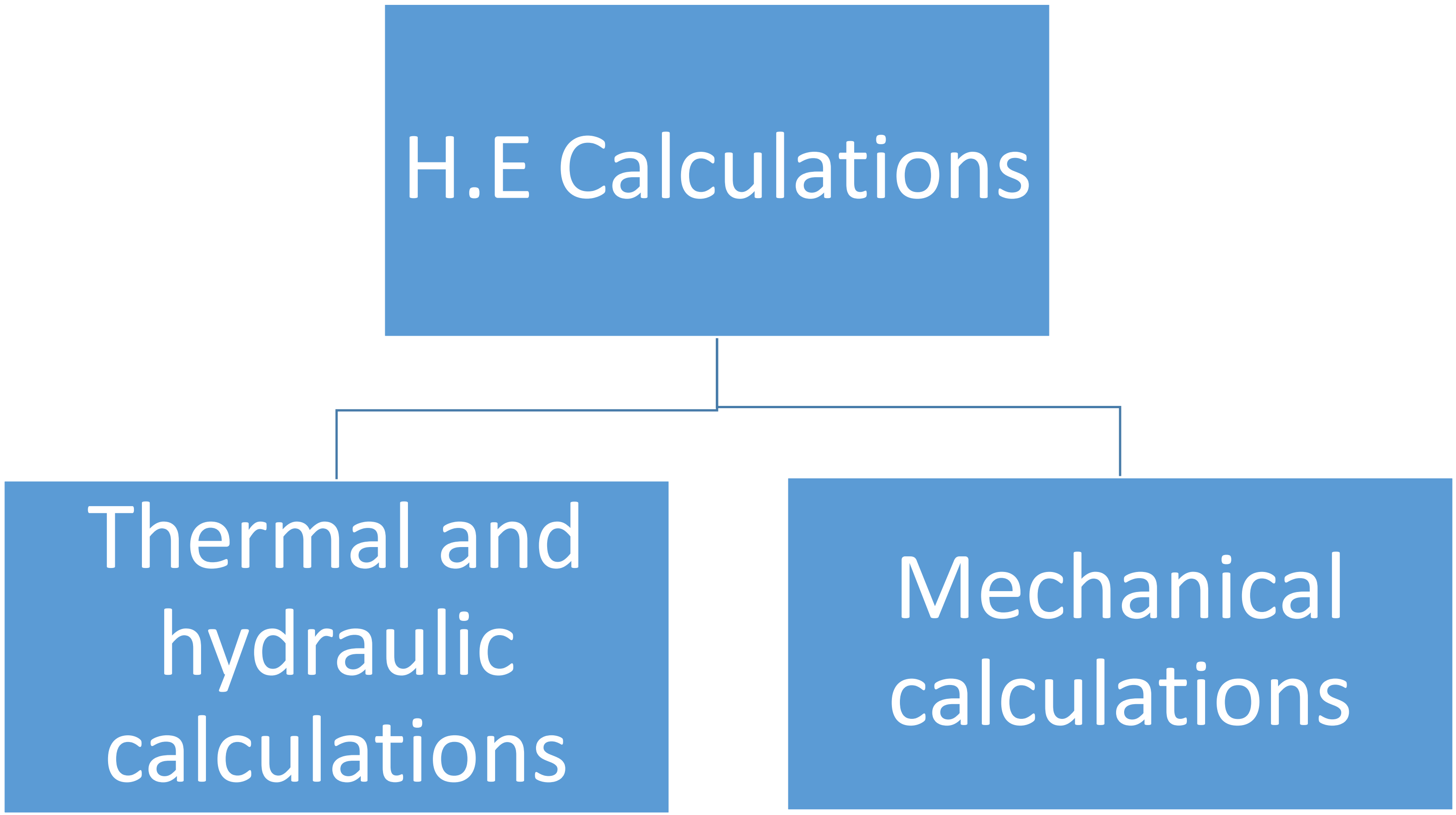
Heat Exchangers
1

Introduction

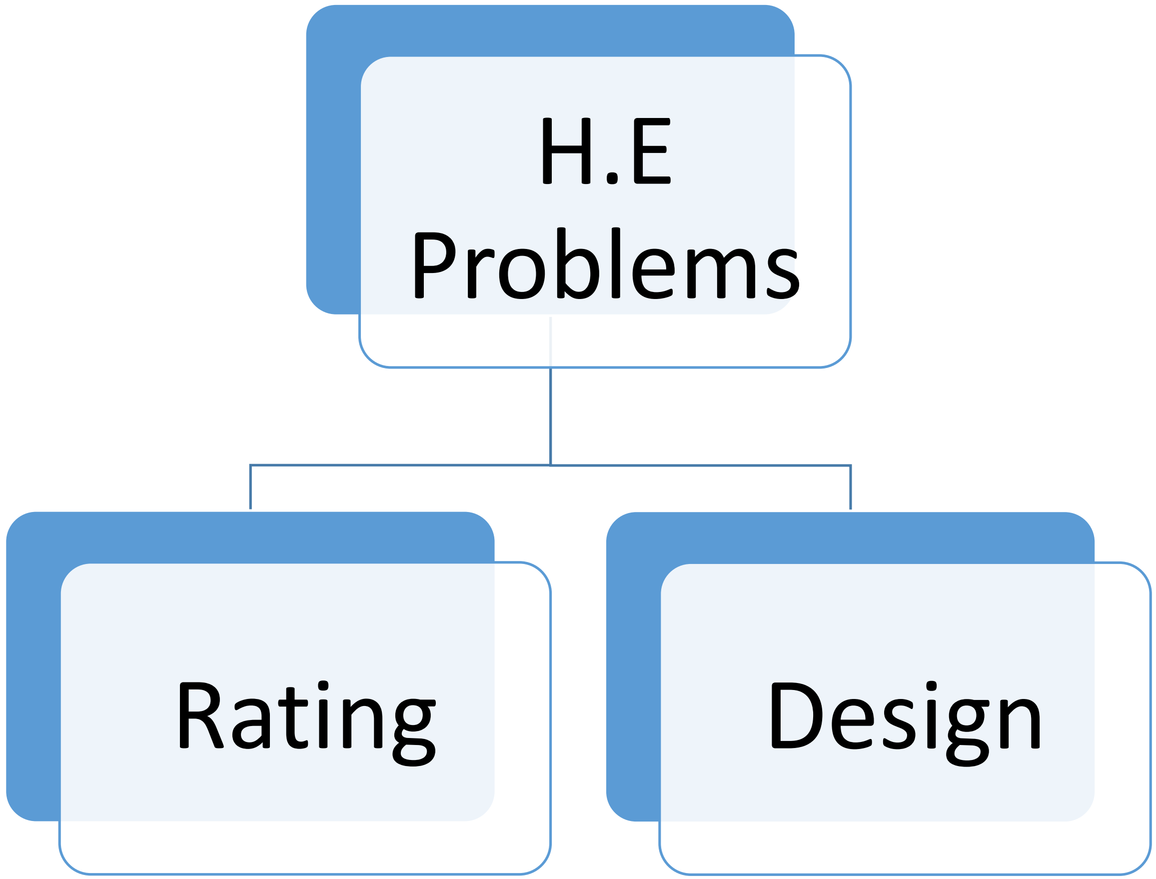
- Definition.
- In this introduction, the discussion will be limited to two common exchangers; namely, the double pipe exchanger and the shell-and-tube exchanger.
- The double pipe is the simplest type of heat exchanger (H.E), while the shell-and-tube is the most widely used type of exchanger in the chemical process industries.
- H.E calculations includes two types of calculations.


H.E Calculations
Thermal and hydraulic calculations
Mechanical calculations

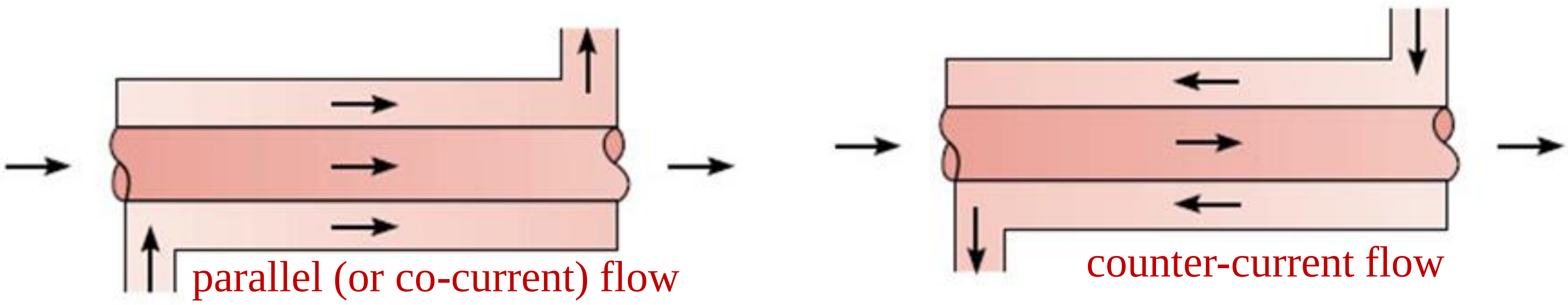
Notes

- Thermal and hydraulic calculations are made to determine heat-transfer rates and pressure drops needed for equipment sizing.
- Mechanical design calculations are concerned with detailed equipment specifications, and include considerations such as stress and tube vibration analyses.

