Heat Exchangers

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Objectives

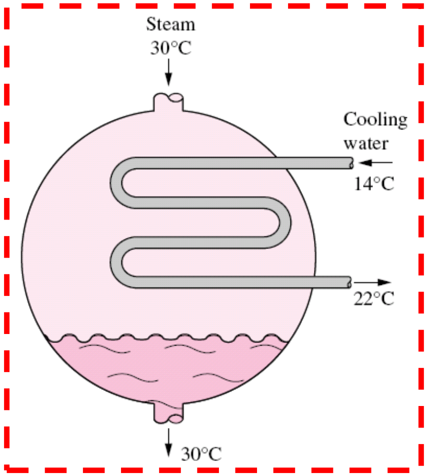
When you finish studying this chapter, you should be able to:

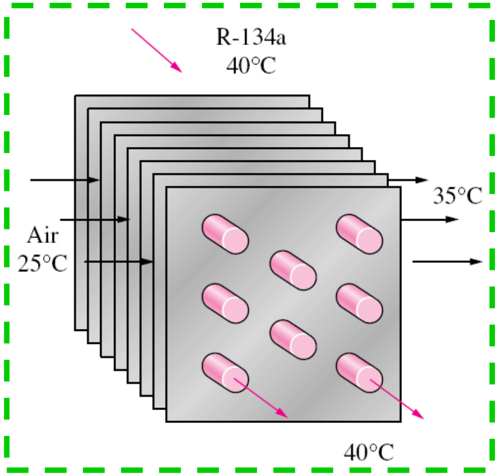
- Recognize numerous types of heat exchangers, and classify them,
- Develop an awareness of fouling on surfaces, and determine the overall heat transfer coefficient for a heat exchanger,
- Perform a general energy analysis on heat exchangers,
- Obtain a relation for the logarithmic mean temperature difference for use in the LMTD method, and modify it for different types of heat exchangers using the correction factor,
- Develop relations for effectiveness, and analyze heat exchangers when outlet temperatures are not known using the effectiveness-NTU method,
- Know the primary considerations in the selection of heat exchangers.

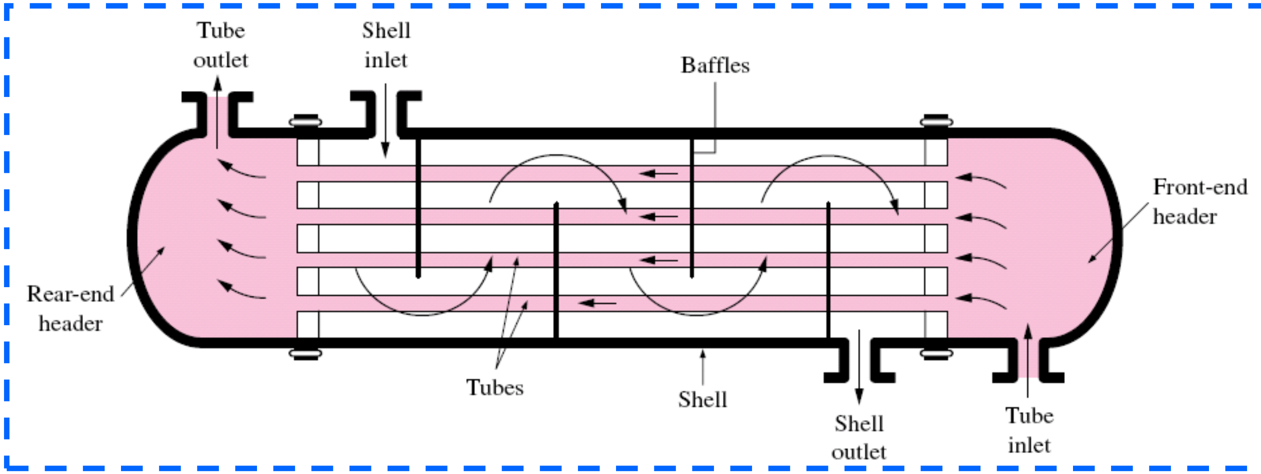
Types of Heat Exchangers

- Different heat transfer applications require different types of hardware and different configurations of heat transfer equipment.

What should we choose?

