Chapter (4)

Heat Exchanger

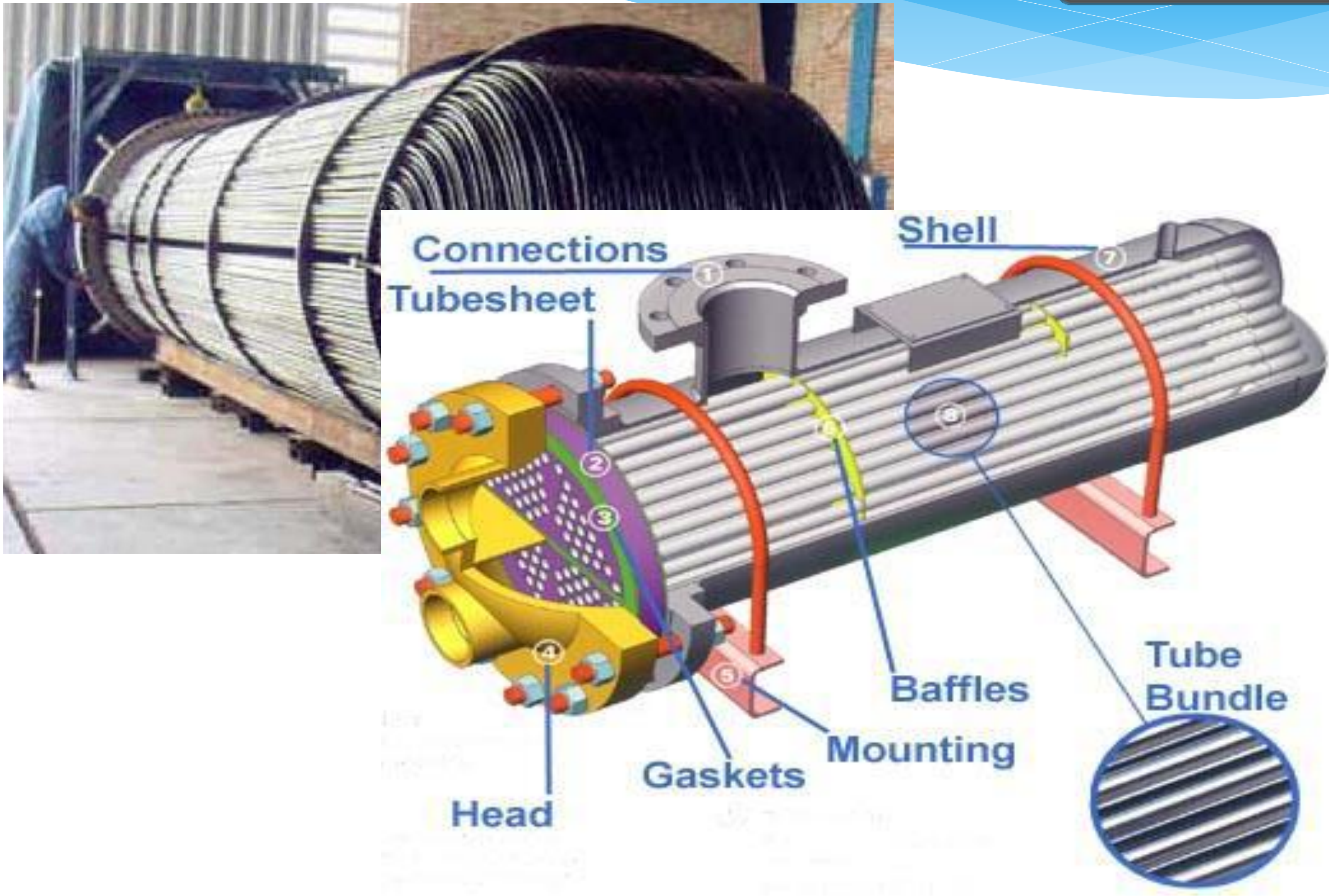
Goals:

By the end of today's lecture, you should be able to:

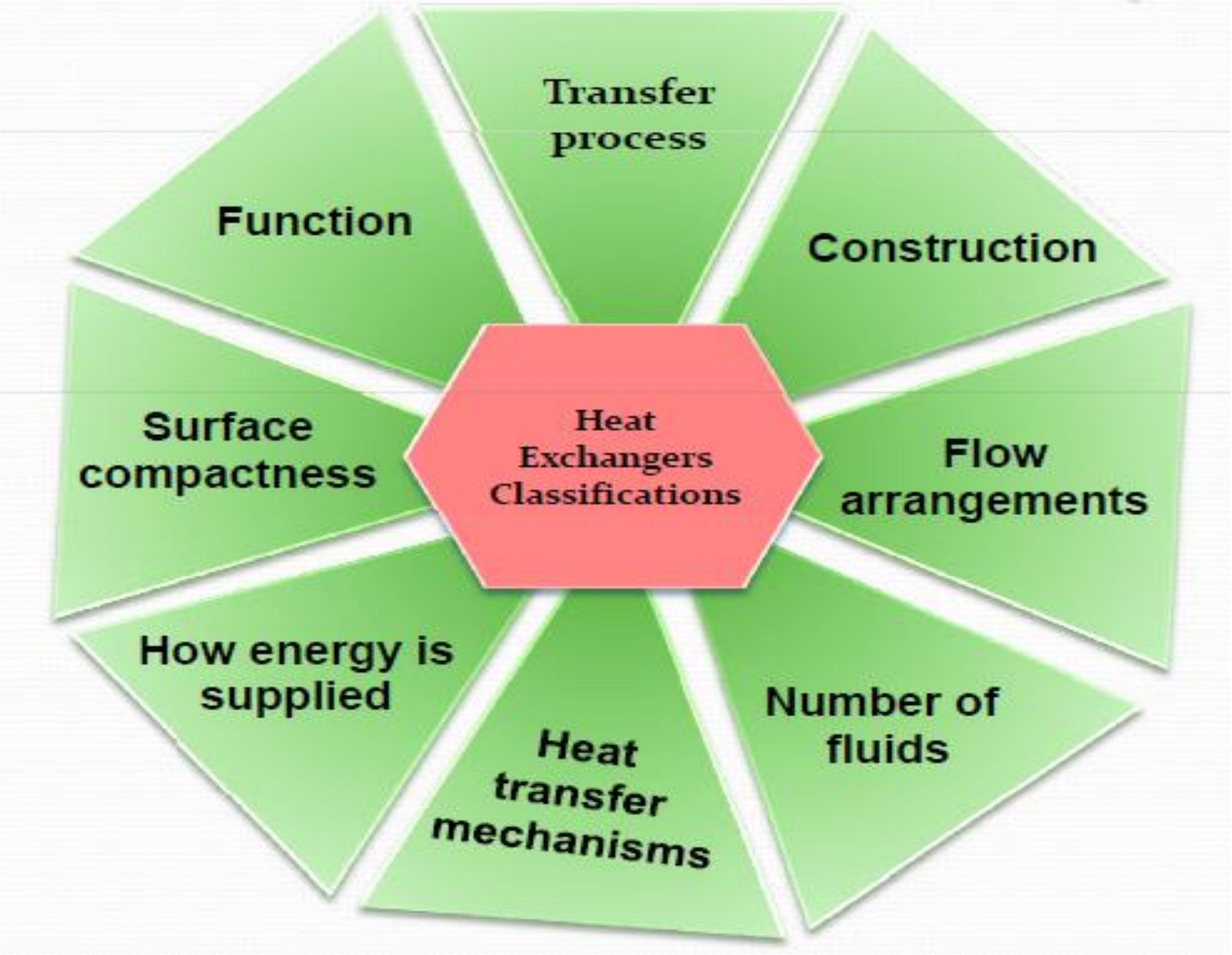
- Learn how to deal with heat exchanger problems.
- Learn how to design and select heat exchanger according to the application.

What Are Heat Exchanger?

Heat exchangers are units designed to transfer heat from a hot flowing fluid to a cold flowing fluid.