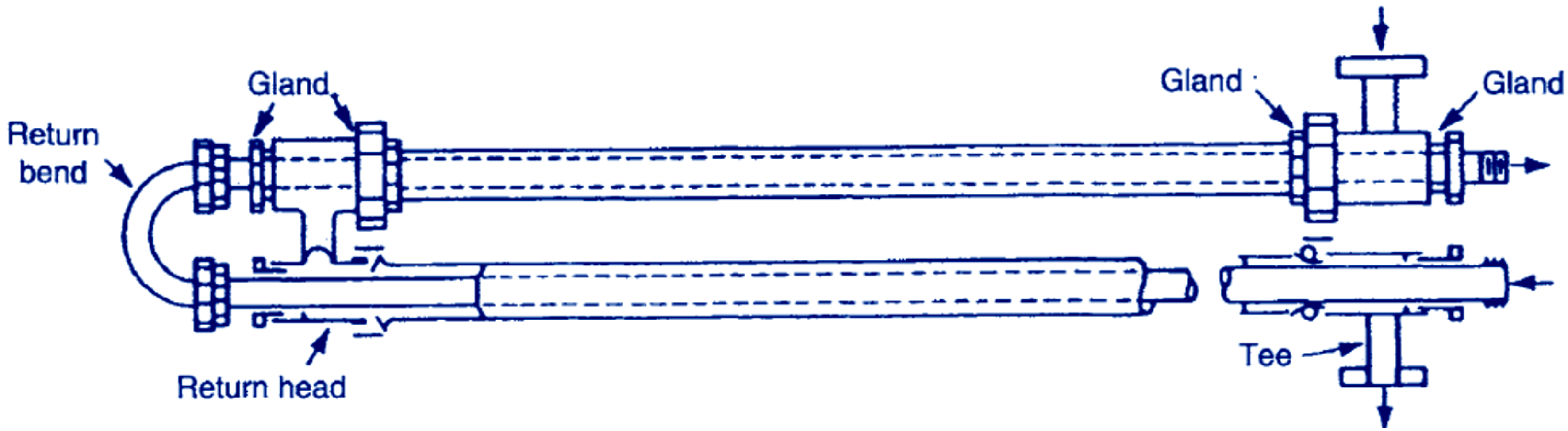
Heat-exchanger Problems



Double-Pipe Equipment



Concentric tube exchangers

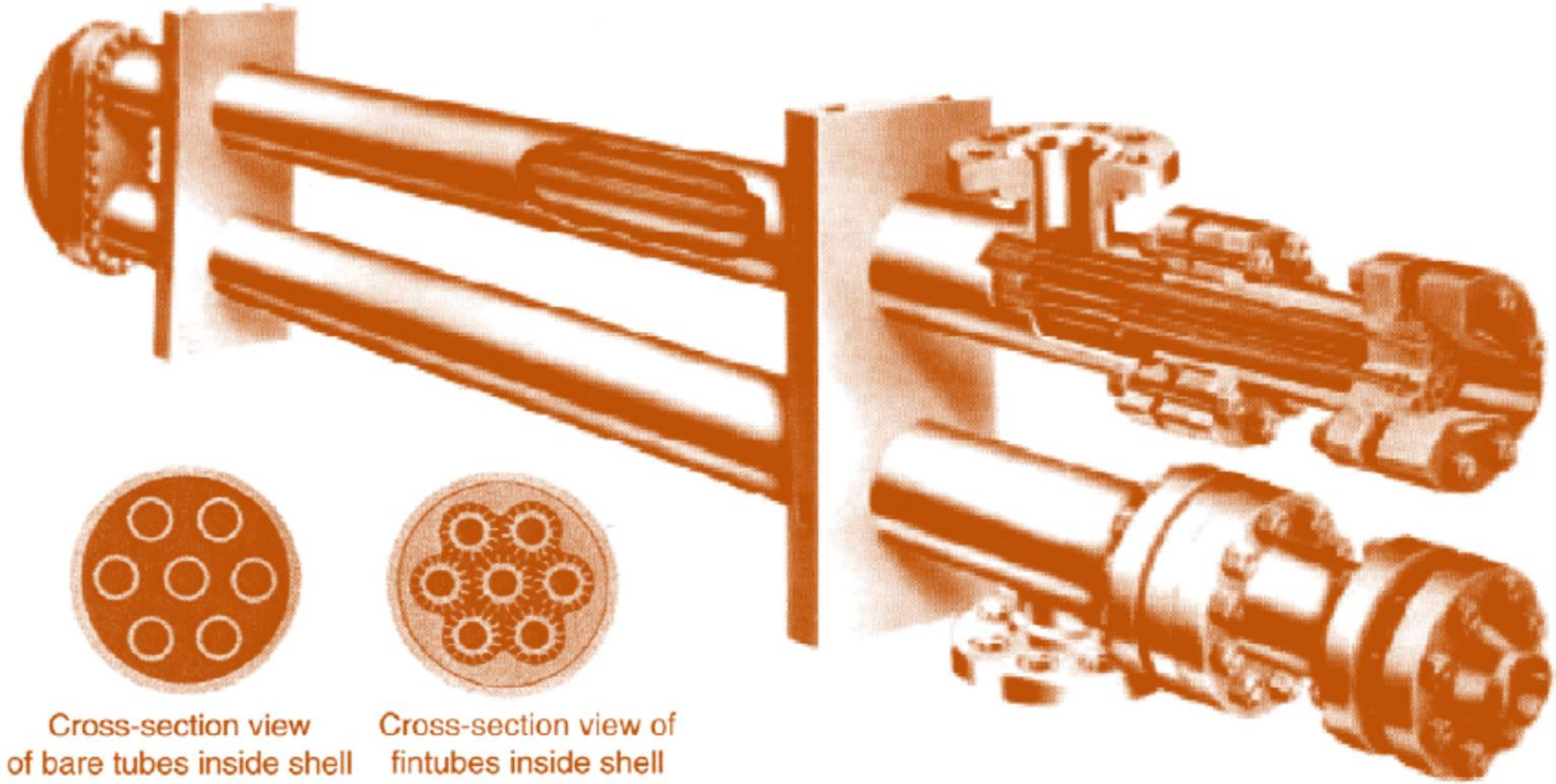


Simple double-pipe exchanger (one hairpin)

characteristics of hairpin exchanger

- Batteries of hairpins connected in series or in series-parallel arrangements are commonly employed to provide adequate surface area for heat transfer.
- The outer pipe may be insulated to minimize heat transfer to or from the environment.
- Nozzles may be provided on the inner-pipe (tube) side as well as on the annulus side to facilitate connection to process piping.
- Multi-tube exchangers are also available in which the inner pipe is replaced by a bundle of U-tubes, as shown in the next slide.

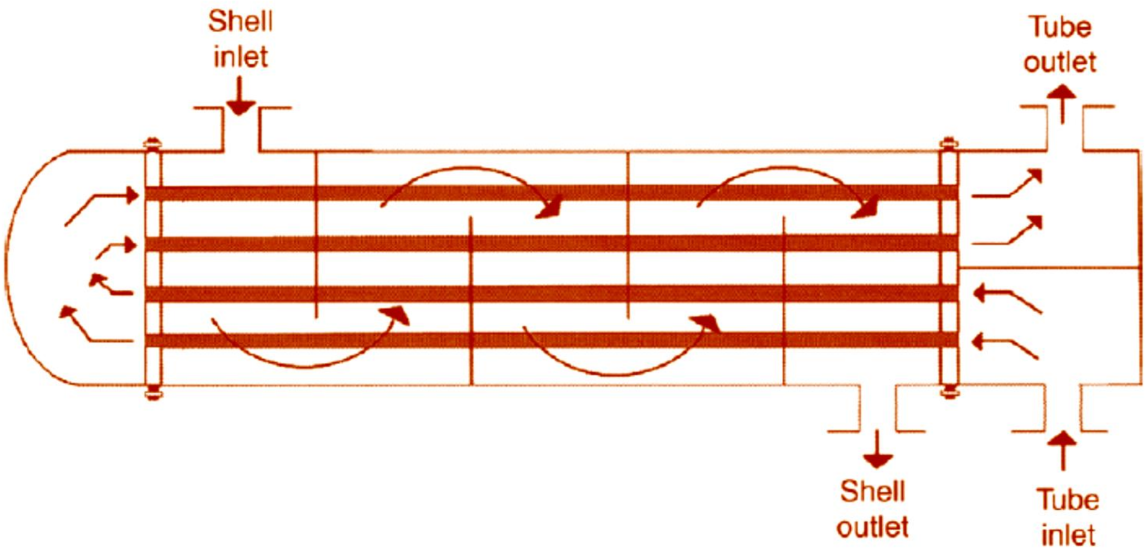
Multi-tube hairpin exchanger



- Simple double-pipe exchangers are commercially available with outer-pipe sizes ranging from 2 to 8 in. and inner pipes from 3/4 to 6 in.
- Multi-tube units with outer-pipe sizes as large as 36 in. are commercially available.
- Double-pipe exchangers are commonly used in applications involving relatively low flow rates and high temperatures or pressures, for which they are well suited.
- Other advantages include low installation cost, ease of maintenance, and flexibility.

