Chapter 6 Basic Heat Transfer

(Key Refs: Geankoplis, Cht.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** of the body (A). 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,

$$q = -kA\frac{dT}{dx} \qquad (1)$$

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 ^{o}C/m or ^{o}F/ft. Then the **unit for k is W/m-^{o}C or Btu/ft-hr-^{o}F**. Conversion: 1 Btu/ft-h-^{o}F=4.1365×10^{-3} cal/s.cm.^{o}C=1.73073 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,

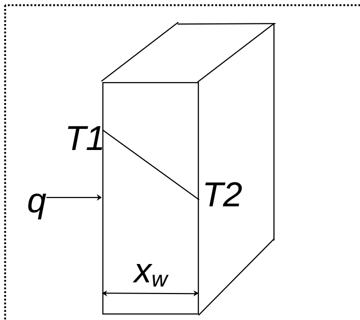

Fig. 1 Conduction heat transfer through a flat wall.

$$q = \frac{T_1 - T_2}{x_w/kA} = \frac{T_1 - T_2}{R} \qquad (2)$$

where $\boldsymbol{R = x_w/kA}$ 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 $\boldsymbol{A_i = \pi D_i L}$ and the

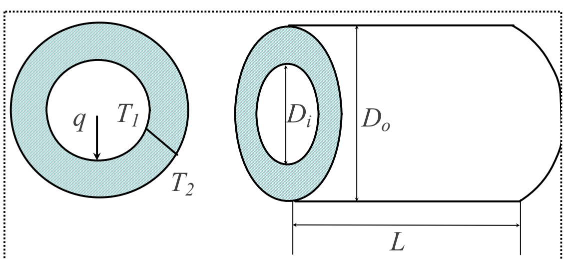

Fig. 2 Conduction heat transfer through a cylindrical wall.

outside surface $\boldsymbol{A_o = \pi D_o L}$. The *log-mean* heat transfer area of the pipe is defined as,

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

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

$$\boldsymbol{A = 2\pi r L}.$$

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

$$R = \frac{x_w}{kA_{lm}} \qquad (4)$$

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

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

where the heat resistance of the walls is given by

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

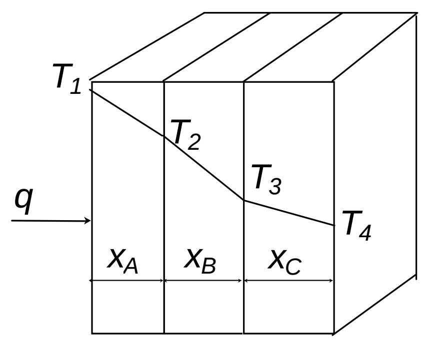

Fig. 3 Conduction heat transfer through a series of flat walls.

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

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

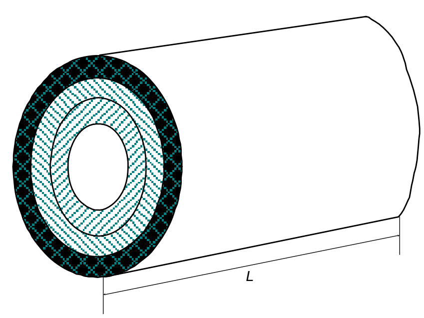

Fig. 4 Conduction heat transfer through a series of cylindrical walls.

A general equation for heat transfer through composite walls can be written as

$$q = \frac{T_1 - T_n}{\Sigma R_i} \qquad (8)$$

i stands for the ith wall, and can be from 1 to any number of walls. Therefore, the heat transfer resistance is additive, similar to the conduction of electricity through a series of resistance.

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, ΔT_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

$$q = hA_f \Delta T_f \qquad (9)$$

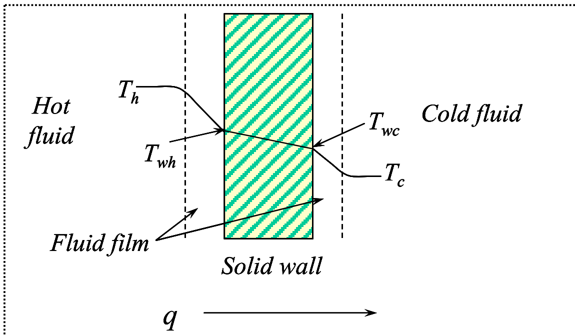

Fig. 5 Film model for convective heat transfer from a hot fluid to a cold fluid through a solid wall.