Connections
Tubesheet
Shell
Head
Gaskets
Mounting
Baffles
Tube
Bundle
1
2
3
4
5
6
7
8

Classification of Heat Exchanger

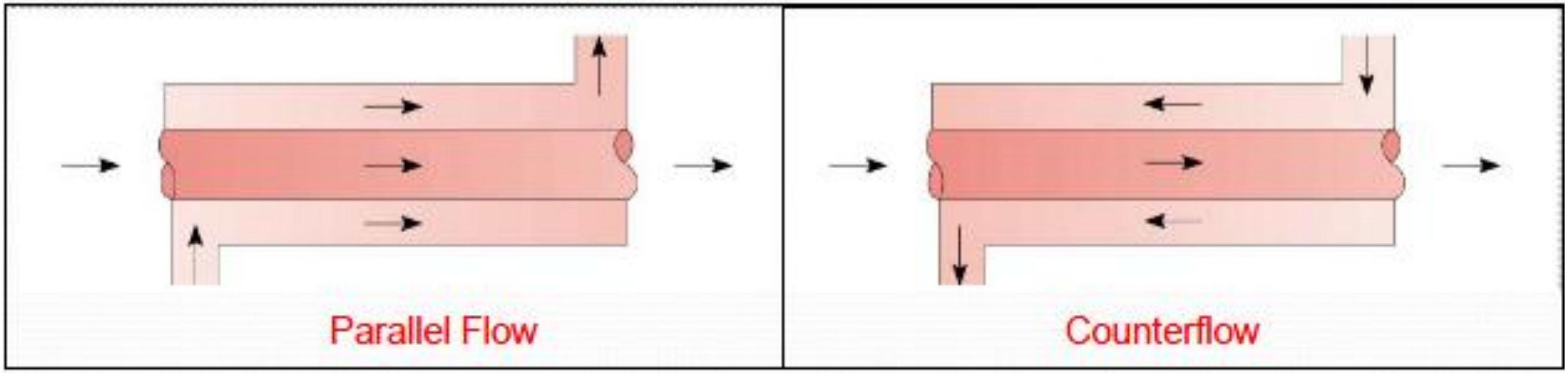


Heat Exchanger Types

- **According to flow arrangement**
- **According to type of construction**

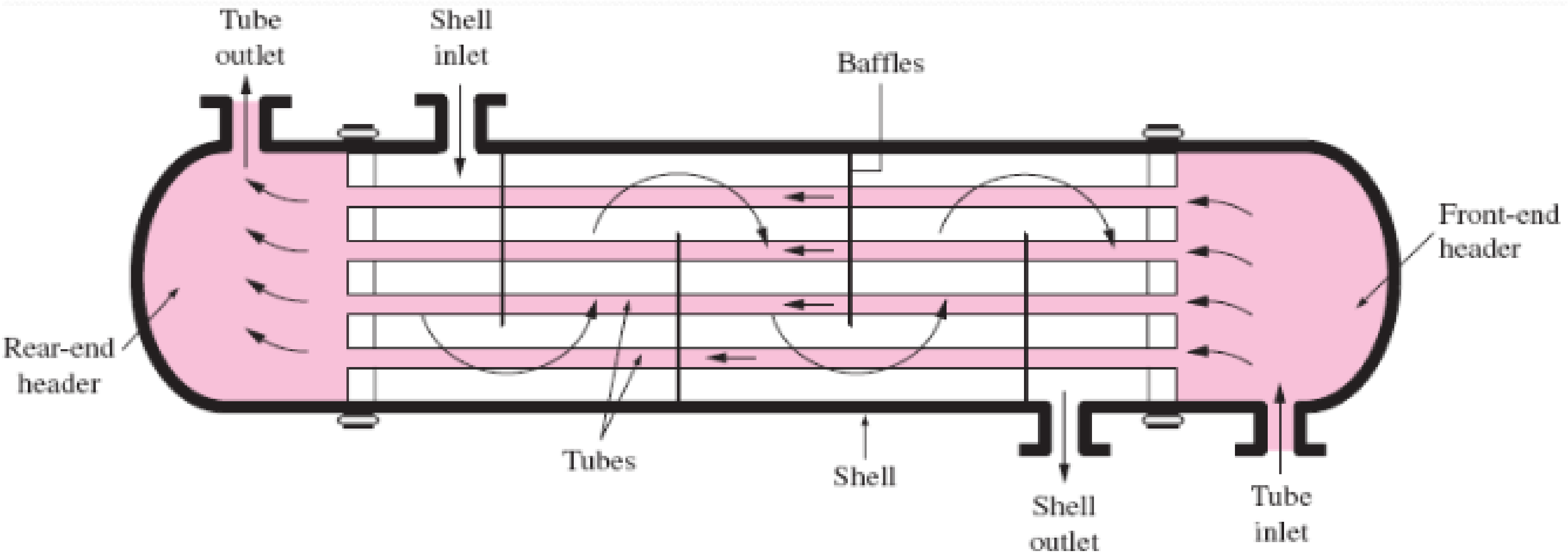
- There are many types of heat exchangers in use:
  - Concentric tube (double pipe)
    - Counter-flow or parallel flow
    - Mixed or unmixed cross flows
  - Shell-and-tube
    - Parallel or cross flow
  - Compact

☐ Concentric tube (double pipe)



- Simplest configuration.
- Superior performance associated with counter flow.

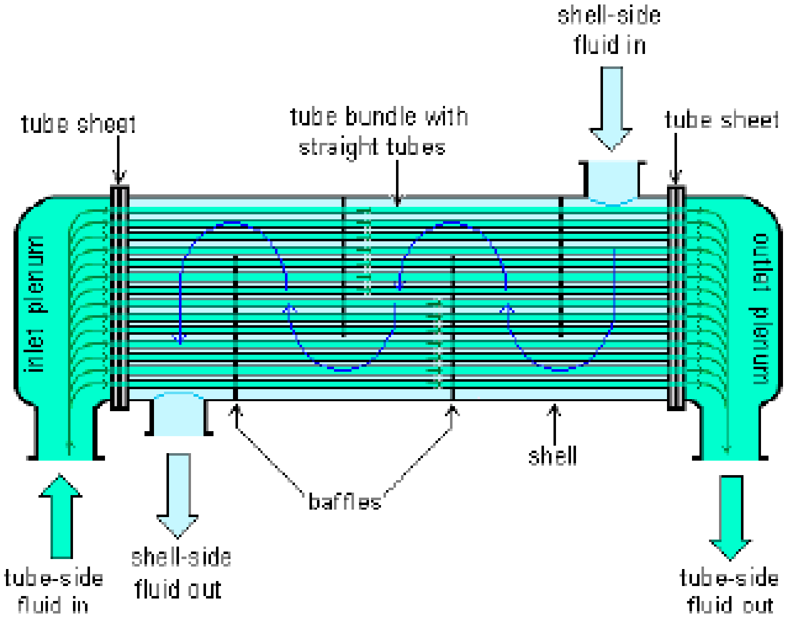
❑ Shell-and-tube



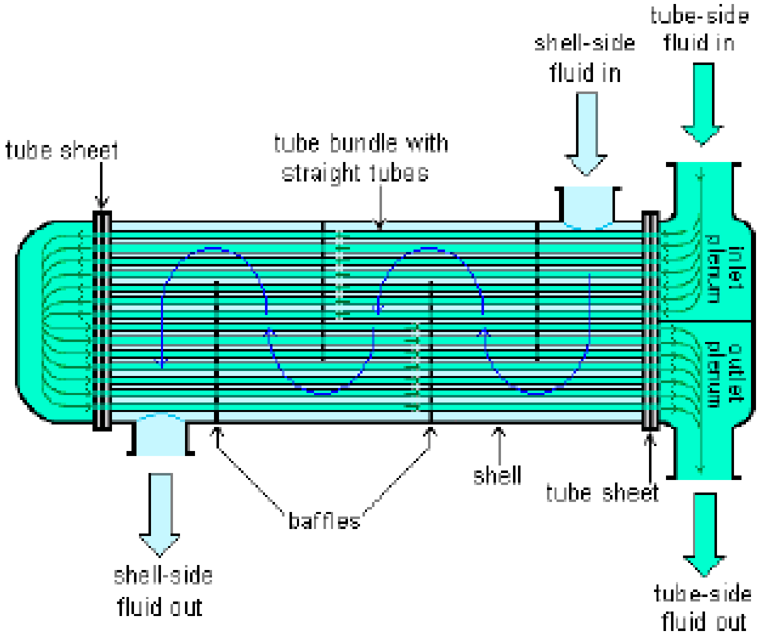
- **Baffles** are used to establish a cross-flow and to induce turbulent mixing of the shell-side fluid, both of which enhance convection and to support the tubes