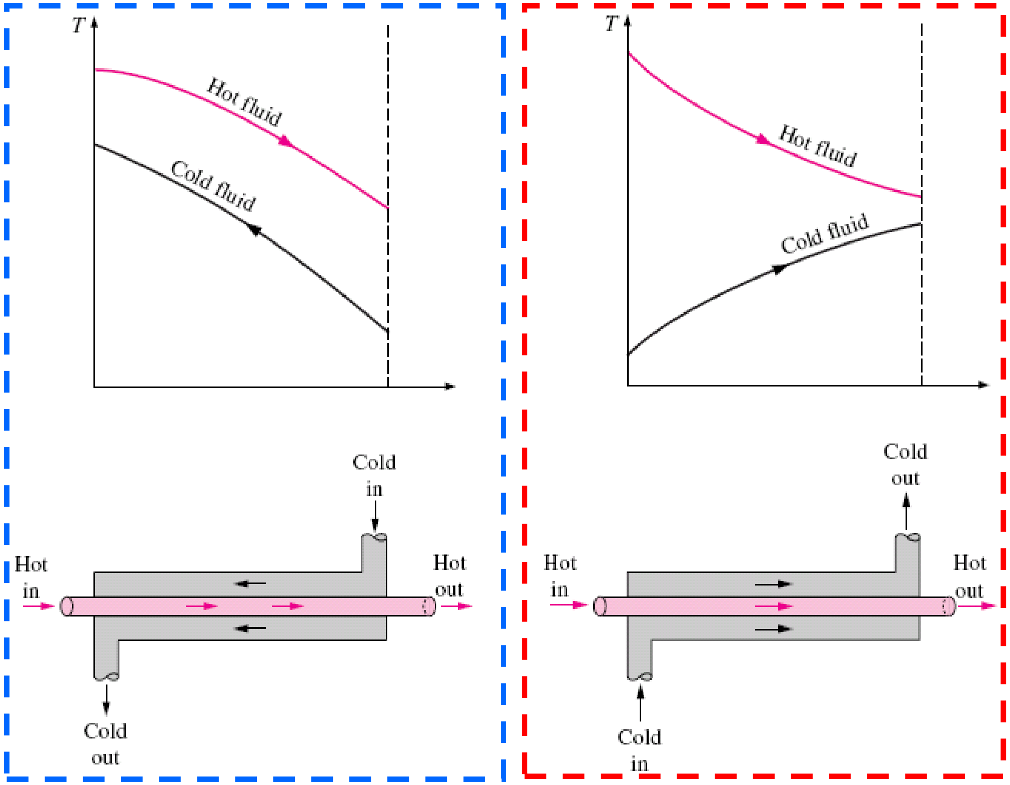






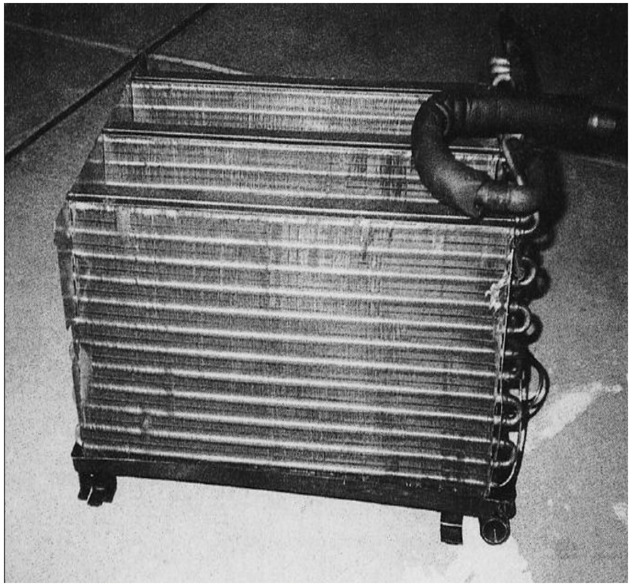
Double-Pipe Heat Exchangers

- The simplest type of heat exchanger is called the **double-pipe** heat exchanger.
- One fluid flows through the smaller pipe while the other fluid flows through the annular space between the two pipes.
- Two types of flow arrangement
  - **parallel flow**,
  - **counter flow**.



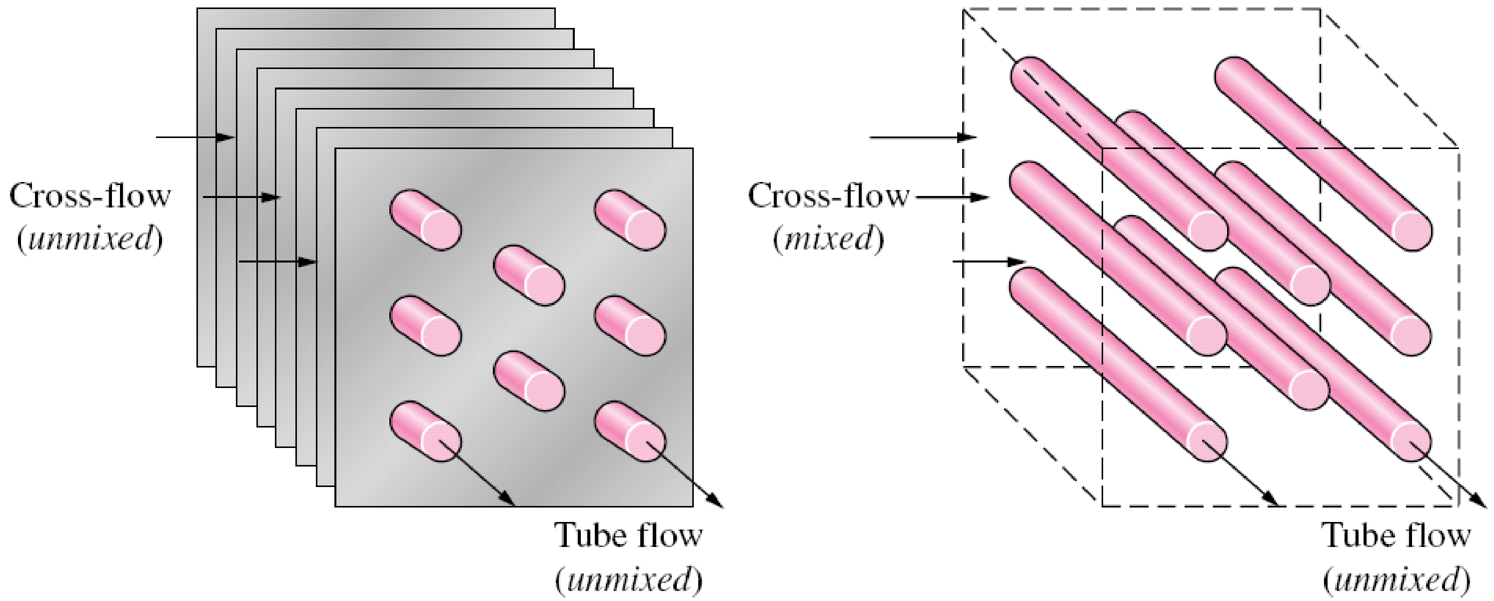
Compact Heat Exchanger

- Large heat transfer surface area per unit volume.
- *Area density* β – heat transfer surface of a heat exchanger to volume ratio.
- Compact heat exchanger β >700 m^2/m^3.
- Examples:
  - car radiators (β ≈1000 m^2/m^3),
  - glass-ceramic gas turbine heat exchangers (β ≈6000 m^2/m^3),
  - the regenerator of a Stirling engine (β ≈15,000 m^2/m^3), and
  - the human lung (β ≈20,000 m^2/m^3).