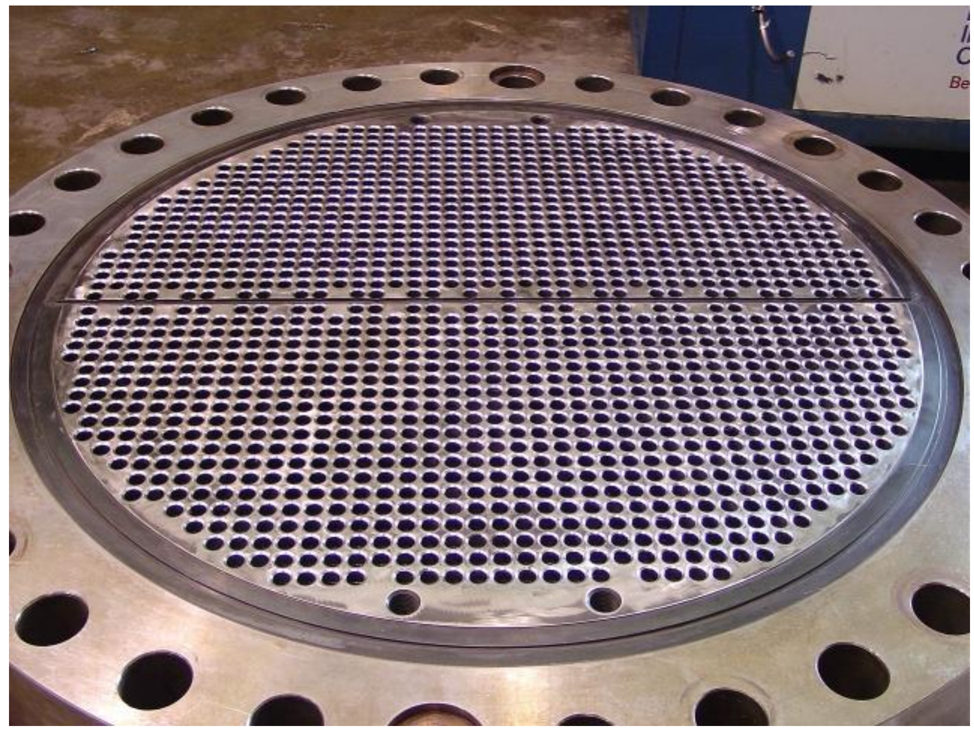
Shell-and-Tube Equipment

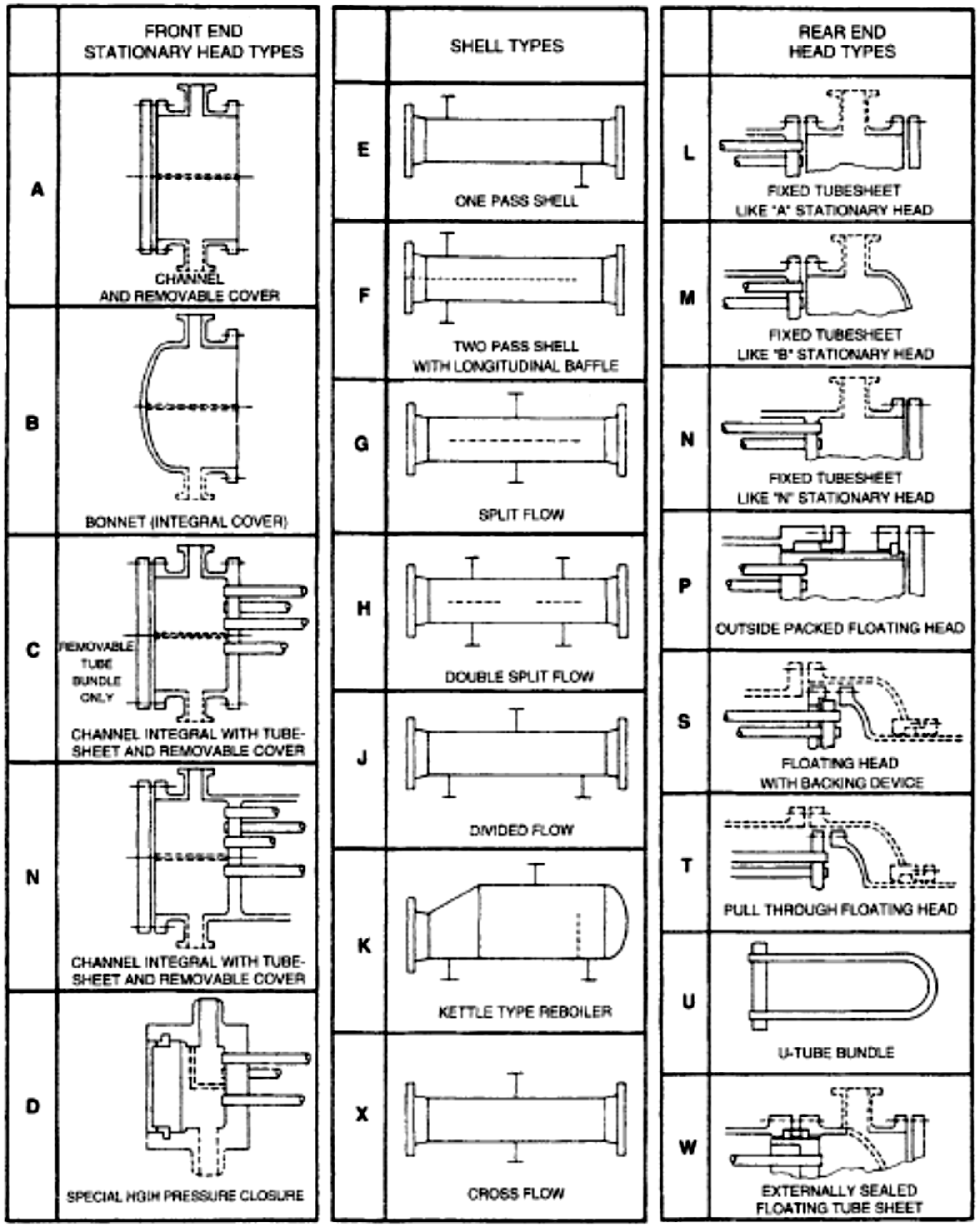
- A shell-and-tube exchanger consists of a bundle of tubes contained in a cylindrical shell.



- Tubes could be fixed or removable.
- Tube sheets are used to fix the tubes and to prevent fluids mixing. {See next slide}
- A number of different head and shell designs are commercially available. See next slides

Tube sheet

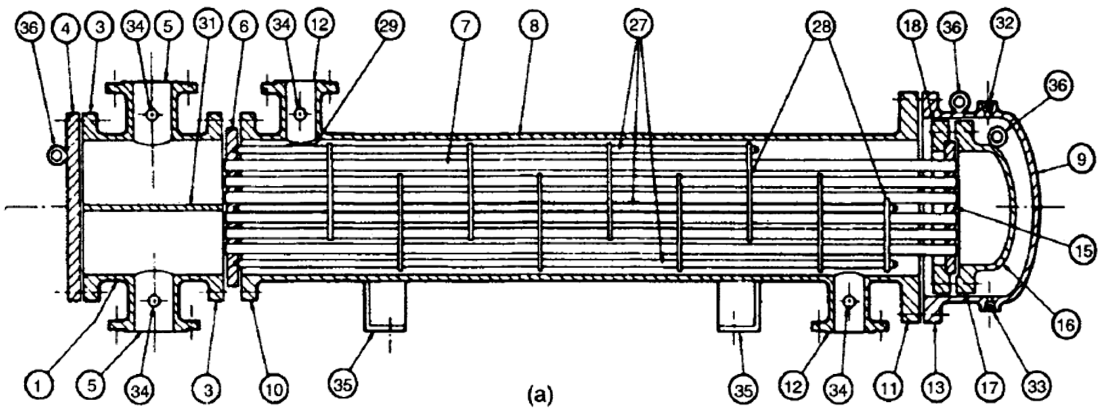




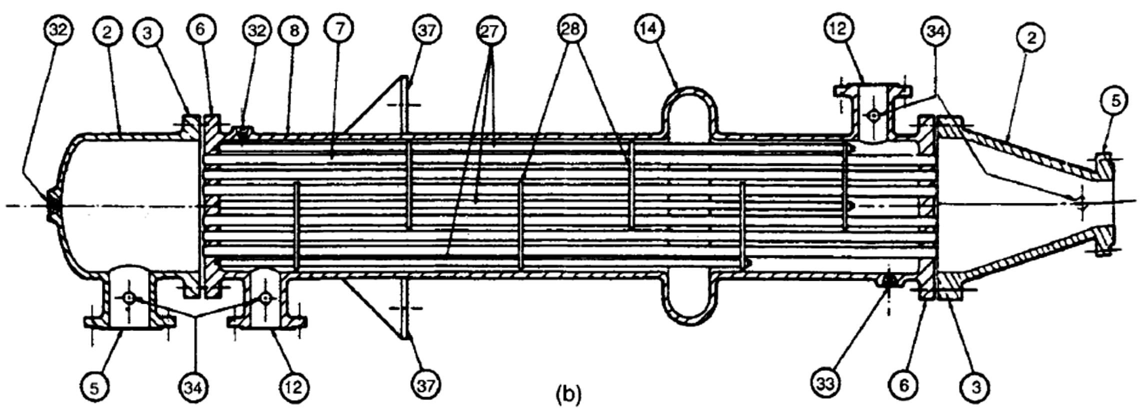
TEMA designations for shell-and-tube exchangers

Notes

The Tubular Exchanger Manufacturers Association (TEMA) employs a three-letter code to specify the front-end, shell, and rear-end types. For example, a floating-head type AES and fixed tube-sheet type BEM exchangers are shown in the following figure.