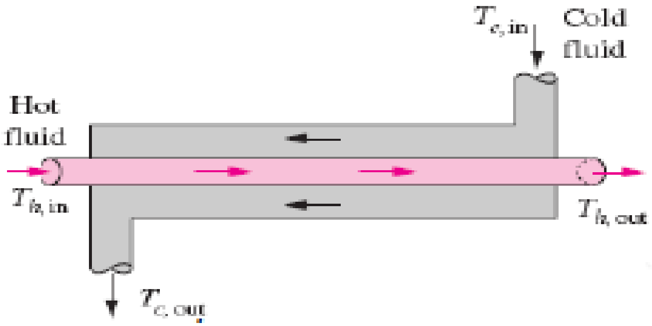
- The number of tube and shell passes may be varied.

- **Straight Tube Heat Exchanger (One Pass Tube Side)**

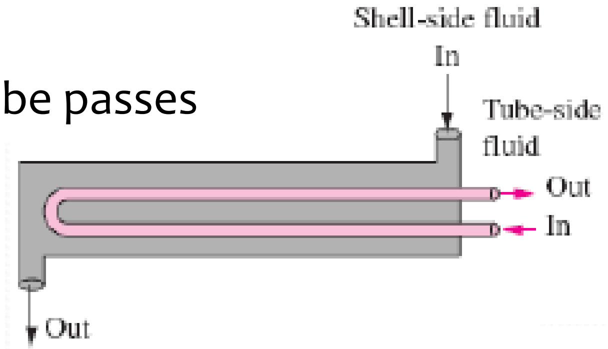


- **Straight Tube Heat Exchanger (Two Pass Tube Side)**

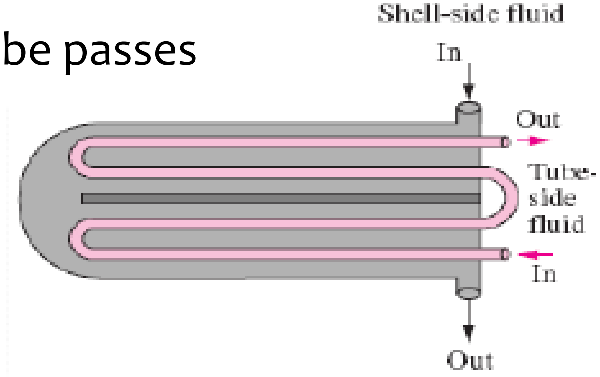




- ➢ One-shell pass and one-tube passes



- ➢ One-shell pass and two-tube passes

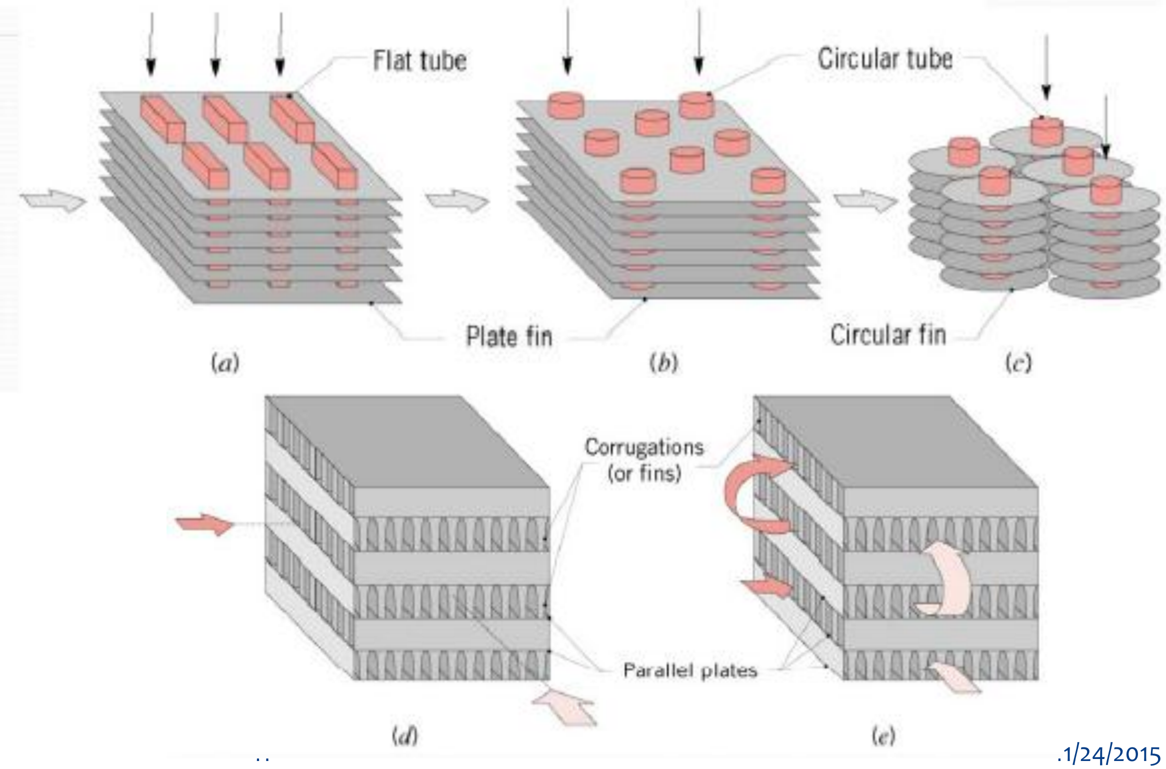


- ➢ Two-shell passes and four-tube passes

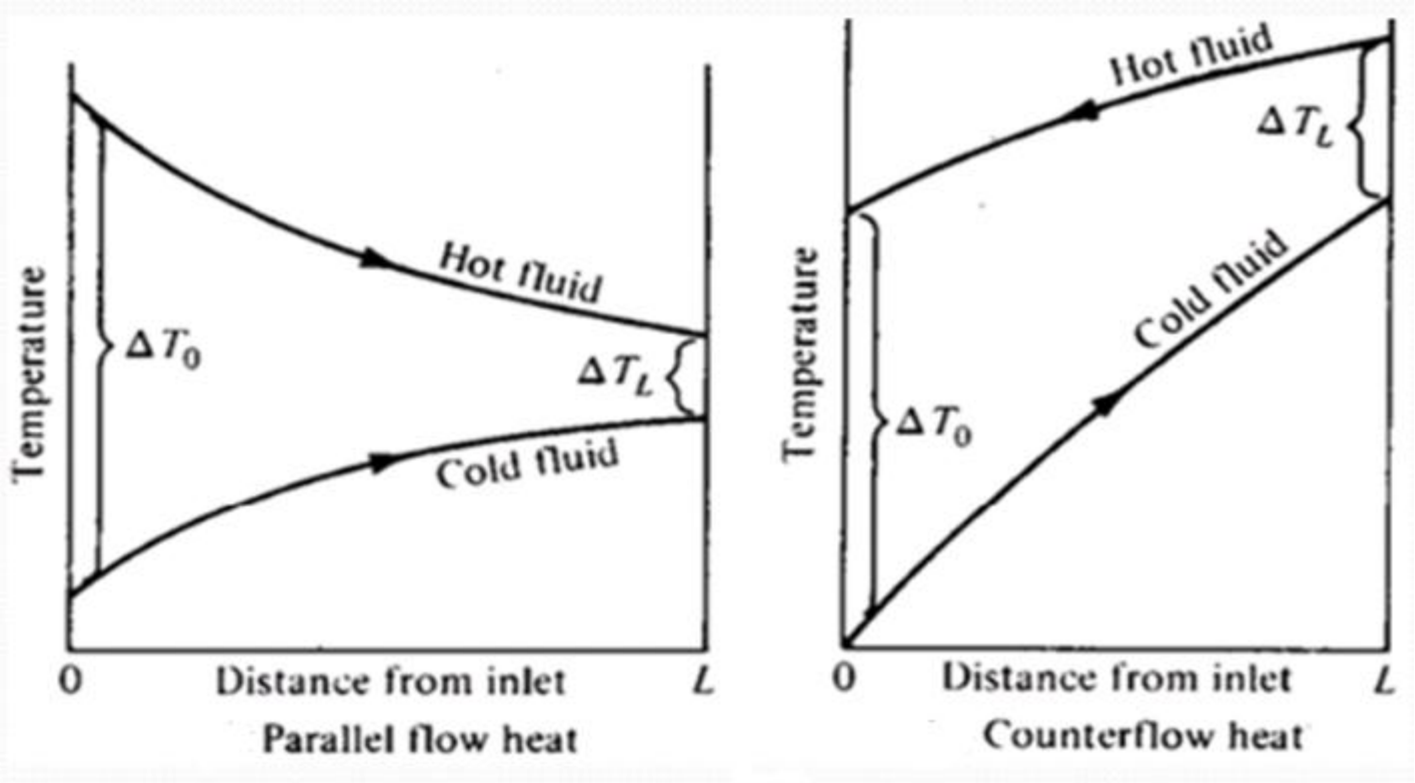
❑ Compact

- ➢ Widely used to achieve large heat rates per unit volume, particularly when one or both fluids is a gas.
- ➢ Characterized by large heat transfer surface areas per unit volume, small flow passages, and laminar flow.

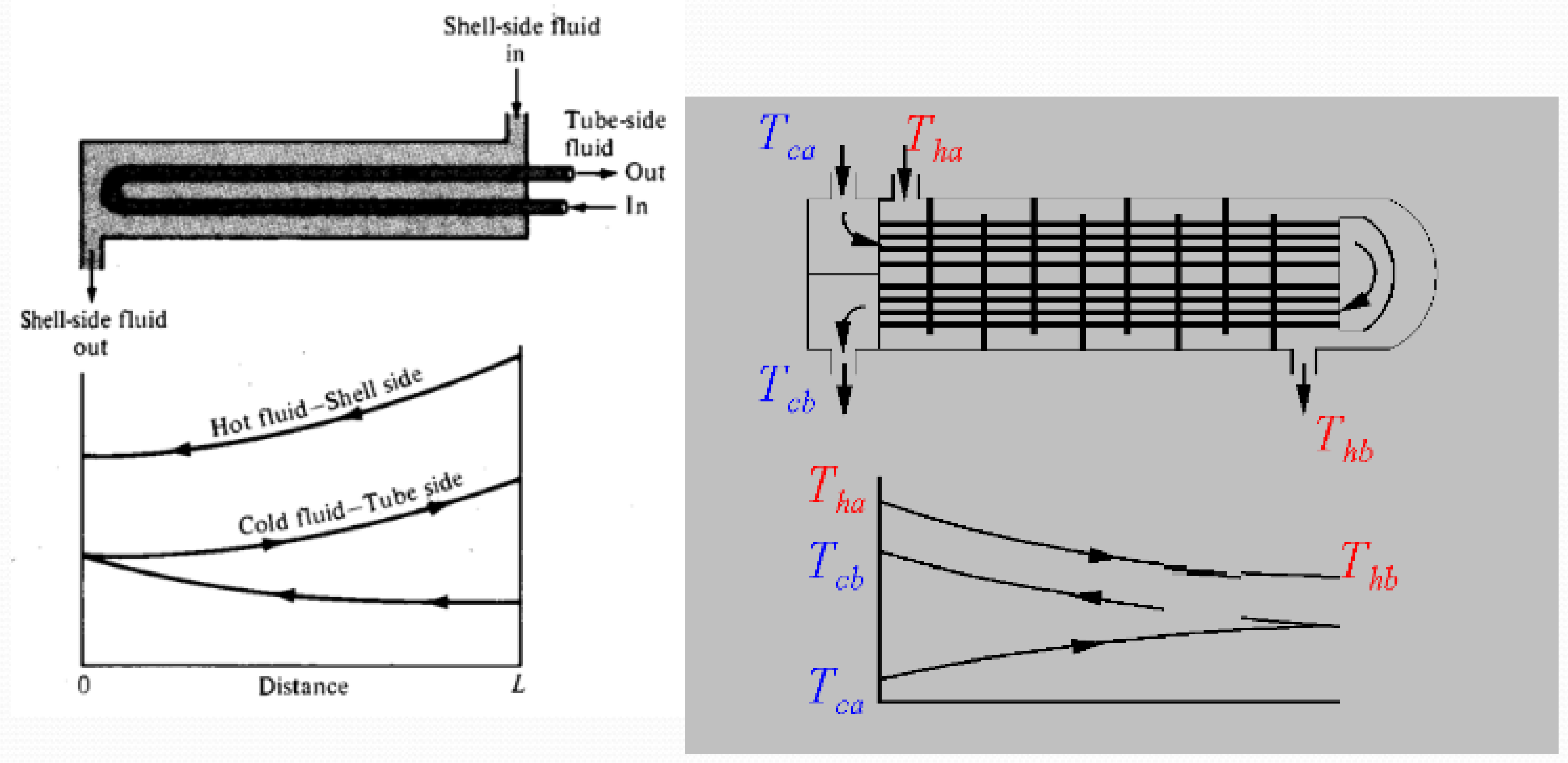
(a) Fin-tube (flat tubes, continuous plate fins)
(b) Fin-tube (circular tubes, continuous plate Fins
(c) Fin-tube (circular tubes, circular fins)
