Chapter 7 Heat Exchangers

7-1 Introduction

The application of the principles of heat transfer to the design of equipment to accomplish a certain engineering objective is of extreme importance, for in applying the principles to design, the individual is working toward the important goal of product development for economic gain. Eventually, economics plays a key role in the design and selection of heat-exchange equipment, and the engineer should bear this in mind when embarking on any new heat-transfer design problem. The weight and size of heat exchangers used in space or aeronautical applications are very important parameters, and in these cases cost considerations are frequently subordinated insofar as material and heat-exchanger construction costs are concerned; however, the weight and size are important cost factors in the overall application in these fields and thus may still be considered as economic variables.

7-2 The Overall Heat-Transfer Coefficient

We have already discussed the overall heat-transfer coefficient in chapter 2 with the heat transfer through the plane wall of Figure 7-1 expressed as

$$q = \frac{T_A - T_B}{\frac{1}{h_1 A} + \frac{\Delta x}{kA} + \frac{1}{h_2 A}} \qquad 7\text{-}1$$

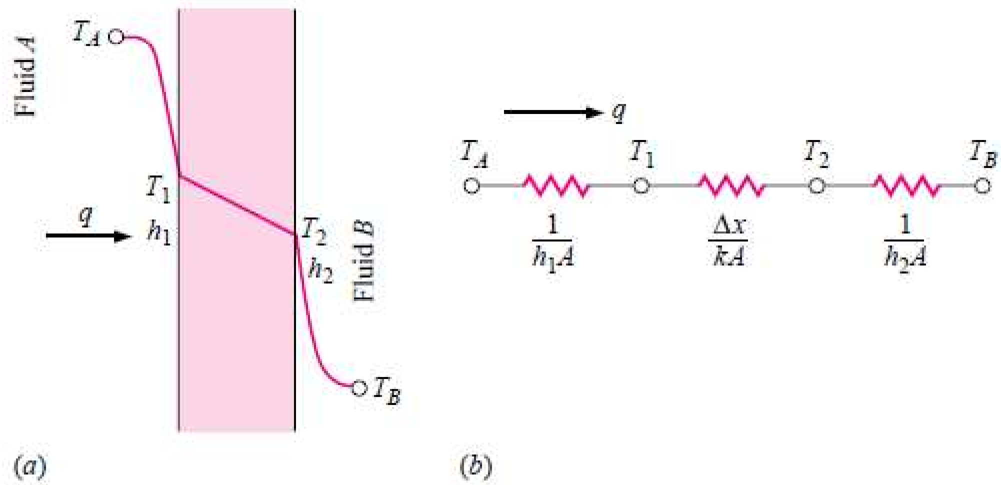


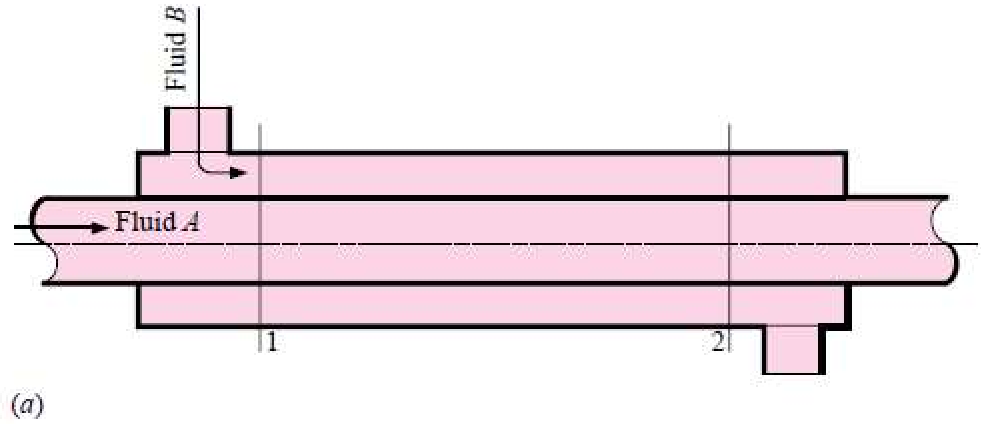
Figure 7-1 Overall heat transfer through a plane wall.