(a) Type AES floating-head exchanger



(b) type BEM fixed-tube sheet exchanger with conical rear head

1. Stationary Head-Channel
2. Stationary Head-Bonnet
3. Stationary Head Flange-Channel or Bonnet
4. Channel Cover
5. Stationary Head Nozzle
6. Stationary Tubesheet
7. Tubes
8. Shell
9. Shell Cover
10. Shell Flange-Stationary Head End
11. Shell Flange-Rear Head End
12. Shell Nozzle
13. Shell Cover Flange
14. Expansion Joint
15. Floating Tubesheet
16. Floating Head Cover
17. Floating Head Cover Flange
18. Floating Head Backing Device
19. Split Shear Ring
20. Slip-on Backing Flange
21. Floating Head Cover-External
22. Floating Tubesheet Skirt
23. Packing Box
24. Packing
25. Packing Gland
26. Omitted
27. Tierods and Spacers
28. Transverse Baffles or Support Plates
29. Impringement Plate
30. Longitudinal Baffle
31. Pass Partition
32. Vent Connection
33. Drain Connection
34. Instrument Connection
35. Support Saddle
36. Lifting Lug
37. Support Bracket
38. Weir
39. Liquid Level Connection
40. Floating Head Support

Numbers for the previous figure (Also see text _ Serth).

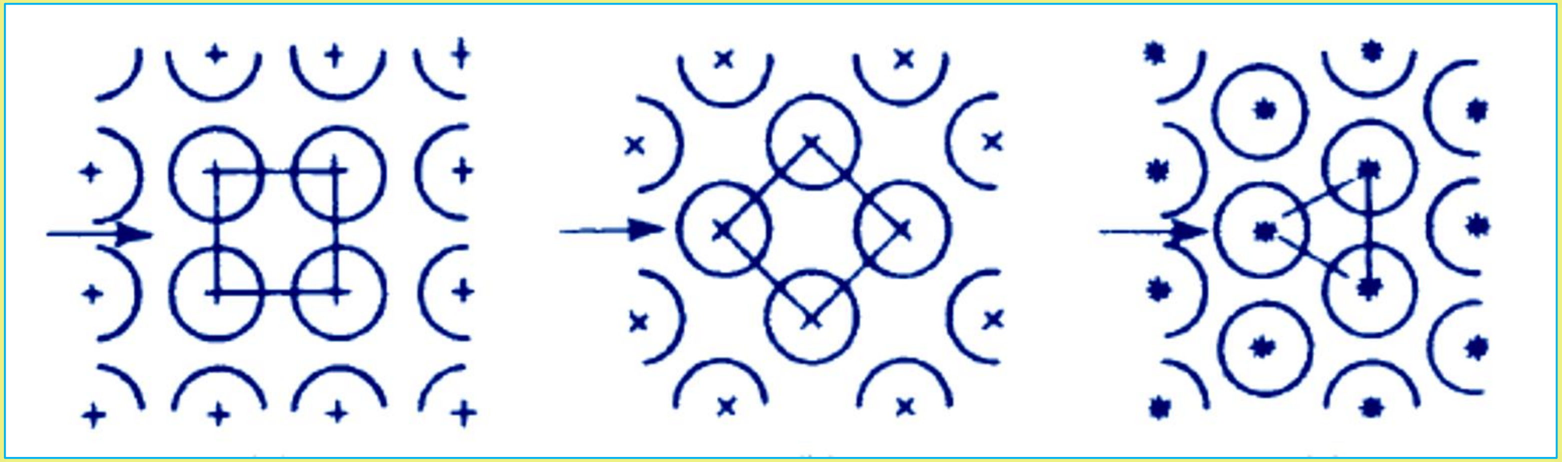
- **Shells** are available with inside diameters in discrete sizes up to 120 in. Shells up to 24 in. in diameter are generally made from steel pipes, while larger sizes are made from rolled steel plate.
- **Tubes** are available with sizes from 1/4 to 2 in. outside diameter. Finned tubing is also available. See the next slid for properties of steel pipes.

Properties of steel pipes (see the text for detail).

Nominal pipe size (in.)	Outside diameter (in.)	Schedule No.	Wall thickness (in.)	Inside diameter (in.)	Cross-sectional area		Circumference (ft) or surface (ft²/ft of length)		Capacity at 1 ft/s velocity		Weight of plain-end pipe (lb/ft)
					Metal (in.²)	Flow (ft²)	Outside	Inside	US gal/min	lb/h water	
$\frac{1}{8}$	0.405	10S	0.049	0.307	0.055	0.00051	0.106	0.0804	0.231	115.5	0.19
		40ST, 40S	0.068	0.269	0.072	0.00040	0.106	0.0705	0.179	89.5	0.24
		80XS, 80S	0.095	0.215	0.093	0.00025	0.106	0.0563	0.113	56.5	0.31
$\frac{1}{4}$	0.540	10S	0.065	0.410	0.097	0.00092	0.141	0.107	0.412	206.5	0.33
		40ST, 40S	0.088	0.364	0.125	0.00072	0.141	0.095	0.323	161.5	0.42
		80XS, 80S	0.119	0.302	0.157	0.00050	0.141	0.079	0.224	112.0	0.54
$\frac{3}{8}$	0.675	10S	0.065	0.545	0.125	0.00162	0.177	0.143	0.727	363.5	0.42
		40ST, 40S	0.091	0.493	0.167	0.00133	0.177	0.129	0.596	298.0	0.57
		80XS, 80S	0.126	0.423	0.217	0.00098	0.177	0.111	0.440	220.0	0.74
$\frac{1}{2}$	0.840	5S	0.065	0.710	0.158	0.00275	0.220	0.186	1.234	617.0	0.54
		10S	0.083	0.674	0.197	0.00248	0.220	0.176	1.112	556.0	0.67
		40ST, 40S	0.109	0.622	0.250	0.00211	0.220	0.163	0.945	472.0	0.85
		80XS, 80S	0.147	0.546	0.320	0.00163	0.220	0.143	0.730	365.0	1.09
		160	0.188	0.464	0.385	0.00117	0.220	0.122	0.527	263.5	1.31
		XX	0.294	0.252	0.504	0.00035	0.220	0.066	0.155	77.5	1.71
$\frac{3}{4}$	1.050	5S	0.065	0.920	0.201	0.00461	0.275	0.241	2.072	1036.0	0.69
		10S	0.083	0.884	0.252	0.00426	0.275	0.231	1.903	951.5	0.86
		40ST, 40S	0.113	0.824	0.333	0.00371	0.275	0.216	1.665	832.5	1.13
		80XS, 80S	0.154	0.742	0.433	0.00300	0.275	0.194	1.345	672.5	1.47
		160	0.219	0.612	0.572	0.00204	0.275	0.160	0.917	458.5	1.94
		XX	0.308	0.434	0.718	0.00103	0.275	0.114	0.461	230.5	2.44
1	1.315	5S	0.065	1.185	0.255	0.00768	0.344	0.310	3.449	1725	0.87
		10S	0.109	1.097	0.413	0.00656	0.344	0.287	2.946	1473	1.40
		40ST, 40S	0.133	1.049	0.494	0.00600	0.344	0.275	2.690	1345	1.68
		80XS, 80S	0.179	0.957	0.639	0.00499	0.344	0.250	2.240	1120	2.17
		160	0.250	0.815	0.836	0.00362	0.344	0.213	1.625	812.5	2.84
		XX	0.358	0.599	1.076	0.00196	0.344	0.157	0.878	439.0	3.66

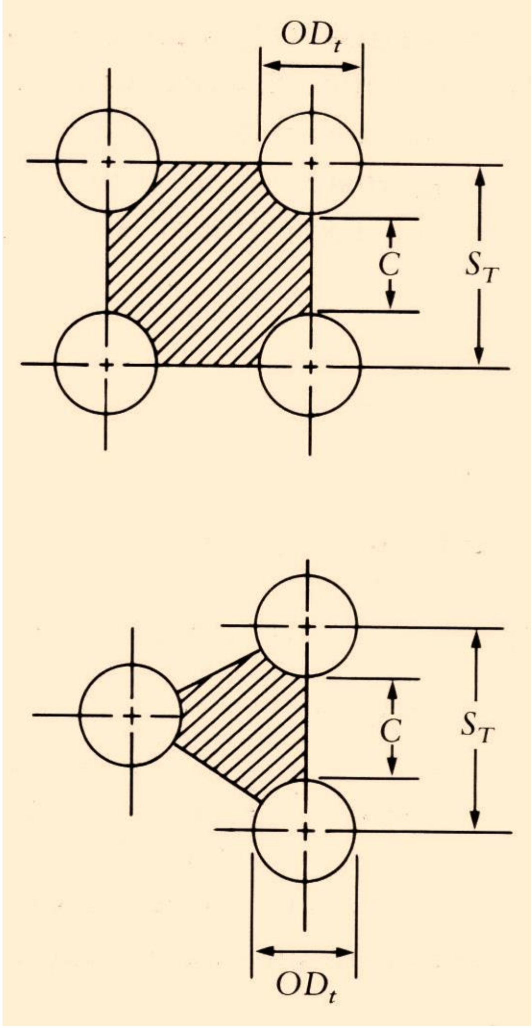
Tube layout

❖The tubes are arranged in the bundle according to specific patterns. The most common are square (90°), rotated square (45°) and equilateral triangle (30°) as shown in the following Figure:



❖ The square and rotated square layouts permit mechanical cleaning of the outsides of the tubes.