(d) Plate single pass)
(e) Plate-fin (multipass)



❑ Heat Exchanger Temperature Profile



Axial temperature distribution in typical single pass heat transfer matrices



Axial temperature distribution in one shell pass, two tube pass heat exchanger

Method of Heat Exchanger Design Calculations

➢ The Log Mean Temperature Difference (LMTD) Method

- A form of Newton's Law of Cooling may be applied to heat exchangers by using a log-mean value of the temperature difference between the two fluids:

$$\boxed{q = UA\,\Delta T_m}$$

- The temperature difference at each end of the exchanger is calculated and combined using the following equation to give the log mean temperature difference:

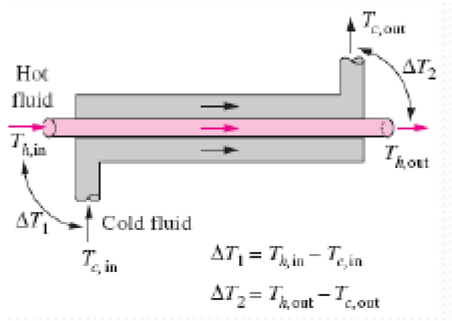
$$\boxed{\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln \frac{\Delta T_2}{\Delta T_1}}}$$

➢ The Log Mean Temperature Difference (LMTD) Method

Evaluation of depends on the heat exchanger type.