where T_A and T_B are the fluid temperatures on each side of the wall. The overall heat-transfer coefficient U is defined by the relation

$$q = UA\Delta T_{overall} \qquad 7\text{-}2$$

From the standpoint of heat-exchanger design, the plane wall is of infrequent application; a more important case for consideration would be that of a double-pipe heat exchanger, as shown in Figure 7-2. In this application one fluid flows on the inside of the smaller tube while the other fluid flows in the annular space between the two tubes. The convection coefficients are calculated by the methods described in previous chapters, and the overall heat transfer is obtained from the thermal network of Figure 7-2*b* as

$$q = \frac{T_A - T_B}{\frac{1}{h_i A_i} + \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi kL} + \frac{1}{h_o A_o}} \qquad 7\text{-}3$$



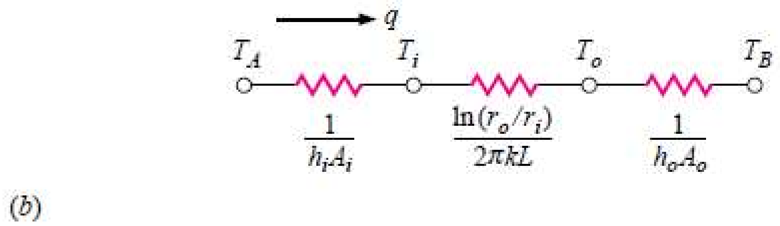


Figure 7-2 Double-pipe heat exchange: (*a*) schematic; (*b*) thermal-resistance network for overall heat transfer.

where the subscripts *i* and *o* pertain to the inside and outside of the smaller inner tube. The overall heat-transfer coefficient may be based on either the inside or outside area of the tube at the discretion of the designer. Accordingly,

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{A_i \ln\left(\frac{r_o}{r_i}\right)}{2\pi kL} + \frac{A_i}{h_o A_o}} \qquad \text{7-4a}$$

$$U_o = \frac{1}{\frac{A_o}{A_i h_i} + \frac{A_o \ln\left(\frac{r_o}{r_i}\right)}{2\pi kL} + \frac{1}{h_o}} \qquad \text{7-4b}$$

10-4 Types of Heat Exchangers

10-4-1 Double Pipe Heat Exchanger

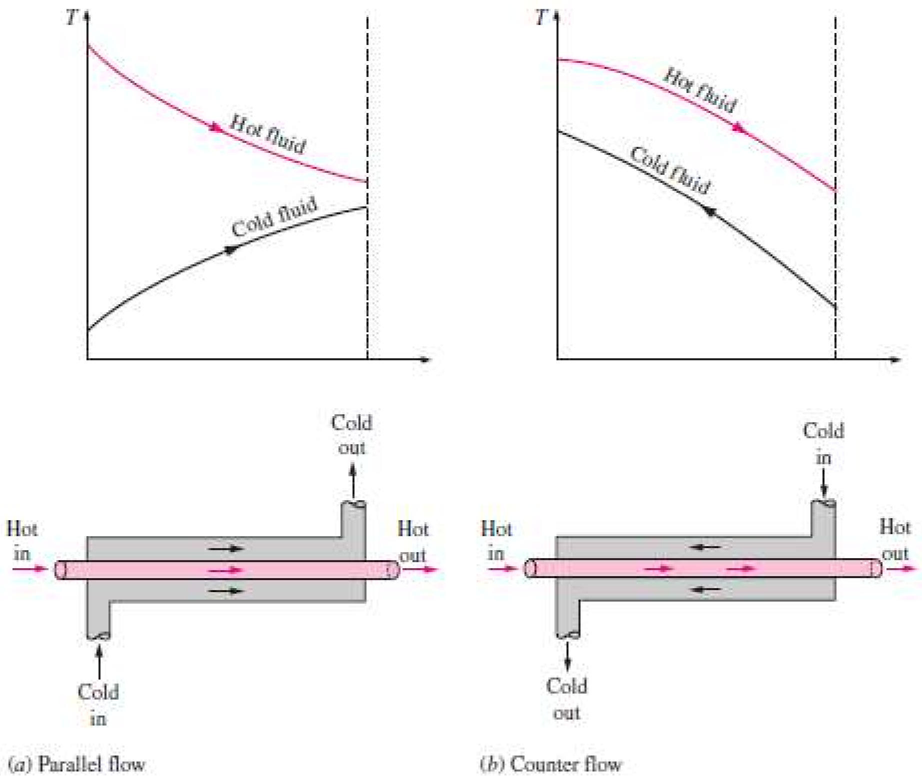


Figure 7–3 Different flow regimes and associated temperature profiles in a double-pipe heat exchanger.