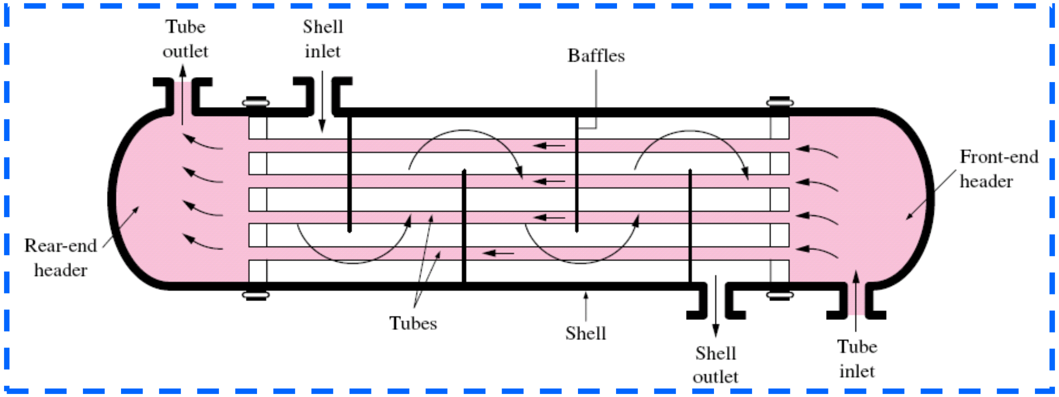
- Compact heat exchangers are commonly used in
  - gas-to-gas and
  - gas-to liquid (or liquid-to-gas) heat exchangers.
- Typically cross-flow configuration – the two fluids move *perpendicular* to each other.
- The cross-flow is further classified as
  - *unmixed flow*

    and
  - *mixed flow.*



Shell-and-Tube Heat Exchanger

- The most common type of heat exchanger in industrial applications.
- Large number of tubes are packed in a shell with their axes parallel to that of the shell.
- The other fluid flows outside the tubes through the shell.
- *Baffles* are commonly placed in the shell.
- Shell-and-tube heat exchangers are relatively large size and weight.
- Shell-and-tube heat exchangers are further classified according to the number of shell and tube passes involved.



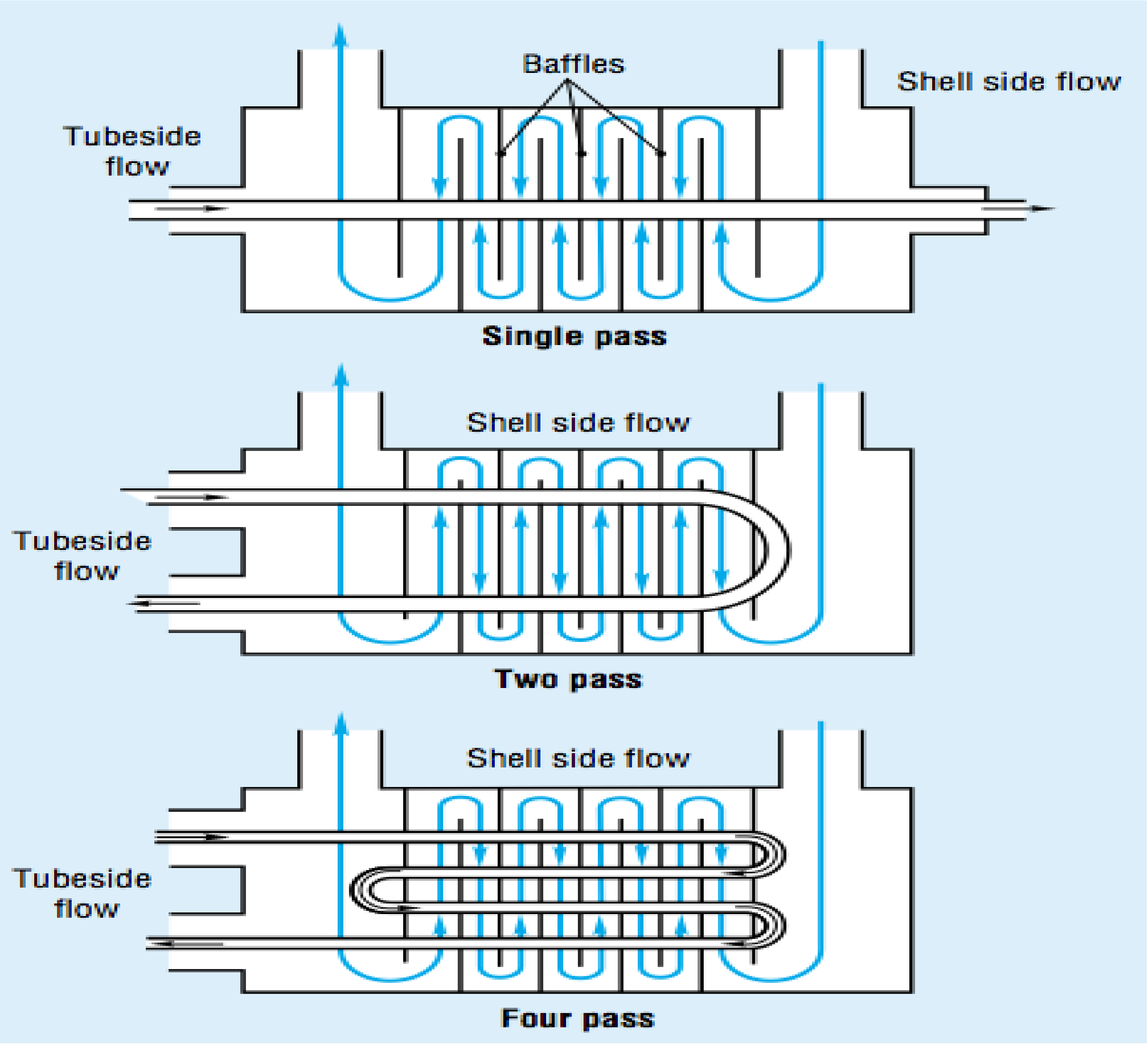
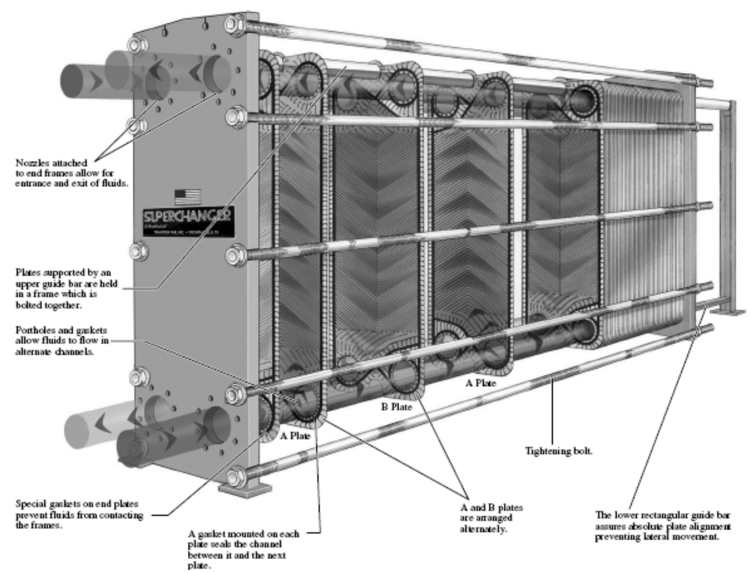