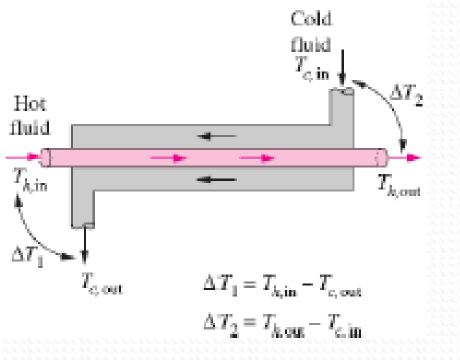
Parallel-flow:

$$\Delta T_{lm} = LMTD = \frac{(T_{h,o} - T_{c,o}) - (T_{h,i} - T_{c,i})}{\ln[(T_{h,o} - T_{c,o})/(T_{h,i} - T_{c,i})]}$$



Counter flow:

$$\Delta T_{lm} = LMTD = \frac{(T_{h,o} - T_{c,i}) - (T_{h,i} - T_{c,o})}{\ln[(T_{h,o} - T_{c,i})/(T_{h,i} - T_{c,o})]}$$



➢ The Log Mean Temperature Difference (LMTD) Method

Cross-flow & Multi-pass (shell & tube)

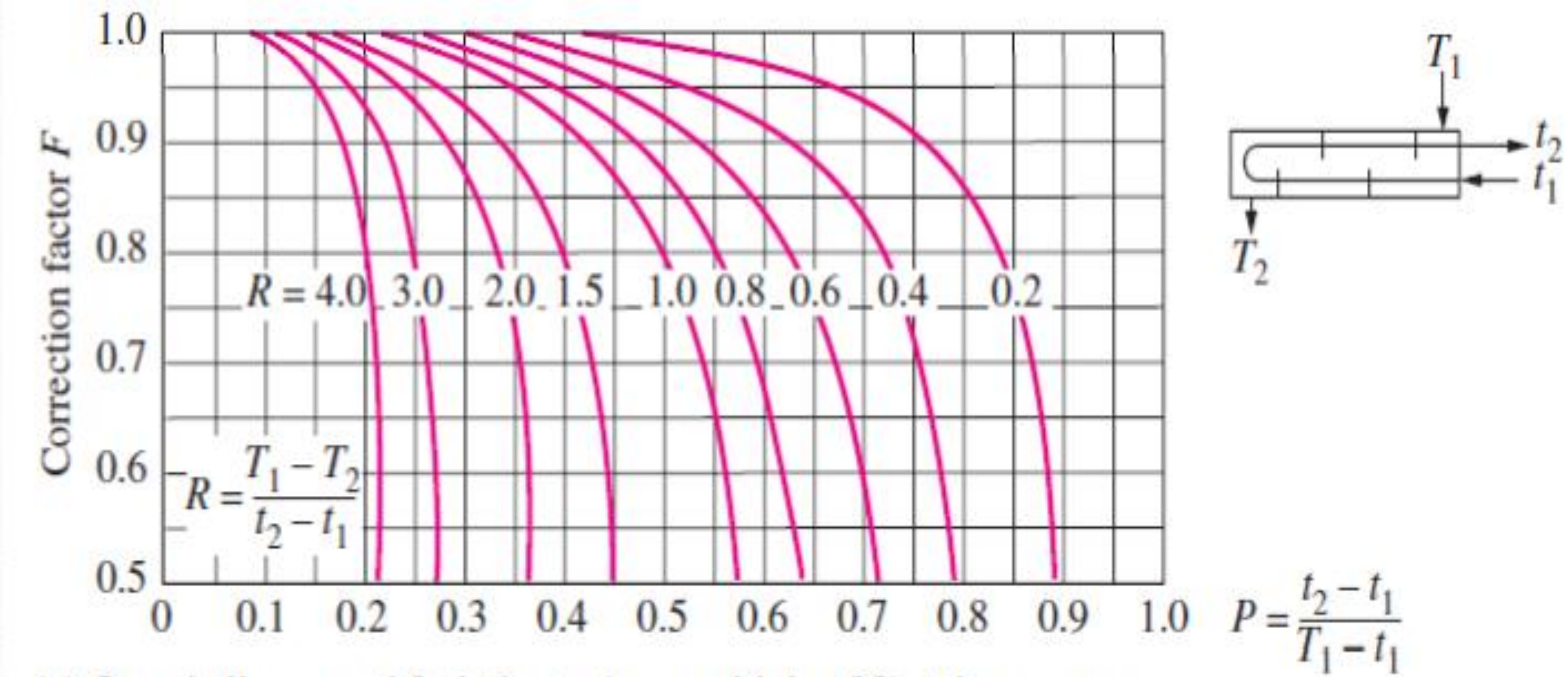
$$\left[\Delta T_{lm}\right]_{counter\ flow} = F\left[\Delta T_{lm}\right]_{cross\ flow}$$

$$\Delta T_{lm} = LMTD = F\,\frac{(T_{h,o}-T_{c,i})-(T_{h,i}-T_{c,o})}{\ln[(T_{h,o}-T_{c,i})/(T_{h,i}-T_{c,o})]}$$