7-4-2 Cross Flow Heat Exchanger

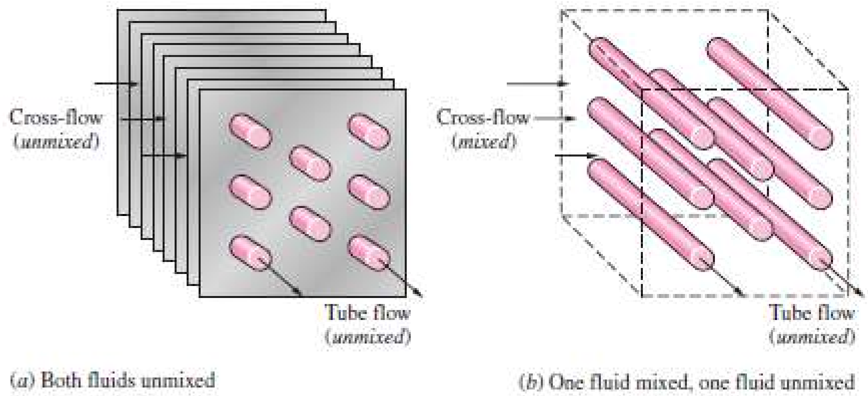


Figure 7–4 Different flow configurations in cross-flow heat exchangers.

7-4-3 Shell And Tube Heat Exchanger

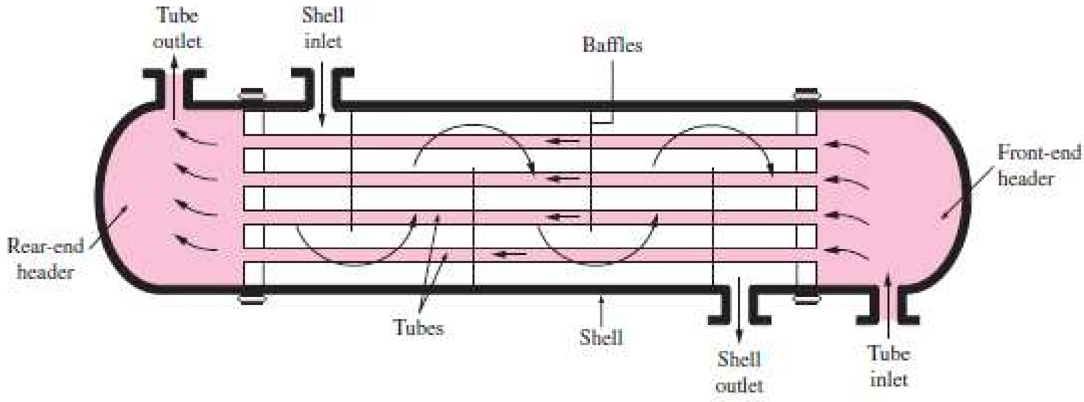


Figure 7–5 The schematic of a shell-and-tube heat exchanger (one-shell pass and one-tube pass).

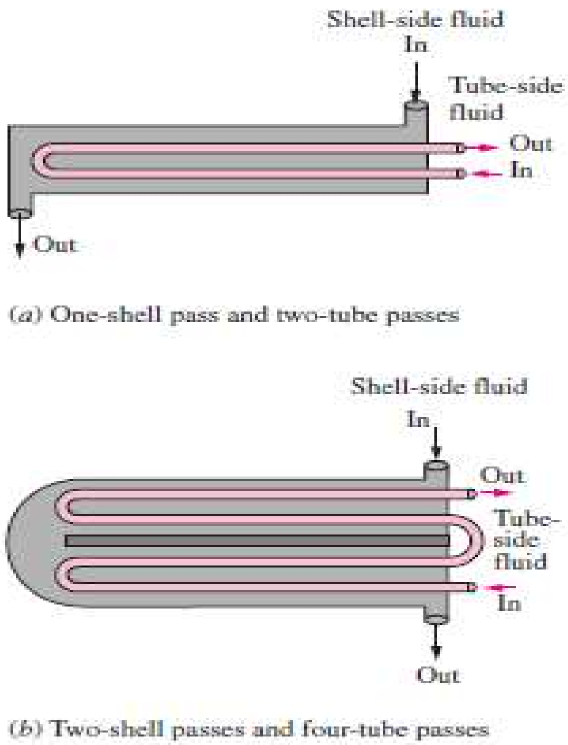


Figure 7–6 Multi-pass flow arrangements in shell and- tube heat exchangers.