Equivalent diameter for shell side



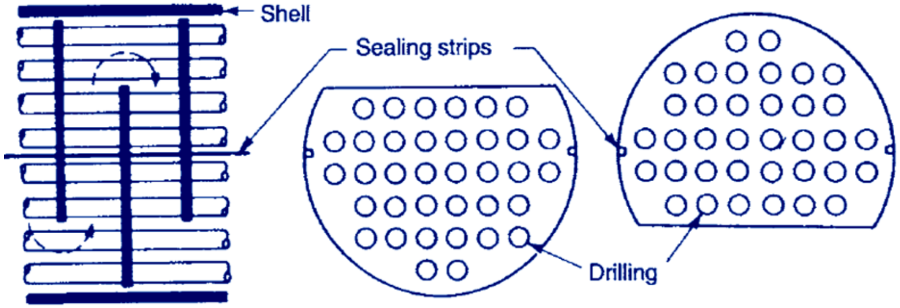
$$D_e = \frac{4 \times \text{Area}}{\text{Wetted perimeter}}$$

$$D_e = \frac{4[S_T^2 - \pi(OD_t)^2/4]}{\pi(OD_t)}$$

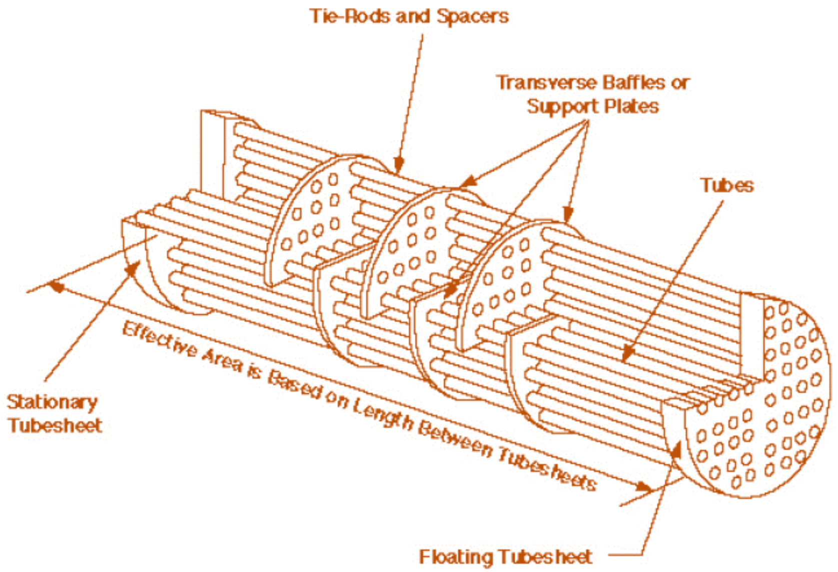
$$D_e = \frac{4[S_T/2)(0.86S_T) - \pi(OD_t)^2/8]}{\pi(OD_t)/2}$$

Baffles

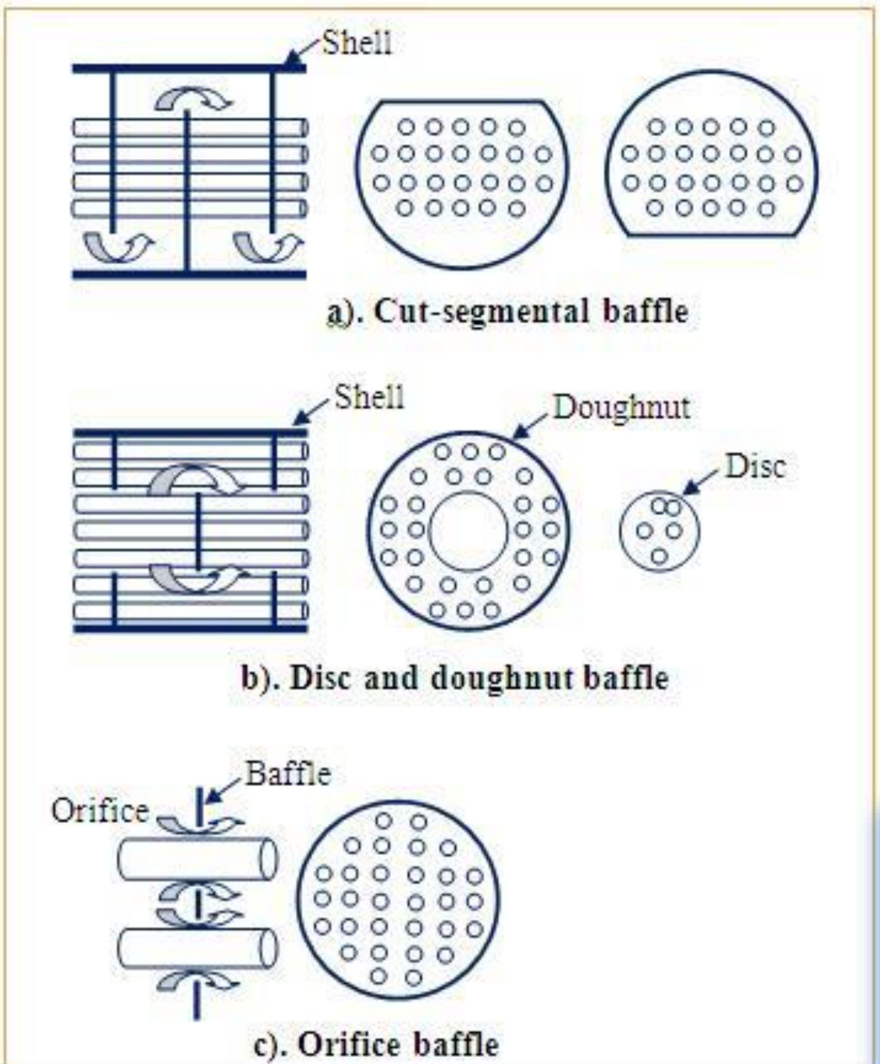
- Baffles are a number of discs installed inside the shell side of the H.E.
- Used to support the tube bundle and to withstand vibrations and bending.
- Typical types are