F = correction factor

➢ The Log Mean Temperature Difference (LMTD) Method

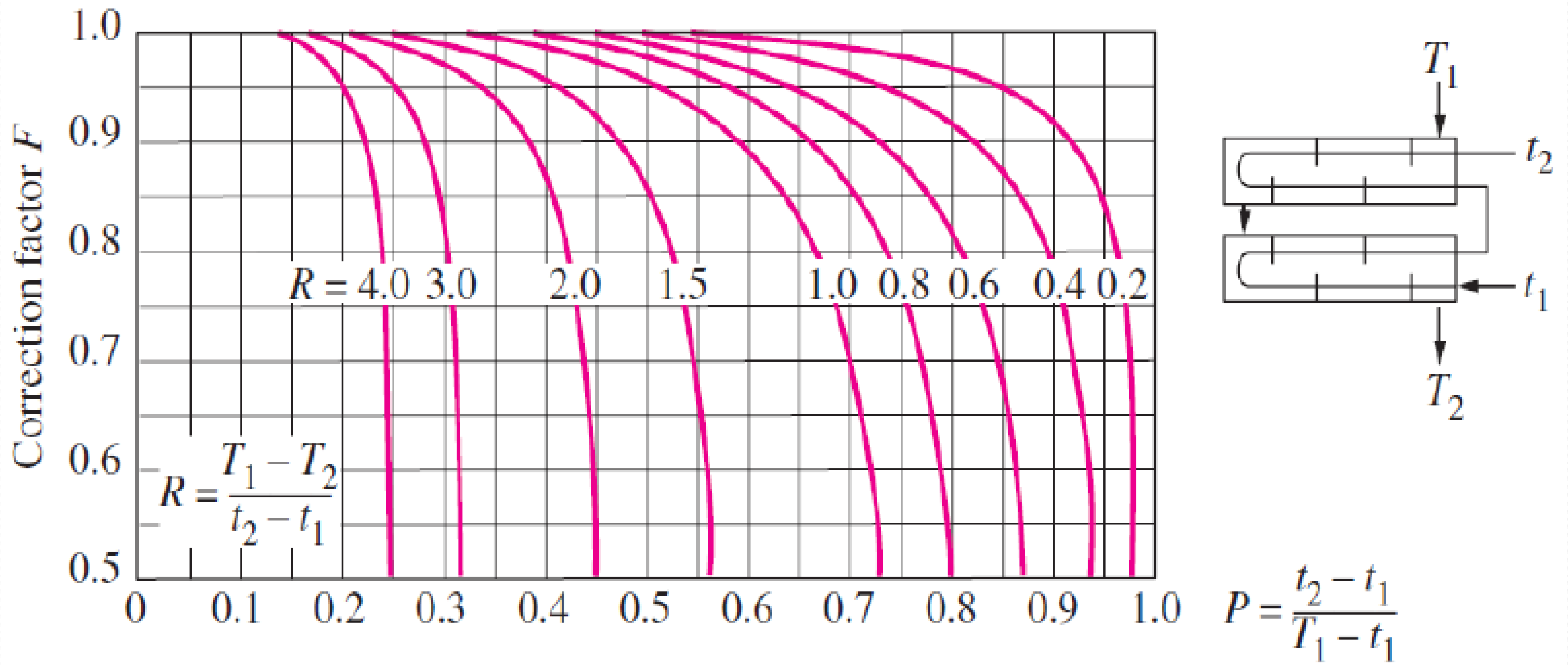
F = correction factor



(*a*) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes

➢ The Log Mean Temperature Difference (LMTD) Method

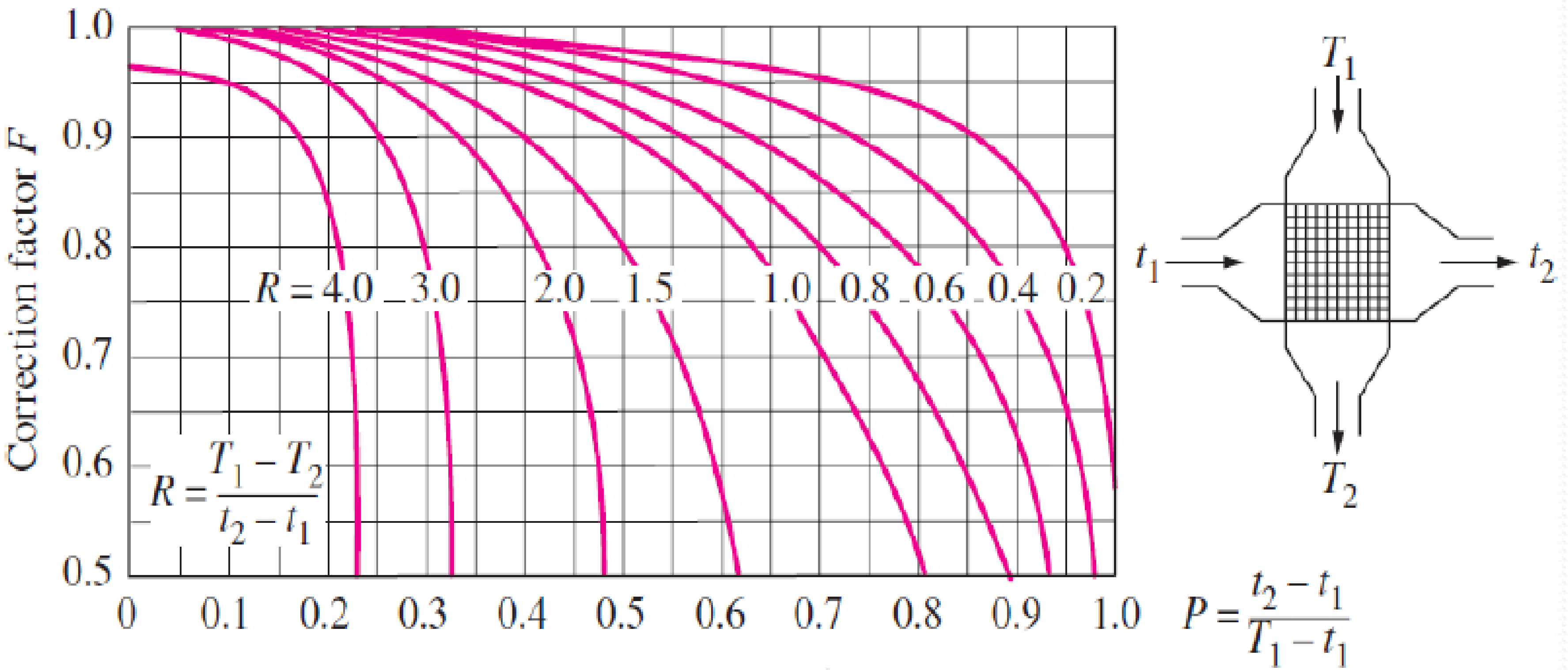
F = correction factor



(*b*) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes

The Log Mean Temperature Difference (LMTD) Method

F = correction factor



(c) Single-pass cross-flow with both fluids *unmixed*

The Effectiveness, ε-NTU Method

- When one or more temperature value for the streams at the inlet or outlet of the heat exchanger are **NOT** known, a trial and error procedure may be needed.

- Instead, the method of number of transfer units (NTU) based on HEX effectiveness may be used.

- The ε-NTU method is based on the fact that the inlet or exit temperature differences of a heat exchanger are a function of UA/C_c and C_c/C_h.

- The HEX heat transfer equations may be written in dimensionless form resulting in some dimensionless groups.

NTU stands for "Number of Transfer Units"

The Effectiveness, ε-NTU Method

The HEX heat transfer equations may be written in dimensionless form resulting in some dimensionless groups.

Dimensionless groups:

1. Heat capacity rate ratio.

2. HEX heat transfer effectiveness.

➢ The Effectiveness, ε-NTU Method

Heat Capacity Rate.

- ➢ The heat capacity rate of a fluid stream represents the rate of heat transfer needed to change the temperature of the fluid stream by 1°C as it flows through a heat exchanger

- ➢ For calculations of heat exchangers, we often deal with the heat capacity rate of a fluid:

$$\text{For hot fluid}: \quad C_h = \dot{m}_h C_{p,h}$$

$$\text{For cold fluid}: \quad C_c = \dot{m}_c C_{p,c}$$

Heat Exchanger Effectiveness, ε

$$\varepsilon = \frac{q_{act}}{q_{\max}} \qquad 0 \le \varepsilon \le 1$$

where the maximum possible heat transfer rate of a heat exchanger, q_{max}, occurs when we consider the maximum temperature difference, ΔT_{max} .
The heat transfer rate is defined as:

$$q_{\max} = C_{\min}(T_{h,i} - T_{c,i})$$

Where:

$$C_{min} = C_h \text{ , if } C_h < C_c$$
$$C_{min} = C_c \text{ , if } C_h > C_c$$

the actual heat transfer rate of an exchanger as

$$q_{act} = \varepsilon C_{\min}(T_{h,i} - T_{c,i})$$

➢ The Effectiveness, ε-NTU Method

The heat capacity ratio

$$\boxed{C_r = \frac{C_{\min}}{C_{\max}}}$$

The "Number of Transfer Units" (NTU) is a dimensionless group defined as:

$$\boxed{NTU = \frac{UA}{C_{\min}}}$$

➢ Effectiveness, NTU Relationship

Effectiveness can also be expressed as a function of (NTU) where:

(A) Effectiveness for heat exchangers as a function of (NTU) (Mathematical Correlations)

Example – Concentric tube (double piped)

Parallel Flow:

$$\varepsilon = \frac{1-\exp\left(-NTU\left(1+C_r\right)\right)}{1+C_r}$$

Counter Flow:

$$\varepsilon = \frac{1-\exp\left(-NTU\left(1-C_r\right)\right)}{1-C_r\cdot\exp\left(-NTU\left(1-C_r\right)\right)},\quad C_r<1$$