7-4-4 Flat Plate Heat Exchanger

Figure 7–7 Flat plate heat exchanger.

7-5 THE LOG MEAN TEMPERATURE DIFFERENCE

Consider the double-pipe heat exchanger shown in Figure 7-2. The fluids may flow in either parallel flow or counterflow, and the temperature profiles for these two cases are indicated in Figure 7-8. We propose to calculate the heat transfer in this double-pipe arrangement

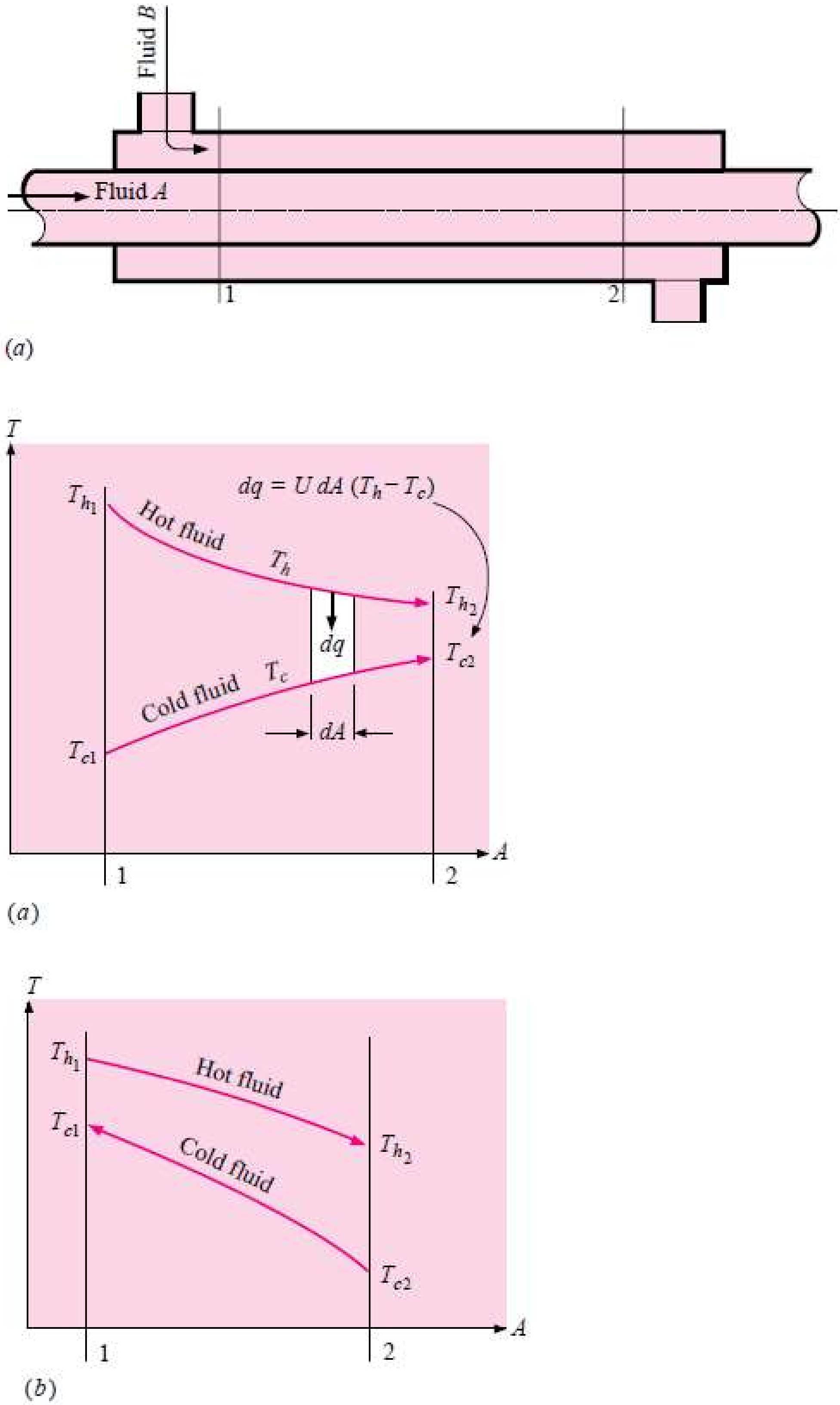


Figure 7-8 Temperature profiles for (*a*) parallel flow and (*b*) counterflow in double pipe heat exchanger.