Baffles
Shell side flow
Tubeside flow
Single pass
Shell side flow
Tubeside flow
Two pass
Shell side flow
Tubeside flow
Four pass

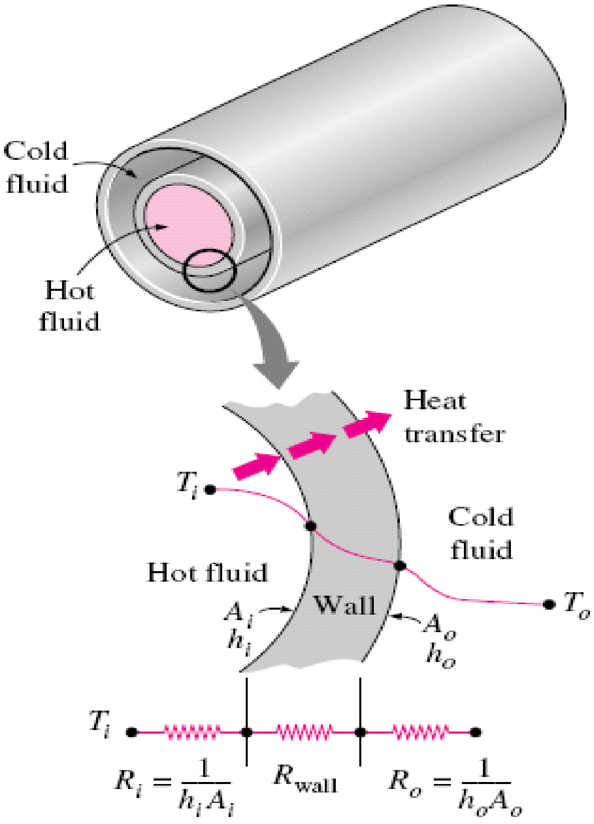
Plate and Frame Heat Exchanger

- Consists of a series of plates with corrugated flat flow passages.
- The hot and cold fluids flow in alternate passages
- Well suited for liquid-to-liquid heat exchange applications, provided that the hot and cold fluid streams are at about the same pressure.



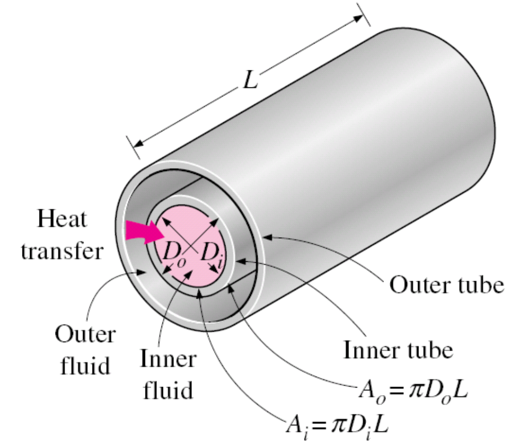
The Overall Heat Transfer Coefficient

- A heat exchanger typically involves two flowing fluids separated by a solid wall.
- Heat is transferred
  - from the hot fluid to the wall by *convection*,
  - through the wall by *conduction*, and
  - from the wall to the cold fluid by *convection*.
- The thermal resistance network
  - two convection and
  - one conduction resistances.



- For a double-pipe heat exchanger, the *thermal resistance* of the tube wall is

$$R_{wall} = \frac{\ln\left(D_0/D_i\right)}{2\pi kL}$$



- The *total thermal resistance*

$$R_{total} = R_i + R_{wall} + R_o = \frac{1}{h_i A_i} + \frac{\ln\left(D_0/D_i\right)}{2\pi kL} + \frac{1}{h_o A_o}$$

- When one fluid flows inside a circular tube and the other outside of it, we have

$$A_i = \pi D_i L \quad ; \quad A_o = \pi D_o L$$

- It is convenient to combine all the thermal resistances in the path of heat flow from the hot fluid to the cold one into a single resistance *R*

U is the **overall heat transfer coefficient**, whose unit is W/m²ºC.

- Canceling *T*, Eq. 11–3 reduces to

$$\dot{Q} = \frac{\Delta T}{R} = UA\Delta T = U_i A_i \Delta T = U_o A_o \Delta T$$

$$\frac{1}{UA_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = R = \frac{1}{h_i A_i} + R_{wall} + \frac{1}{h_o A_o}$$

- When the wall thickness of the tube is small and the thermal conductivity of the tube material is high (R_{wall}=0) and the inner and outer surfaces of the tube are almost identical ($A_i \approx A_o \approx A_s$),

simplifies to

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o}$$

- When $h_i >> h_o$

$$\frac{1}{U} \approx \frac{1}{h_o}$$

- When $h_i << h_o$

$$\frac{1}{U} \approx \frac{1}{h_i}$$

Fouling Factor

- The performance of heat exchangers usually deteriorates with time as a result of accumulation of *deposits* on heat transfer surfaces.
- The layer of deposits represents *additional resistance* to heat transfer and causes the rate of heat transfer in a heat exchanger to decrease.
- The **fouling factor** R_f – The net effect of these accumulations on heat transfer.
- Two common type of fouling:
  - *precipitation* of solid deposits in a fluid on the heat transfer surfaces.
  - *corrosion* and other *chemical fouling*.