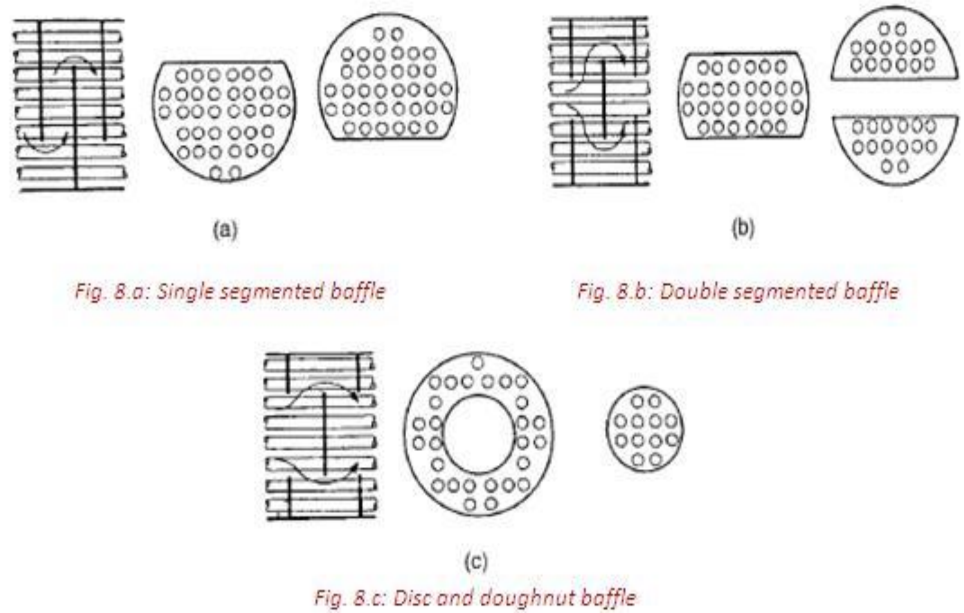


Segmental baffles



Baffles



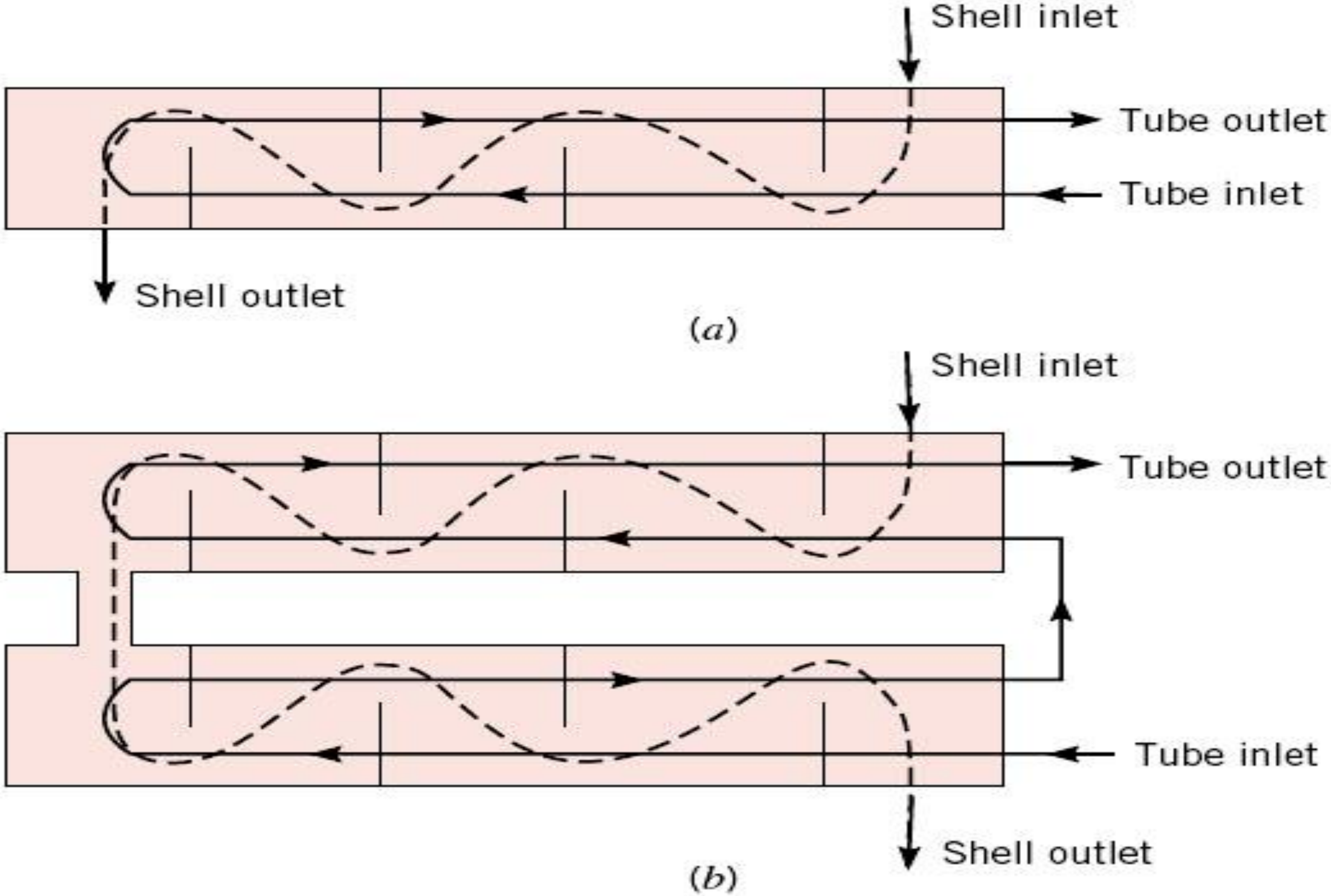


Note: **The baffles serve the function of directing the flow of the shell-side fluid across the tube bundle, thereby enhancing the rate of heat transfer.**

Notes: Sealing strips (metal strips attached to the baffles) are used to minimize the channeling of fluid between the outer row of tubes and the shell.

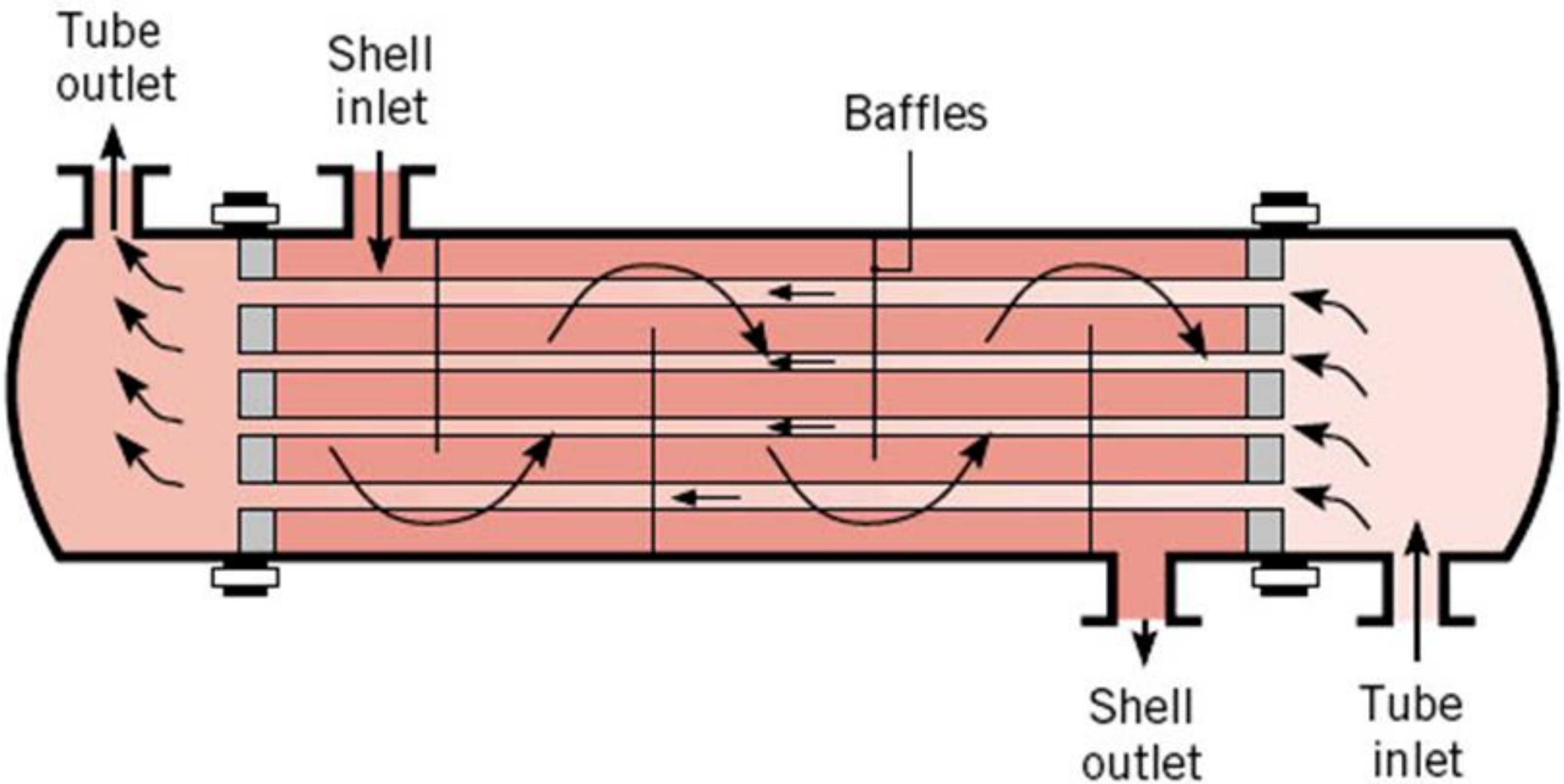
Tube and shell passes

- Tube side:
  - multiple passes are achieved by means of U-tubes or by partitioning the headers.
  - The number of tube-side passes is usually one, two, four, or six, but may be as high as 16.
- Shell side:
  - Multiple passes on the shell side are achieved by partitioning the shell with a longitudinal baffle (type F-shell) or by connecting two or more single-pass shells together.
  - number of shell-side passes is usually between one and six.

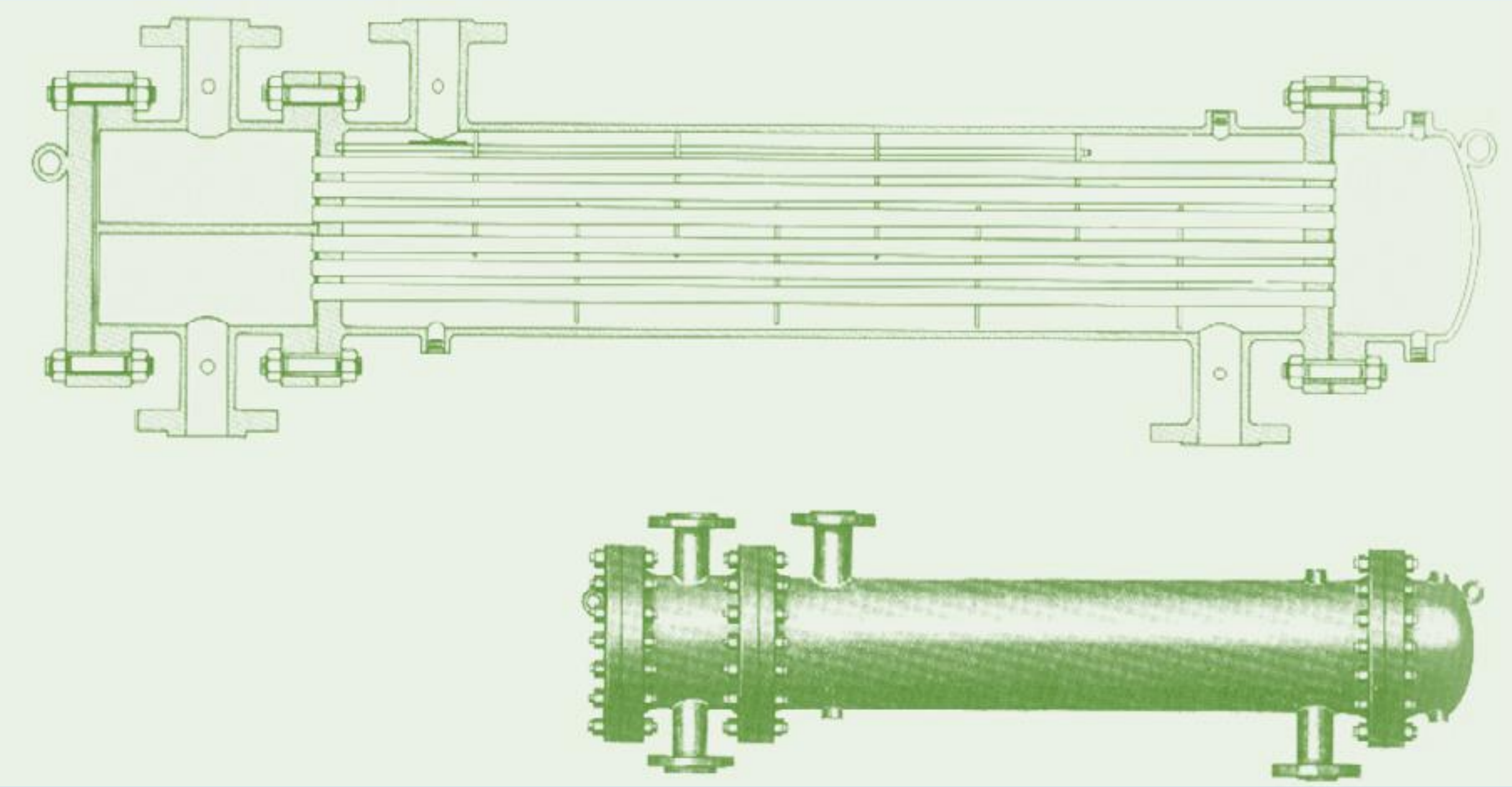


Shell-and-tube heat exchangers. (*a*) One shell pass and two tube passes. (*b*) Two shell passes and four tube passes.