$q = UA\Delta T_m$ 7-5

where

U = overall heat-transfer coefficient

A = surface area for heat transfer consistent with definition of U

ΔT_m = suitable mean temperature difference across heat exchanger

For the parallel-flow heat exchanger shown in Figure 7-8, the heat transferred through an element of area dA may be written

$dq = -\dot{m}_h c_h dT_h = \dot{m}_c c_c dT_c$ 7-6

where the subscripts *h* and *c* designate the hot and cold fluids, respectively. The heat transfer could also be expressed

$dq = U(T_h - T_c)dA$ 7-7

From Equation (7-6)

$$dT_h = \frac{-dq}{\dot{m}_h c_h}$$

$$dT_c = \frac{dq}{\dot{m}_c c_c}$$

where $\dot{m}$ represents the mass-flow rate and *c* is the specific heat of the fluid. Thus

$dT_h - dT_c = d(T_h - T_c) = -dq\left(\frac{1}{\dot{m}_h c_h} + \frac{1}{\dot{m}_c c_c}\right)$ 7.8

Solving for *dq* from Equation (7-7) and substituting into Equation (7-8) gives

$\frac{d(T_h - T_c)}{T_h - T_c} = -U\left(\frac{1}{\dot{m}_h c_h} + \frac{1}{\dot{m}_c c_c}\right)dA$ 7-9

This differential equation may now be integrated between conditions 1 and 2 as indicated in Figure 7-8. The result is

$\ln\frac{T_{h2} - T_{c2}}{T_{h1} - T_{c1}} = -UA\left(\frac{1}{\dot{m}_h c_h} + \frac{1}{\dot{m}_c c_c}\right)$ 7-10

Returning to Equation (7-6), the products $\dot{m}_c c_c$ and $\dot{m}_h c_h$ may be expressed in terms of the total heat transfer q and the overall temperature differences of the hot and cold fluids. Thus

$$\dot{m}_h c_h = \frac{q}{T_{h1} - T_{h2}}$$

$$\dot{m}_c c_c = \frac{q}{T_{c2} - T_{c1}}$$

Substituting these relations into Equation (7-10) gives

$$q = UA \frac{(T_{h2} - T_{c2}) - (T_{h1} - T_{c1})}{\ln\left[\frac{(T_{h2} - T_{c2})}{(T_{h1} - T_{c1})}\right]} \qquad 7\text{-}11$$

Comparing Equation (7-11) with Equation (7-5), we find that the mean temperature difference is the grouping of terms in the brackets. Thus

$$\Delta T_m = \frac{(T_{h2} - T_{c2}) - (T_{h1} - T_{c1})}{\ln\left[\frac{(T_{h2} - T_{c2})}{(T_{h1} - T_{c1})}\right]} = \frac{(T_{h1} - T_{c1}) - (T_{h2} - T_{c2})}{\ln\left[\frac{(T_{h1} - T_{c1})}{(T_{h2} - T_{c2})}\right]} \qquad 7\text{-}12$$

This relation may also be used to calculate the LMTDs for counterflow conditions.

The above derivation for LMTD involves two important assumptions: (1) the fluid specific heats do not vary with temperature, and (2) the convection heat-transfer coefficients are constant throughout the heat exchanger.