- The overall heat transfer coefficient needs to be modified to account for the effects of fouling on both the inner and the outer surfaces of the tube.
- For an unfinned shell-and-tube heat exchanger, it can be expressed as

$R_{f,i}$ and $R_{f,o}$ are the **fouling factors** at those surfaces.

$$R = \frac{1}{h_i A_i} + \frac{R_{f,i}}{A_i} + \frac{\ln\left(D_0 / D_i\right)}{2\pi k L} + \frac{R_{f,o}}{A_o} + \frac{1}{h_o A_o}$$

Analysis of Heat Exchangers

- Two methods used in the analysis of heat exchangers:
  - the log mean temperature difference (or LMTD)
  - the effectiveness–NTU method

- The analysis of heat exchangers can be greatly simplify by making the following assumptions, which are closely approximated in practice:
  - steady-flow,
  - kinetic and potential energy changes are negligible,
  - the specific heat of a fluid is constant,
  - axial heat conduction along the tube is negligible,
  - the outer surface of the heat exchanger is perfectly insulated.
- The *first law of thermodynamics* requires that the rate of heat transfer from the hot fluid be equal to the rate of heat transfer to the cold one.

- The transfer rate to the cold fluid:

$$\dot{Q} = \dot{m}_c c_{pc} \left(T_{c,out} - T_{c,in} \right) = C_c \left(T_{c,out} - T_{c,in} \right) \; ; \; C_c = \dot{m}_c c_{pc}$$

- The transfer rate to the hot fluid:

$$\dot{Q} = \dot{m}_h c_{ph} \left(T_{h,in} - T_{h,out} \right) = C_h \left(T_{h,in} - T_{h,out} \right) \; ; \; C_h = \dot{m}_h c_{ph}$$

- Two special types of heat exchangers commonly used in practice are *condensers* and *boilers*.
- One of the fluids in a condenser or a boiler undergoes a phase-change process, and the rate of heat transfer is expressed as

$$\dot{Q} = \dot{m} h_{fg}$$

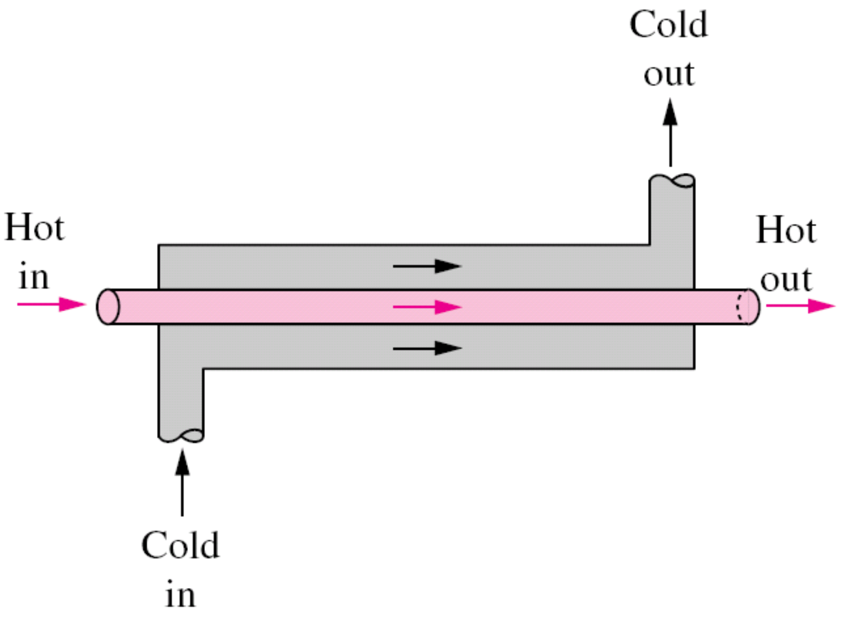
The Log Mean Temperature Difference Method

- The temperature difference between the hot and cold fluids varies along the heat exchanger.

  → it is convenient to have a *mean temperature difference* T_m for use in the relation

$$\dot{Q} = UA_s \Delta T_m$$

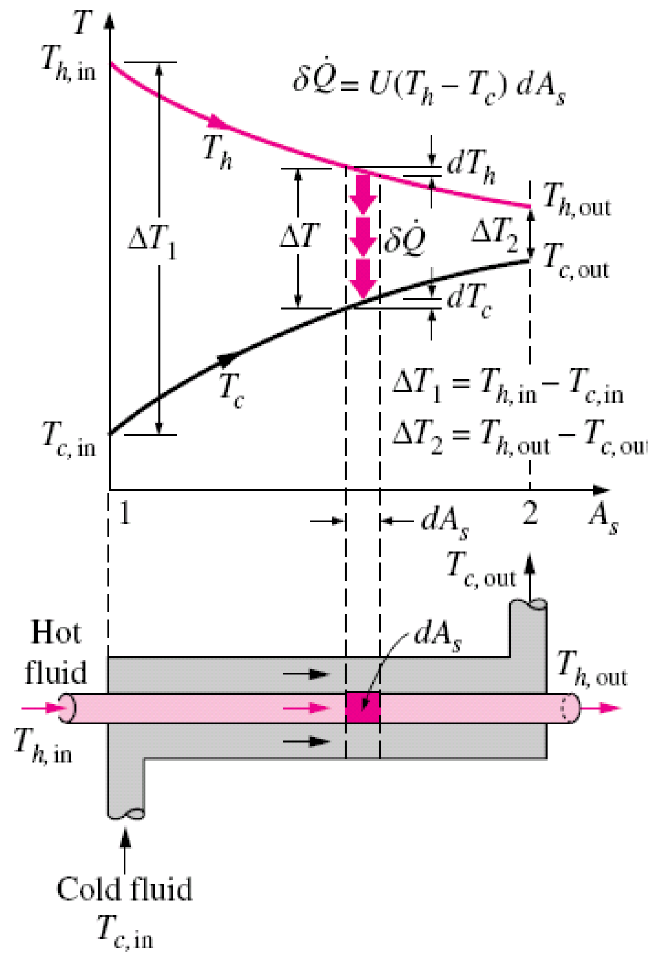
- Consider the *parallel-flow double-pipe* heat exchanger.