$$\varepsilon = \frac{NTU}{1+NTU},\quad C_r-1$$

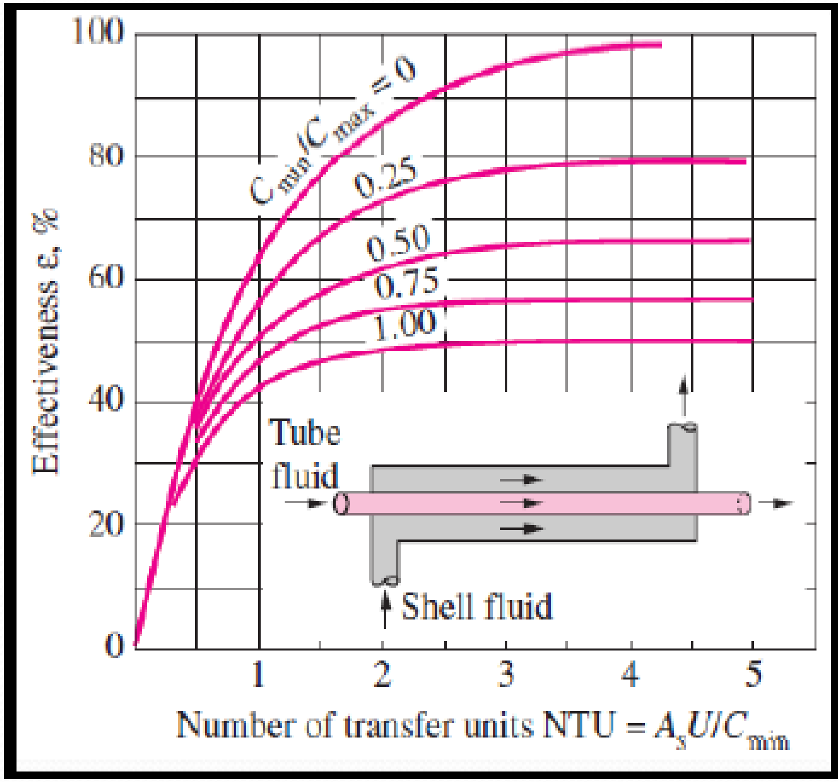
where, Cr is the heat capacity ratio

➢ Effectiveness, NTU Relationship

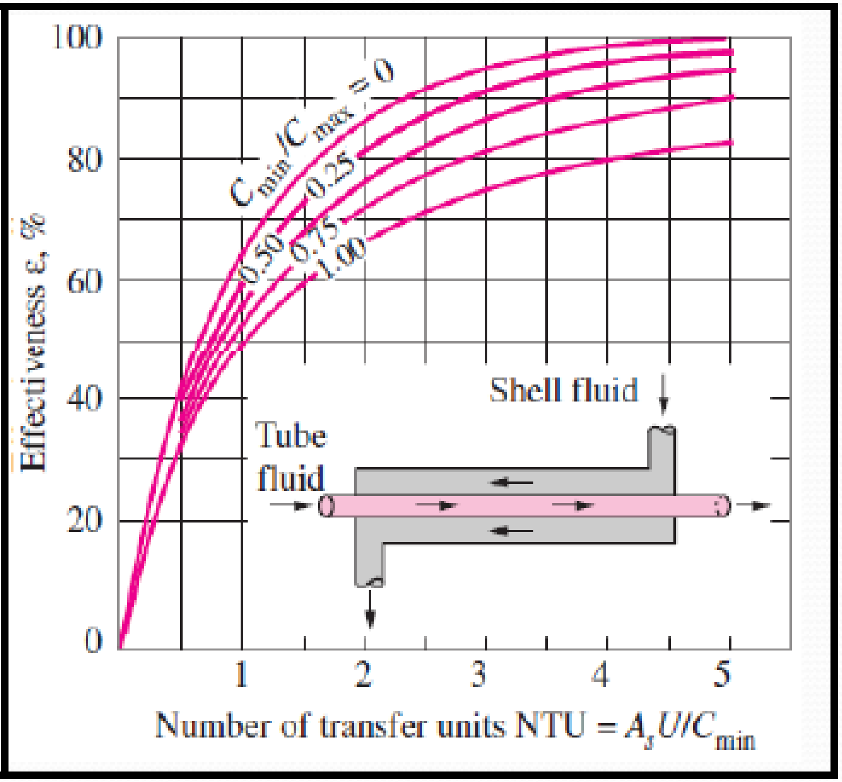
Type of HEX	ε(NTU,C*)	NTU(ε,C*)
Counterflow	$\varepsilon = \dfrac{1-\exp\left[-\left(1-C^*\right)\mathrm{NTU}\right]}{1-C^*\exp\left[-\left(1-C^*\right)\mathrm{NTU}\right]}$	$\mathrm{NTU} = \dfrac{1}{1-C^*}\ln\left(\dfrac{1-\varepsilon C^*}{1-\varepsilon}\right)$
Parallel Flow	$\varepsilon = \dfrac{1}{1+C^*}\left[1-\exp\left[-\left(1+C^*\right)\mathrm{NTU}\right]\right]$	$\mathrm{NTU} = -\dfrac{1}{1+C^*}\ln\left[1-\varepsilon\left(1+C^*\right)\right]$
Cross flow, C_{min} mixed and C_{max} unmixed	$\varepsilon = 1-\exp\left[\dfrac{1-\exp\left(-C^*\mathrm{NTU}\right)}{C^*}\right]$	$\mathrm{NTU} = -\dfrac{1}{C^*}\ln\left[1+C^*\ln\left(1-\varepsilon\right)\right]$
Cross flow, C_{max} mixed and C_{min} unmixed	$\varepsilon = \dfrac{1}{C^*}\left[1-\exp\left\{-C^*\left[1-\exp\left(-\mathrm{NTU}\right)\right]\right\}\right]$	$\mathrm{NTU} = -\ln\left[1+\dfrac{1}{C^*}\ln\left(1-\varepsilon C^*\right)\right]$
1 to 2 shell-and-tube HEX	$\varepsilon = \dfrac{2}{1+C^*+\left(1+C^{*2}\right)^{1/2}\dfrac{1+\exp\left\{-\mathrm{NTU}\left(1+C^{*2}\right)^{1/2}\right\}}{1-\exp\left\{-\mathrm{NTU}\left(1+C^{*2}\right)^{1/2}\right\}}}$	$\mathrm{NTU} = \dfrac{1}{\left(1+C^{*2}\right)^{1/2}}\ln\dfrac{2-\varepsilon\left\{1+C^*-\left(1+C^{*2}\right)^{1/2}\right\}}{2-\varepsilon\left\{1+C^*+\left(1+C^{*2}\right)^{1/2}\right\}}$

➢ Effectiveness, NTU Relationship

(B) Effectiveness for heat exchangers as a function of (NTU) (graphically)



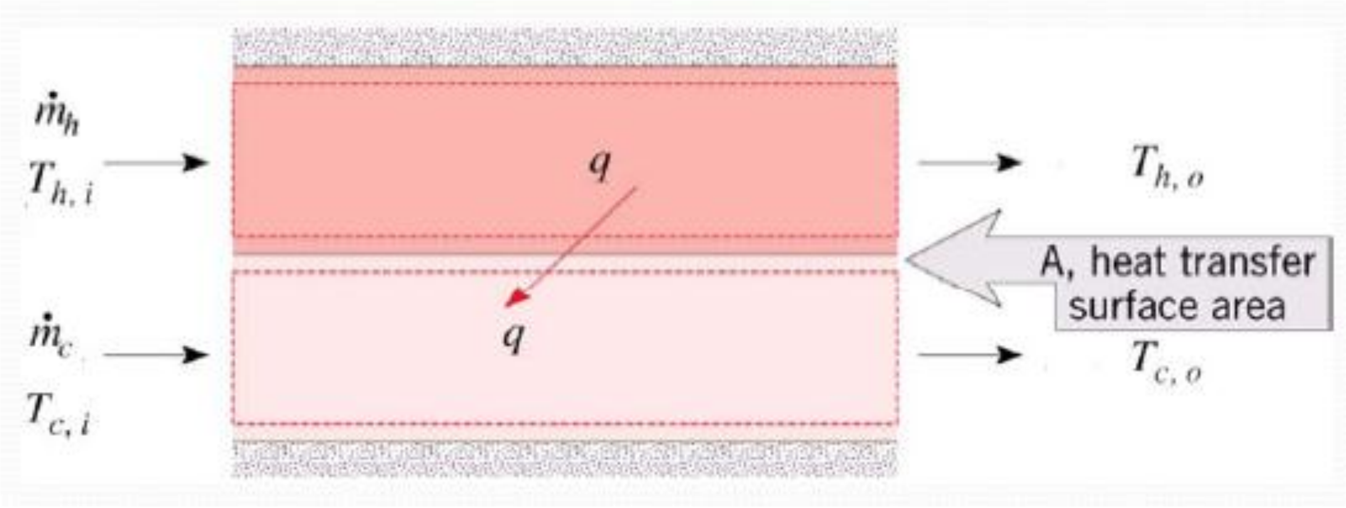
Effectiveness for a parallel flow heat exchanger



Effectiveness for a counter flow heat exchanger

The Total Rate of Heat Transfer Overall Energy Balance

$$\begin{pmatrix}\text{Rate of}\\ \text{heat}\\ \text{transfer by}\\ \text{exchanger}\end{pmatrix} = \begin{pmatrix}\text{Rate of}\\ \text{heat loss}\\ \text{by hot fluid}\end{pmatrix} = \begin{pmatrix}\text{Rate of}\\ \text{heat gain}\\ \text{by cold fluid}\end{pmatrix}$$