If a heat exchanger other than the double-pipe type is used, the heat transfer is calculated by using a correction factor applied to the LMTD ***for a counterflow double-pipe arrangement with the same hot and cold fluid temperatures.*** The heat-transfer equation then takes the form

$$q = UAF\Delta T_m \qquad 7\text{-}13$$

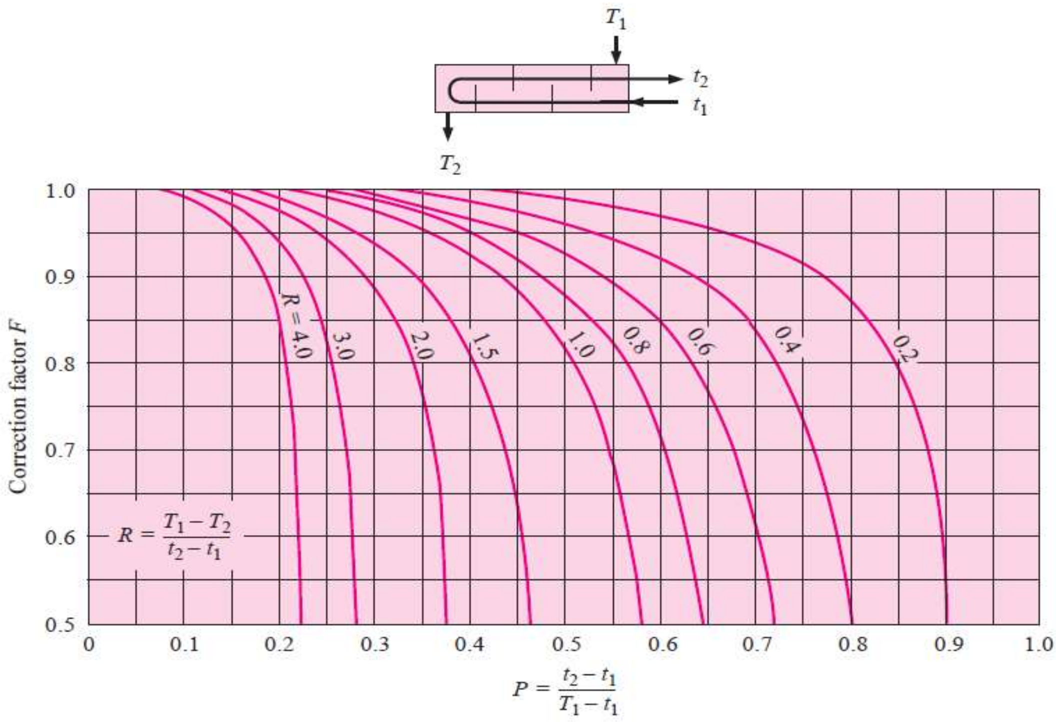


Figure 7-9 Correction-factor plot for exchanger with one shell pass and two, four, or any multiple of tube passes.