- An energy balance on each fluid in a differential section of the heat exchanger

$$\begin{cases} \delta \dot{Q} = -\dot{m}_h c_{ph} dT_h & \textbf{(11-16)} \\ \delta \dot{Q} = \dot{m}_c c_{pc} dT_c & \textbf{(11-17)} \end{cases}$$

$$\begin{cases} dT_h = -\dfrac{\delta \dot{Q}}{\dot{m}_h c_{ph}} & \textbf{(11-18)} \\ dT_c = \dfrac{\delta \dot{Q}}{\dot{m}_c c_{pc}} & \textbf{(11-19)} \end{cases}$$



- Taking their difference, we get

$$dT_h - dT_c = d\left(T_h - T_c\right) = -\delta \dot{Q}\left(\frac{1}{\dot{m}_h c_{ph}} + \frac{1}{\dot{m}_c c_{pc}}\right) \quad \textbf{(11-20)}$$

- The rate of heat transfer in the differential section of the heat exchanger can also be expressed as

- Substituting this equation into Eq. 11–20 and rearranging give

(11-21)

$$\delta \dot{Q} = U\left(T_h - T_c\right) dA_s$$

- Integrating from the inlet of the heat exchanger to its outlet, we obtain

$$\frac{d\left(T_h - T_c\right)}{T_h - T_c} = -UdA_s\left(\frac{1}{\dot{m}_h c_{ph}} + \frac{1}{\dot{m}_c c_{pc}}\right) \quad \textbf{(11-22)}$$

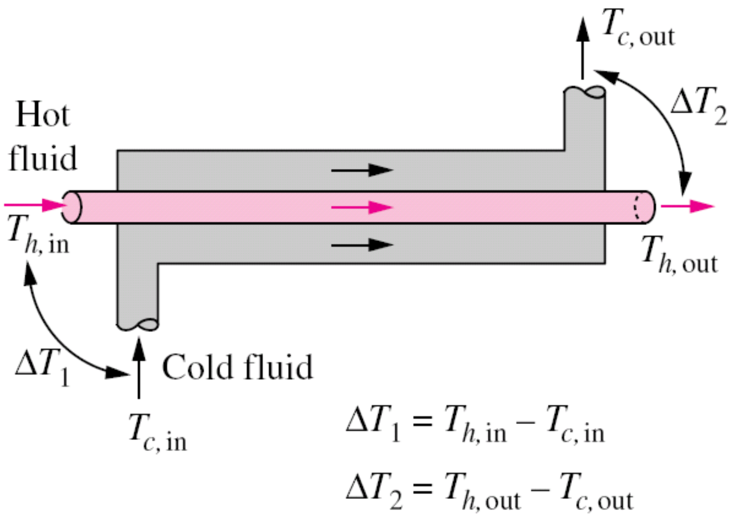
$$\ln \frac{T_{h,out} - T_{c,out}}{T_{h,in} - T_{c,in}} = -UA_s\left(\frac{1}{\dot{m}_h c_{ph}} + \frac{1}{\dot{m}_c c_{pc}}\right) \quad \textbf{(11-23)}$$

- Solving Eqs. 11–9 and 11–10 for $m_c c_{pc}$ and $m_h c_{ph}$ and substituting into Eq. 11–23 give

$$\dot{Q} = UA_s \Delta T_{lm} \qquad \textbf{(11-24)}$$

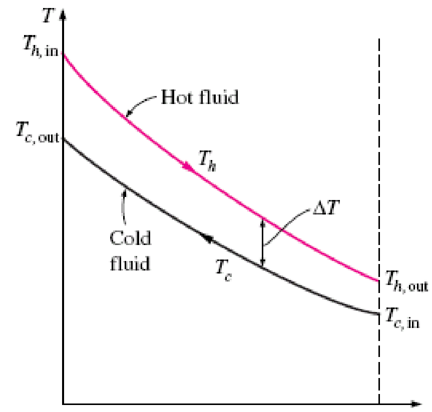
$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\Delta T_1 / \Delta T_2\right)} \qquad \textbf{(11-25)}$$

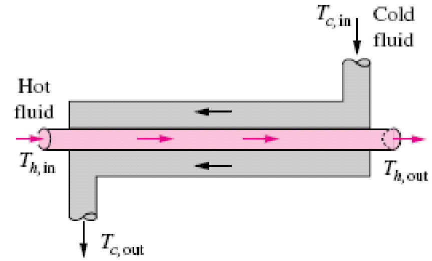
- ΔT_{lm} is the **log mean temperature difference**.
- ΔT_1 and ΔT_2 are the temperature difference between the two fluids at the two ends (inlet and outlet).
- It makes no difference which end of the heat exchanger is designated as the inlet or the outlet.

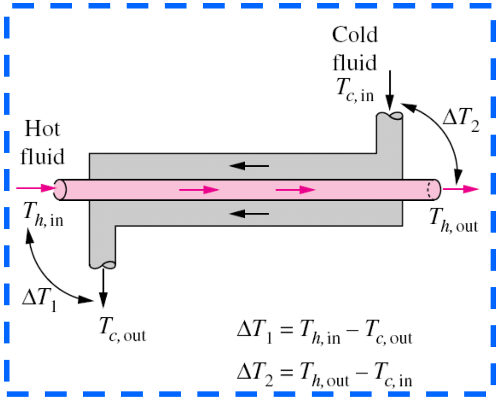


Counter-Flow Heat Exchangers

- The relation already given for the log mean temperature difference for parallel-flow heat exchanger can be used for a counter-flow heat exchanger.
- ΔT_1 and ΔT_2 are expressed as shown in the Fig. 11–15.
- $\Delta T_{lm,\,CF} > \Delta T_{lm,\,PF}$
- A smaller surface area (a smaller heat exchanger) is needed to achieve a specified heat transfer rate in a counter-flow heat exchanger.