The Total Rate of Heat Transfer
Overall Energy Balance

$$q = \dot{m}_h c_{p,h} (T_{h,i} - T_{h,o})$$

$$= \dot{m}_c c_{p,c} (T_{c,o} - T_{c,i})$$

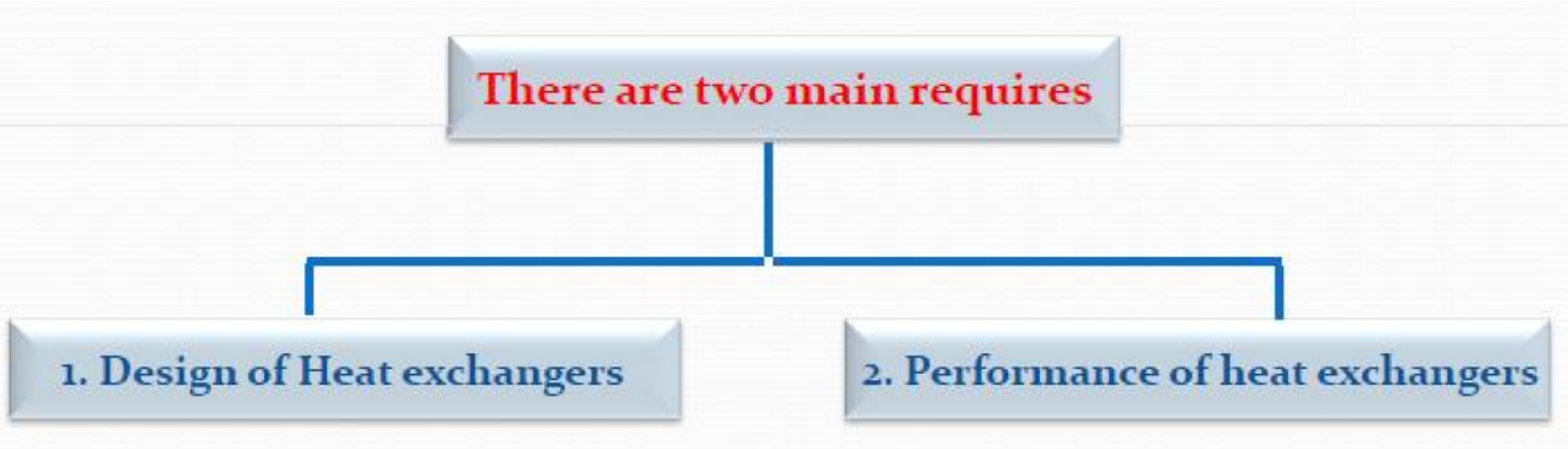
$$q = UA \Delta T_m$$

Where:

U: Overall Heat Transfer Coefficient

$$R = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} \approx \frac{1}{h_i A_i} + \frac{1}{h_o A_o} \qquad \& \qquad U_h A_h = U_C A_C$$

Methods of Heat Exchanger Calculations



There are two main requires

1. Design of Heat exchangers

2. Performance of heat exchangers

Methods of Heat Exchanger Calculations

➢ Heat Exchanger Design Problems

For this type of problems, it is the engineer who must chose the appropriate heat exchanger type and determine its size (i.e. heat transfer surface area)

Known Parameters: (given or desired)

$$T_{h,i}, T_{h,o}, T_{c,o}, T_{c,i}, \dot{m}_h, \dot{m}_c$$

Energy balance:

$$\boxed{\begin{aligned} q &= \dot{m}_h c_{p,h} (T_{h,i} - T_{h,o}) \\ &= \dot{m}_c c_{p,c} (T_{c,o} - T_{c,i}) \end{aligned}}$$

Methods of Heat Exchanger Calculations

➢ Heat Exchanger Design Problems

With the LMTD method, the task is to *select a heat exchanger that will meet* the prescribed heat transfer requirements. The procedure to be followed by the selection process is:

1) Select the type of heat exchanger suitable for the application.
2) Determine any unknown inlet or outlet temperature and the heat transfer rate using an energy balance.
3) Calculate the log mean temperature difference *Tlm* and the correction factor *F*, if necessary.
4) Obtain (select or calculate) the value of the overall heat transfer coefficient *U*.
5) Calculate the heat transfer surface area *As* .

Methods of Heat Exchanger Calculations

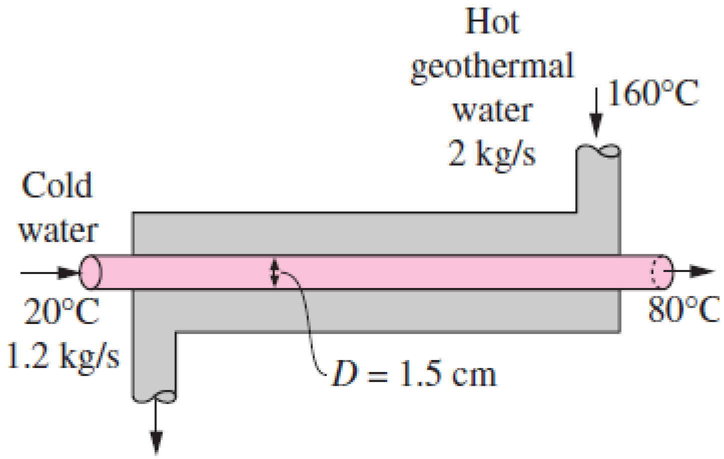
➢ Performance Calculation Problem

- ✓ Here the heat exchanger size and type are known.
- ✓ It is required to determine the heat transfer rate and/or the outlet temperatures of the hot and cold.
- ✓ Here the task is to determine the heat transfer performance of a specified heat exchanger or to determine if a heat exchanger available in storage will do the job.
- ✓ The LMTD method could still be used for this alternative problem, but it is not practical
- ✓ In an attempt to eliminate the iterations from the solution of such problems, the **effectiveness–NTU method,** can be used to simplify heat exchanger analysis.

❑ **The problem in this case is solved by NTU method as an easy and direct solution**

Example

A counter-flow double-pipe heat exchanger is to heat water from 20°C to 80°C at a rate of 1.2 kg/s. The heating is to be accomplished by geothermal water available at 160°C at a mass flow rate of 2 kg/s. The inner tube is thin-walled and has a diameter of 1.5 cm. If the overall heat transfer coefficient of the heat exchanger is 640 $W/m^2 \cdot °C$, determine the length of the heat exchanger required to achieve the desired heating. Assume the specific heats of water and geothermal fluid to be 4.18 and 4.31 kJ/kg · °C, respectively.



Solution

The rate of heat transfer in the heat exchanger can be determined from

$$\dot{Q} = [\dot{m}C_p(T_{\text{out}} - T_{\text{in}})]_{\text{water}} = (1.2\ \text{kg/s})(4.18\ \text{kJ/kg}\cdot{}^\circ\text{C})(80 - 20)^\circ\text{C} = 301\ \text{kW}$$

the outlet temperature of the geothermal water is determined to be

$$\dot{Q} = [\dot{m}C_p(T_{\text{in}} - T_{\text{out}})]_{\text{geothermal}} \longrightarrow T_{\text{out}} = T_{\text{in}} - \frac{\dot{Q}}{\dot{m}C_p}$$

$$= 160^\circ\text{C} - \frac{301\ \text{kW}}{(2\ \text{kg/s})(4.31\ \text{kJ/kg}\cdot{}^\circ\text{C})}$$

$$= 125^\circ\text{C}$$

Knowing the inlet and outlet temperatures of both fluids, the logarithmic mean temperature difference for this counter-flow heat exchanger becomes

$$\Delta T_1 = T_{h,\text{ in}} - T_{c,\text{ out}} = (160 - 80)^\circ\text{C} = 80^\circ\text{C}$$
$$\Delta T_2 = T_{h,\text{ out}} - T_{c,\text{ in}} = (125 - 20)^\circ\text{C} = 105^\circ\text{C}$$

and

$$\Delta T_{\text{lm}} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} = \frac{80 - 105}{\ln(80/105)} = 92.0^\circ\text{C}$$

Then the surface area of the heat exchanger is determined to be

$$\dot{Q} = UA_s\,\Delta T_{\text{lm}} \longrightarrow A_s = \frac{\dot{Q}}{U\,\Delta T_{\text{lm}}} = \frac{301{,}000\text{ W}}{(640\text{ W/m}^2\cdot{}^\circ\text{C})(92.0^\circ\text{C})} = 5.11\text{ m}^2$$

$$A_s = \pi DL \longrightarrow L = \frac{A_s}{\pi D} = \frac{5.11\text{ m}^2}{\pi(0.015\text{ m})} = 108\text{ m}$$