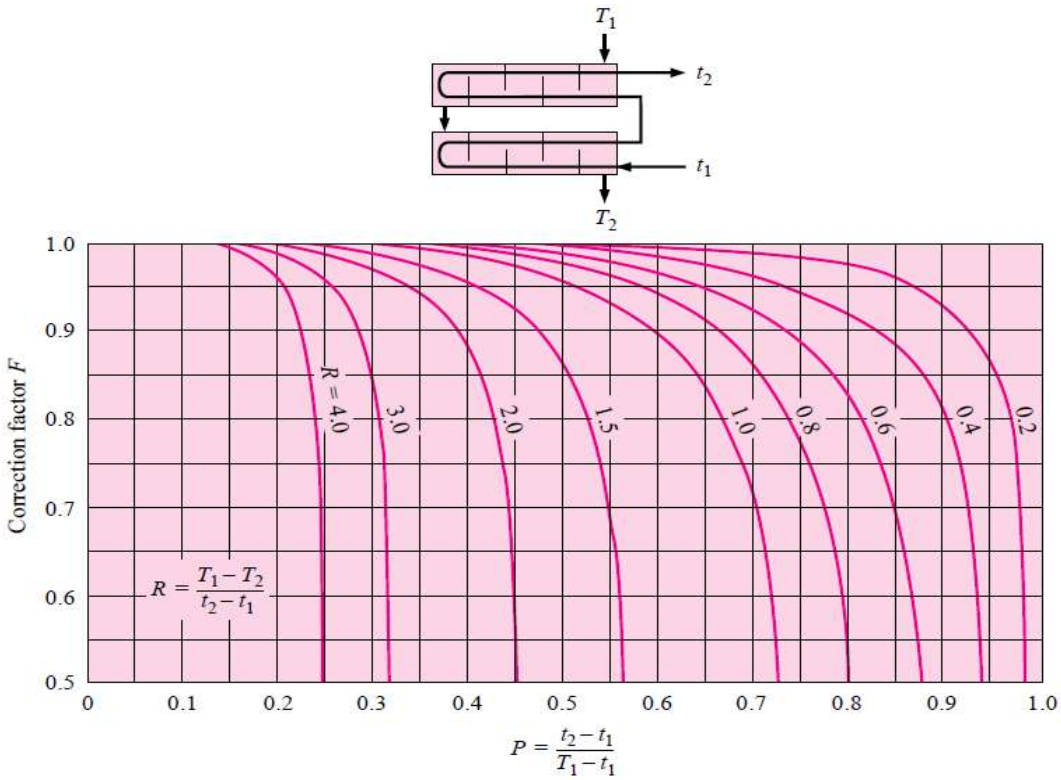


Figure 7-10 Correction-factor plot for exchanger with two shell passes and four, eight, or any multiple of tube passes.

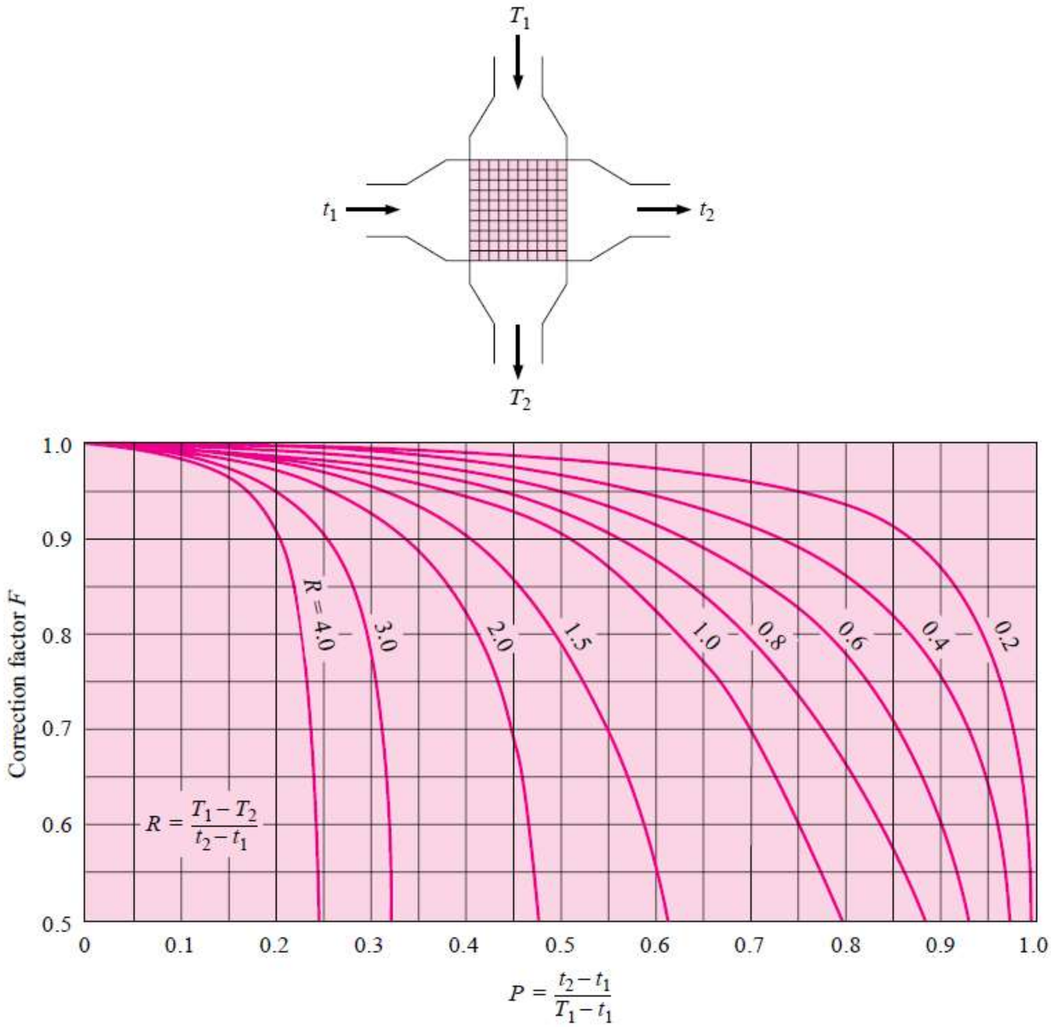


Figure 7-11 Correction-factor plot for single-pass cross-flow exchanger, both fluids unmixed.