Multipass and Cross-Flow Heat Exchangers: Use of a Correction Factor

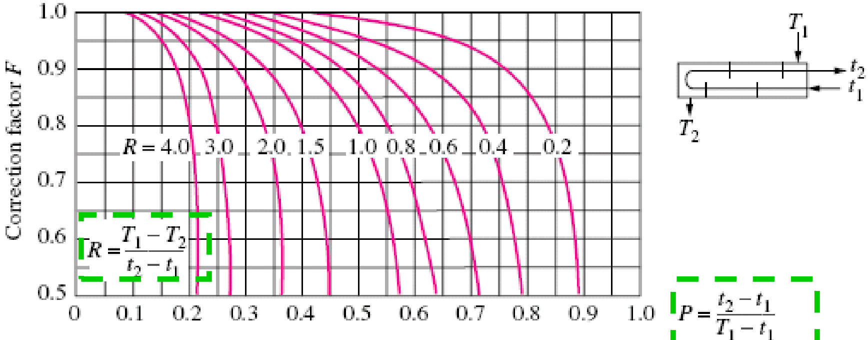
- The log mean temperature difference relation developed earlier is limited to parallel-flow and counter-flow heat exchangers only.
- To simplify the analysis of *cross-flow* and *multipass shell-and-tube* heat exchangers, it is convenient to express the log mean temperature difference relation as

$$\Delta T_{lm} = F\,\Delta T_{lm,CF} \qquad \textbf{(11-26)}$$

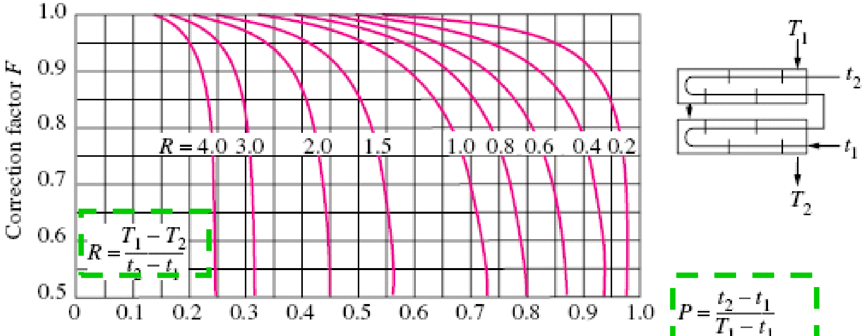
- ***F*** is the **correction factor**, and $\Delta T_{\mathrm{lm,\,CF}}$ is the log mean temperature for counter-flow case.

F Charts for Common Shell-and-Tube and Cross-Flow Heat Exchangers.

Shell and Tube Heat Exchanger

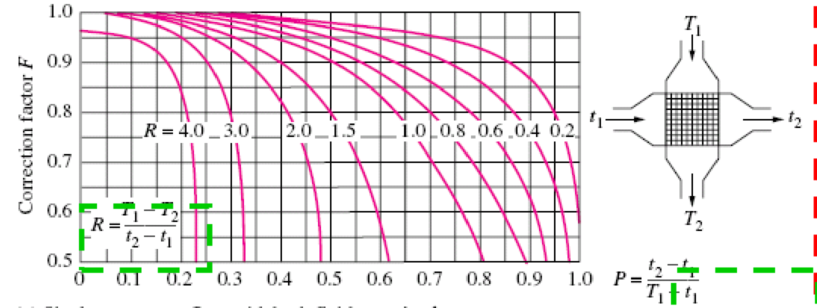


(*a*) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes

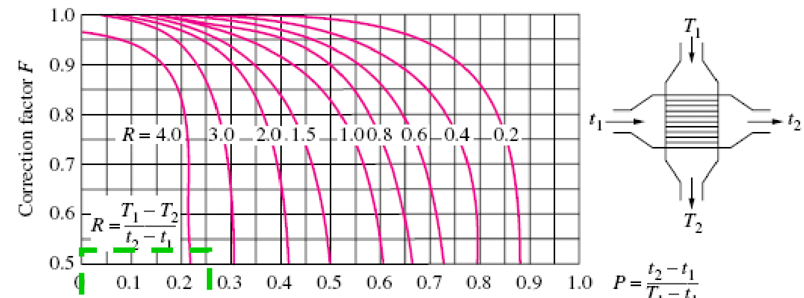


(*b*) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes

Cross Flow Heat Exchanger



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



(*d*) Single-pass cross-flow with one fluid *mixed* and the other *unmixed*

The Heat Exchanger Design Procedure using the LMTD

- 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 ΔT_{lm} and the correction factor F, if necessary.

4. Obtain (select or calculate) the value of the overall heat transfer co-efficient U.

5. Calculate the heat transfer surface area A_s needed to meet requirements.

The Effectiveness – NTU Method

- This method is based on a dimensionless parameter called the **heat transfer effectiveness** ε

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{\textbf{Actual heat transfer rate}}{\textbf{Maximum possible heat transfer rate}} \qquad \textbf{(11-29)}$$

- The **actual heat transfer rate** in a heat exchanger

$$\dot{Q} = C_c\left(T_{c,out} - T_{c,in}\right) = C_h\left(T_{h,in} - T_{h,out}\right) \qquad \textbf{(11-30)}$$

- The *maximum temperature difference*

$$\Delta T_{\max} = T_{h,in} - T_{c,in} \qquad \textbf{(11-31)}$$

- The **maximum possible heat transfer rate** in a heat exchanger

$$\dot{Q}_{\max} = C_{\min}\Delta T_{\max} = C_{\min}\left(T_{h,in} - T_{c,in}\right) \qquad \textbf{(11-32)}$$

- Once the effectiveness of the heat exchanger is known, the actual heat transfer rate can be determined from

- The effectiveness of a heat exchanger depends on:
  - the geometry of the heat exchanger, and
  - the flow arrangement.

