat exchangers may be considered as the simplest form of shell-and-tube exchanger, consisting of a single tube placed concentrically inside a shell (Fig. 6 and Fig. 9). Double-pipe heat exchangers are used primarily for low flow rates and high temperature ranges. These double-pipe sections are well-adapted to high temperature and high pressure applications because of their relatively small diameters, which allow the use of small flanges and thin wall sections as compared with conventional shell-and-tube equipment.
5. Heat Transfer and Energy Balances

Based on energy balance, the heat released by the hot (or heating) fluid should equal the heat gained by the cold (or cooling) fluid in a heat exchanger, if heat loss is negligible. The rate of heat release and gain should then equal the rate transfer as given by

\[ q = UA \Delta T_m = -q_h = q_c \]

where \( \Delta T_m \) = mean temperature difference between the hot and the cold fluids, \( q_h \) = heat released by the hot fluid, and \( q_c \) = heat absorbed by the cold fluid.

The gaining or loosing heat can involve a temperature change in the fluid, known as the sensible heat,

\[ q = mC_p(T_i - T_o) \]

where \( m \) = mass flow rate, \( C_p \) = specific heat, \( T_i \) = fluid temperature at the inlet, \( T_o \) = fluid temp. at the outlet. It may also involve a phase transition, latent heat: \( H_v \), heat of vaporization or condensation. As learnt in energy balance, the above heats may also be estimated based on enthalpy changes,

\[ q = m(\hat{H}_i - \hat{H}_o) \]

where \( \hat{H}_i, \hat{H}_o \) = specific enthalpy (enthalpy per unit mass) of the fluid at the inlet and the outlet of the exchanger, respectively. For water and steam, specific enthalpy may be found from a steam table with given temperature and pressure.

Summary of heat transfer (conduction and convection)

1. The basic means or mechanisms of heat transfer: conduction, convection and radiation.
2. Fourier’s law of conduction heat transfer, conduction through flat walls and circular walls, single wall and composite walls.
3. Convective heat transfer (in fluid media), the film concept and the film heat transfer coefficient, the overall heat transfer coefficient (between two fluids separated by a solid wall) and resistance. Understand all the terms in \( q = hA_f \Delta T_f = U_fA_f \Delta T_m = U_oA_o \Delta T_m \) and be able to calculate all of them.
4. Log-mean quantities, \( A_{im}, \Delta T_{lm} \) (know when do you use them), LMTD in parallel flow and countercurrent flow.
5. Understand the major factors affecting the convective heat transfer coef. and the ways to improve heat transfer in heat exchangers.
6. Calculation of heat transfer and energy balance simultaneously.