One shell pass and one tube pass $\Rightarrow$ pure counter current flow



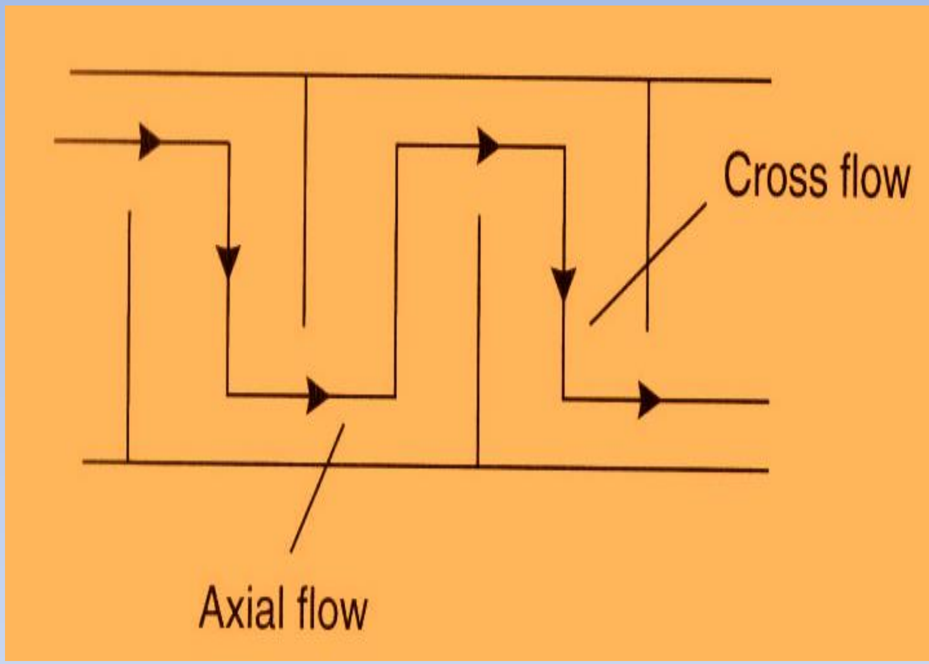
Common type (1-2) exchanger



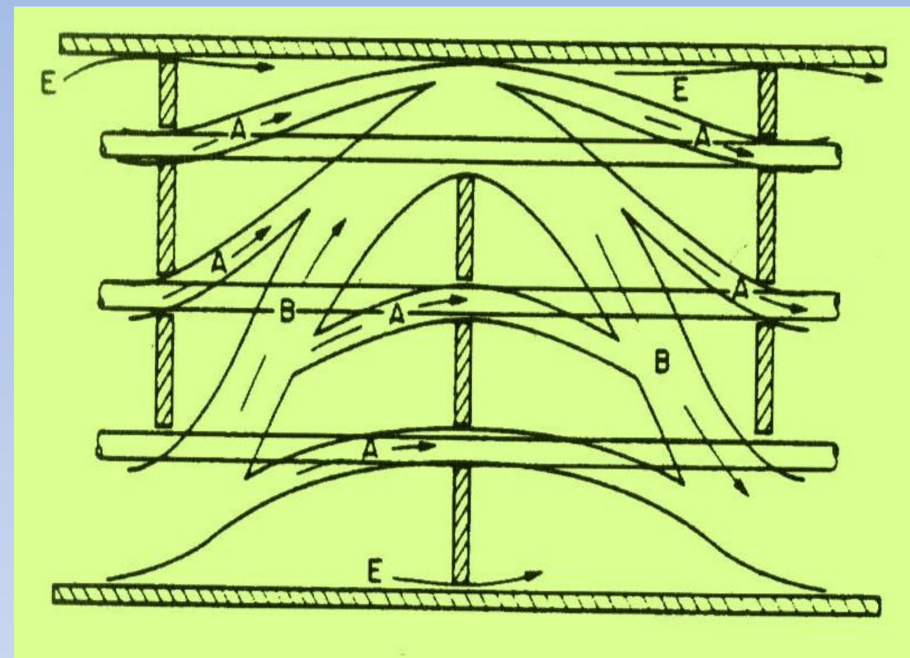
Notes

- The main **advantage** of shell-and-tube exchangers is that they provide a relatively large amount of heat-transfer surface per unit of volume and weight, and require a minimum number of connections. They are extremely versatile, and can be designed to meet almost any heat-transfer service. As a result, they are used in a wide variety of applications.
- **Flow pattern** in the shell is a sinuous motion both transverse and parallel to the tubes.
- **Streams bypass**: part of the fluid bypasses the main heat-transfer surface as a result of various leakages. The bypass streams include the tube-to-baffle leakage stream, the tube bundle-to-shell bypass stream, and the baffle-to-shell leakage stream. See next slide for good design by passing.

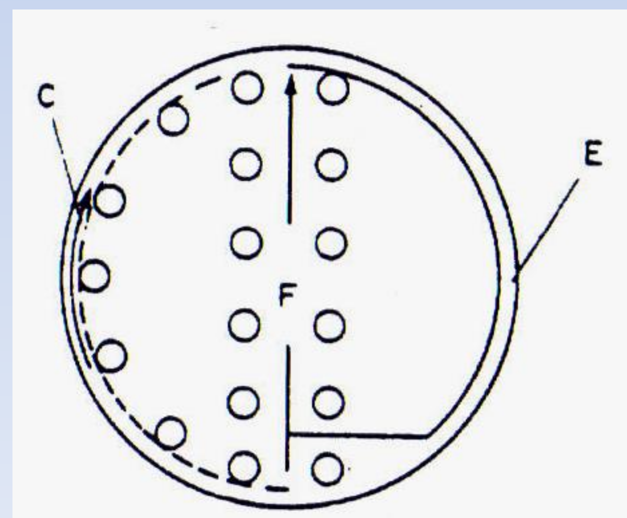
Shell side leakage and by pass



Idealized maim stream flow



- A tube-to-baffle leakage stream
- B actual cross-flow stream
- C bundle-to shell bypass stream
- E baffle-to-shell leakage stream
- F the pass-partition stream



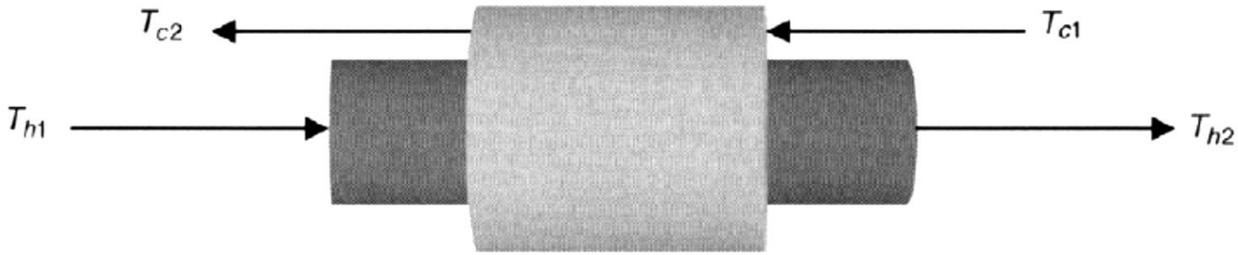
Shell-Side Bypass Flows

Stream	Percentage in turbulent flow	Percentage in laminar flow
Cross flow	30–65	10–50
Bundle bypass	15–35	30–80
Baffle-shell leakage	6–21	6–48
Tube-baffle leakage	9–23	0–10

- *Look!! The main stream flowing across the tube bundle may comprise less than 50% of the total shell-side flow due to bypass flow.*
- *The presence of these bypass streams complicates the analysis of shell-side heat transfer and pressure drop.*

The Overall Heat-Transfer Coefficient

- Consider the a double-pipe section as shown below.
- Let the hot fluid (arbitrarily) to flow through the inner pipe.



Section of a double-pipe exchanger.

- Explain the heat transfer from hot to cold stream.
- To describe this overall process, an overall heat transfer coefficient, U, is defined by:

$$q = U\,A\,\Delta T_m$$

Heat transfer Area

The heat-transfer area, A, is the surface area of the inner pipe, and may be based on either the inside or outside diameter. In practice, however, the outside diameter is commonly used, so that:

$$A = A_o = \pi D_o L$$

Temperature difference

- The temperature difference, ΔT_m , is the mean temperature difference between the two fluid streams.
- It can be shown that when U is independent of position along the exchanger, ΔT_m is the logarithmic mean temperature difference;

$$\Delta T_m = \Delta T_{\ln} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)}$$

- where ΔT_1 and ΔT_2 are the temperature differences at the two ends of the exchanger.
- The above equation is valid regardless of whether counter flow or parallel flow is employed.