(11-33)

$$\dot{Q} = \varepsilon \dot{Q}_{\max} = \varepsilon C_{\min}\left(T_{h,in} - T_{c,in}\right)$$

- It can be shown that the effectiveness of double-pipe parallel-flow heat exchanger is

$$\varepsilon_{\text{parallel flow}} = \frac{1 - \exp\left[-\frac{UA_s}{C_{\min}}\left(1 + \frac{C_{\min}}{C_{\max}}\right)\right]}{1 + \frac{C_{\min}}{C_{\max}}}$$

- **Effectiveness** relations of the heat exchangers typically involve a *dimensionless* group called the **number of transfer units NTU**

$$NTU = \frac{UA_s}{C_{min}} = \frac{UA_s}{(\dot{m}c_p)_{min}} \qquad \textbf{(11-39)}$$

- For specified values of U and C_{min}, the value of NTU is a measure of the heat transfer surface area A_s.
- The larger the NTU, the larger the heat exchanger.
- It is also convenient to define a **capacity ratio *c***

$$c = \frac{C_{min}}{C_{max}} \qquad \textbf{(11-40)}$$

- The effectiveness of a heat exchanger is a function of the number of transfer units NTU and the capacity ratio *c*.

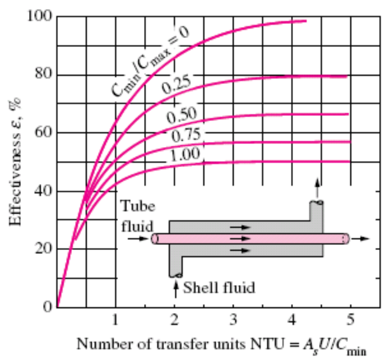
Effectiveness for Several Heat Exchangers

TABLE 11–4

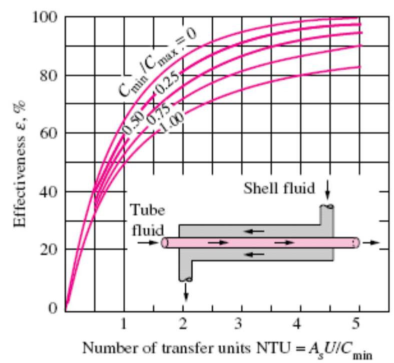
Effectiveness relations for heat exchangers: $NTU = UA_s/C_{min}$ and $c = C_{min}/C_{max} = (\dot{m}c_p)_{min}/(\dot{m}c_p)_{max}$

Heat exchanger type	Effectiveness relation
1 *Double pipe:*	
Parallel-flow	$\varepsilon = \dfrac{1 - \exp[-NTU(1 + c)]}{1 + c}$
Counter-flow	$\varepsilon = \dfrac{1 - \exp[-NTU(1 - c)]}{1 - c\exp[-NTU(1 - c)]}$
2 *Shell-and-tube:* One-shell pass 2, 4, . . . tube passes	$\varepsilon = 2\left\{1 + c + \sqrt{1 + c^2}\dfrac{1 + \exp[-NTU\sqrt{1 + c^2}]}{1 - \exp[-NTU\sqrt{1 + c^2}]}\right\}^{-1}$
3 *Cross-flow (single-pass)*	
Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\dfrac{NTU^{0.22}}{c}[\exp(-c\ NTU^{0.78}) - 1]\right\}$
C_{max} mixed, C_{min} unmixed	$\varepsilon = \dfrac{1}{c}(1 - \exp\{1 - c[1 - \exp(-NTU)]\})$
C_{min} mixed, C_{max} unmixed	$\varepsilon = 1 - \exp\left\{-\dfrac{1}{c}[1 - \exp(-c\ NTU)]\right\}$
4 *All heat exchangers with c = 0*	$\varepsilon = 1 - \exp(-NTU)$

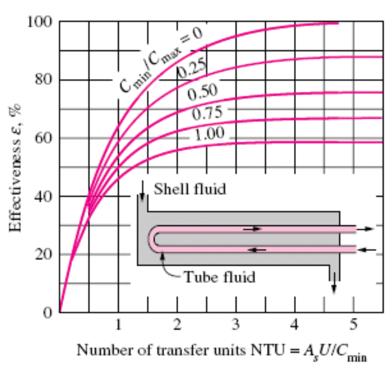
Effectiveness Heat Exchangers Plots



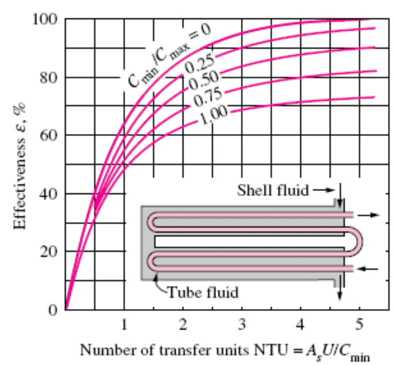
(*a*) Parallel-flow



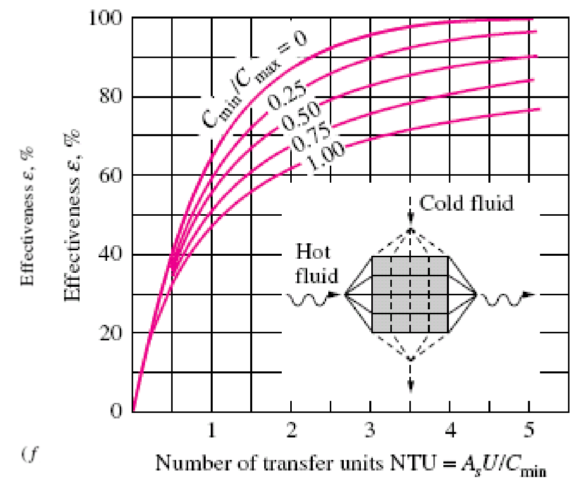
(*b*) Counter-flow



(*c*) One-shell pass and 2, 4, 6, … tube passes



(*d*) Two-shell passes and 4, 8, 12, … tube passes



(*e*) Cross-flow with both fluids unmixed

Selection of Heat Exchangers

- An engineer going through catalogs of heat exchanger manufacturers will be overwhelmed by the type and number of readily available off-the-shelf heat exchangers.
- The proper selection depends on several factors:
  - Heat Transfer Rate
  - Fluid Properties
  - Cost
    - Procurement, Maintenance,
    - Pumping Power,
  - Size And Weight,
  - Type , Materials,
  - Miscellaneous (Leak-tight, Safety And Reliability, Quietness).