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 of J/s-m^2-^{o}C in SI and Btu/h-ft^2-^{o}F in American Eng unit system (1 Btu/h-ft^2-^{o}F=5.6783 J/s-m^2-^{o}C). 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.,

$$q = UA\Delta T_{overall} = \frac{T_h - T_c}{1/UA} \qquad (10)$$

where $\Delta T_{overall}$ 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,

$$R = \frac{1}{UA} = \frac{1}{h_i A_i} + \frac{x_w}{k A_w} + \frac{1}{h_o A_o} \qquad (11)$$

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,$=1/h_iA_i$ and $R_o = 1/h_oA_o$) and that of the wall (R_w,$=x_w/k_wA_w$). 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.,

$$q = UA\Delta T_{overall} = U_i A_i \Delta T_{overall} = U_o A_o \Delta T_{overall} \qquad (12)$$

Obviously, $UA = U_iA_i = U_oA_o$.

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,

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} \qquad (13)$$

The ΔT's are represented by (see diagram in the last page),

- Counter-current flow: $\boldsymbol{\Delta T_1 = T_{hi} - T_{co}}$ $\boldsymbol{\Delta T_2 = T_{ho} - T_{ci}}$

- Parallel/Co-current flow: $\Delta T_1 = T_{hi} - T_{ci}$ $\Delta T_2 = T_{ho} - T_{co}$

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

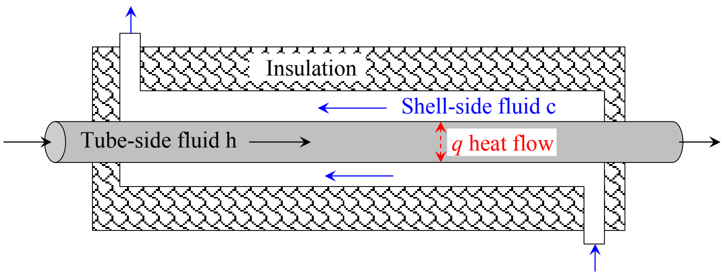

Fig. 6 Fluid flow and heat transfer in a double-pipe heat exchanger (countercurrent flow).

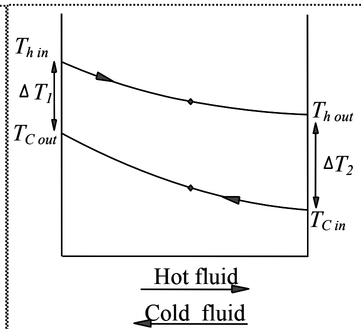

Fig. 7 Temperature profile in countercurrent flow.

Countercurrent and Co-current (parallel) flow: The two fluids in a heat exchanger can flow either in parallel or in opposite directions. Parallel flow is rarely used in practice, though it may be encountered in multipass heat exchangers due to mechanical reasons. In parallel flow, the heat transferred is less than possible in countercurrent flow, due to the smaller log-mean temperature-difference driving force.

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).

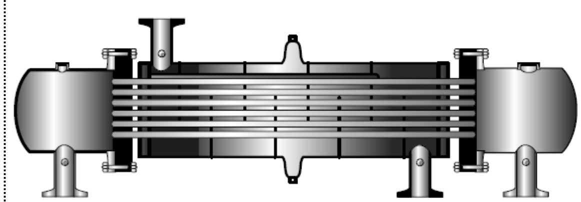

Fig. 8 Schematic diagram of a shell and tube heat exchanger (Himmelbalu, problems workbook)

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.

Fig. 9 A double pipe heat exchanger

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 ΔT_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 $q=hA_f\Delta T_f=U_iA_i\Delta T_m=U_oA_o\Delta T_m$ and be able to calculate all of them.

4. Log-mean quantities, A_{lm}, ΔT_{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.