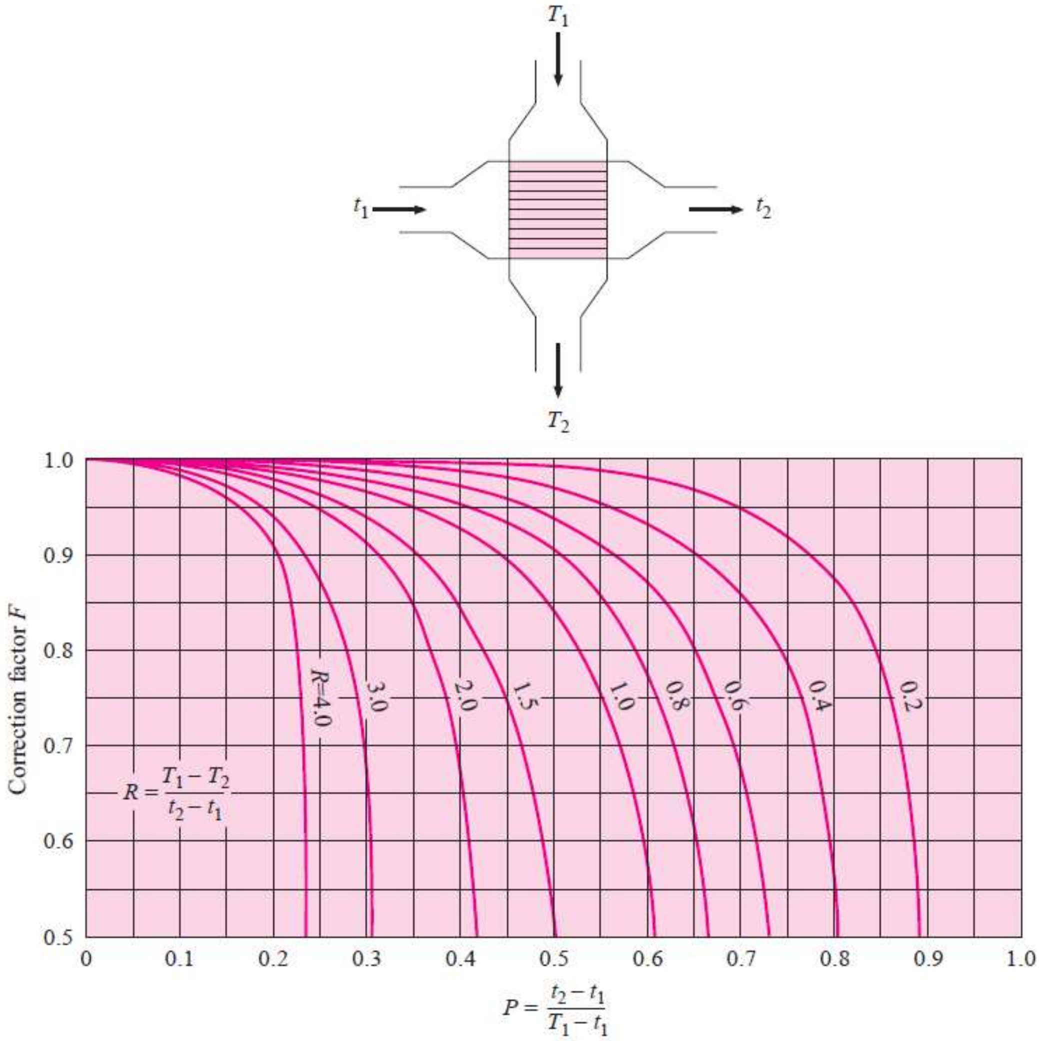


Figure 7-12 Correction-factor plot for single-pass cross-flow exchanger, one fluid mixed, the other unmixed.

When a phase change is involved, as in condensation or boiling (evaporation), the fluid normally remains at essentially constant temperature and the relations are simplified. For this condition, P or R becomes zero and
we obtain

$F = 1.0$ for boiling or condensation.