Thermal resistance & OHTC "U"

- Thermal resistance

$$R_{th} = \frac{1}{UA}$$

$$\frac{1}{UA_o} = \frac{1}{h_i A_i} + \frac{\ln(D_o/D_i)}{2\pi kL} + \frac{1}{h_o A_o} \quad \text{..................(i)}$$

where h_i and h_o are the heat-transfer coefficients for flow in the inner and outer pipes, respectively,

A_i is the surface area of the inner pipe based on the inside diameter, i.e., $A_i = \pi D_i L$

- Multiplying Equation (i) by A_o and inverting yields:

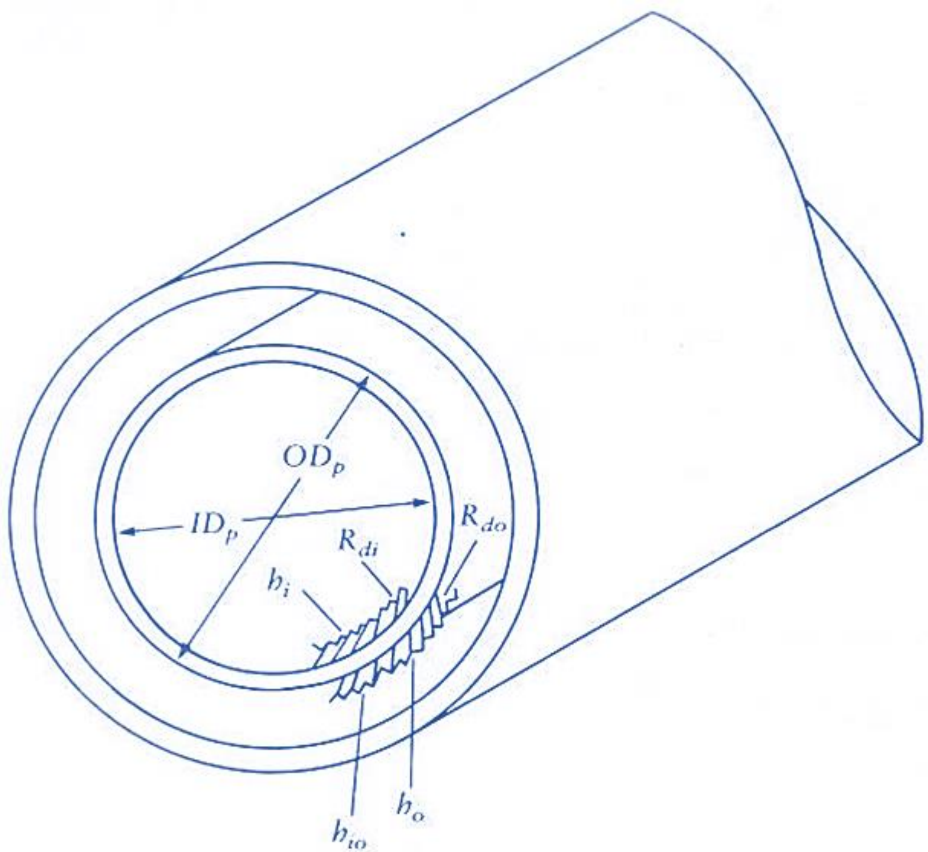
$$U = \left[\frac{D_o}{h_i D_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o}\right]^{-1} \quad \text{..................(ii)}$$

- Equation (ii) is correct when the heat exchanger is new and the heat-transfer surfaces are clean.

Fouling Process

- Fouling process means a formation of a film of dirt or scale on the heat-transfer surfaces over a period of time.
- Most of fluids cause these scales depending upon the nature of the fluids as well as the operating conditions.
- The process of fouling results in decreased performance of the heat exchanger due to the added thermal resistances of the dirt films.
- Fouling is determined experimentally.
- We have two types of fouling factors, R_{Di} and R_{Do}, *(**see next slide**)* which represent the thermal resistances of the dirt films on the inside and outside of the inner pipe.

Dirt and scales build up on the inner pipe surfaces



- Adding these two additional resistances to the main OHTC Equation, we obtain:

$$U_D = \left[\frac{D_o}{h_i D_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o} + \frac{R_{Di} D_o}{D_i} + R_{Do}\right]^{-1}$$

- where U_D is the overall coefficient after fouling has occurred.
- it is necessary to provide more heat-transfer area than is actually required when the exchanger is clean.
- Outlet temperatures will exceed design specifications when the exchanger is

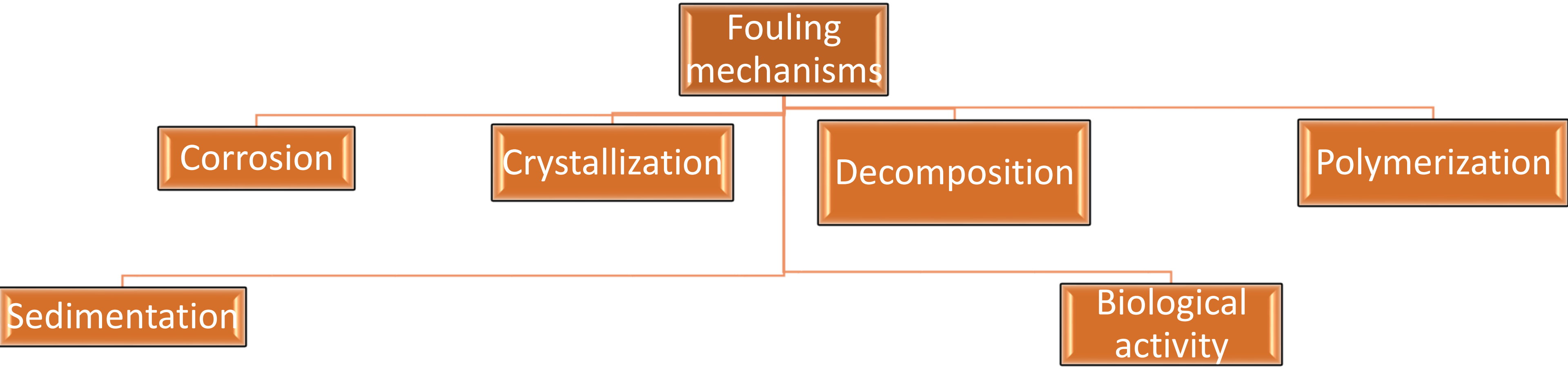
Typical Values of Fouling Factors (h. ft ^{2}.°F/Btu)

Cooling water streams [a]	
• Seawater	0.0005–0.001
• Brackish water	0.001–0.002
• Treated cooling tower water	0.001–0.002
• Municipal water supply	0.001–0.002
• River water	0.001–0.003
• Engine jacket water	0.001
• Distilled or demineralized water	0.0005
• Treated boiler feedwater	0.0005–0.001
• Boiler blowdown	0.002
Service gas streams	
• Ambient air (in air-cooled units)	0–0.0005
• Compressed air	0.001–0.002
• Steam (clean)	0–0.0005
• Steam (with oil traces)	0.001–0.002
• Refrigerants (with oil traces)	0.002
• Ammonia	0.001
• Carbon dioxide	0.002
• Flue gases	0.005–0.01
Service liquid streams	
• Fuel oil	0.002–0.005
• Lubrication oil	0.001
• Transformer oil	0.001
• Hydraulic fluid	0.001
• Organic heat-transfer fluids	0.001–0.002
• Refrigerants	0.001
• Brine	0.003

Process gas streams	
• Hydrogen	0.001
• Organic solvent vapors	0.001
• Acid gases	0.002–0.003
• Stable distillation overhead products	0.001
Process liquid streams	
• Amine solutions	0.002
• Glycol solutions	0.002
• Caustic solutions	0.002
• Alcohol solutions	0.002
• Ammonia	0.001
• Vegetable oils	0.003
• Stable distillation side-draw and bottom products	0.001–0.002
Natural gas processing streams	
• Natural gas	0.001
• Overhead vapor products	0.001–0.002
• C_3 or C_4 vapor (condensing)	0.001
• Lean oil	0.002
• Rich oil	0.001
• LNG and LPG	0.001

Typical Values of Fouling Factors (h. ft ^{2}.°F/Btu)

Oil refinery streams	
• Crude oil[b]	
– Temperature less than 250°F	0.002–0.003
– Temperature between 250°F and 350°F	0.003–0.004
– Temperature between 350°F and 450°F	0.004–0.005
– Temperature greater than 450°F	0.005–0.006
• Liquid product streams	
– Gasoline	0.001–0.002
– Naphtha and light distillates	0.001–0.003
– Kerosene	0.001–0.003
– Light gas oil	0.002–0.003
– Heavy gas oil	0.003–0.005
– Heavy fuel oils	0.003–0.007
– Asphalt and residuum	0.007–0.01
• Other oil streams	
– Refined lube oil	0.001
– Cycle oil	0.002–0.004
– Coker gas oil	0.003–0.005
– Absorption oils	0.002


Fouling mechanisms
Corrosion
Crystallization
Decomposition
Polymerization
Sedimentation
Biological activity

Example

A double-pipe heat exchanger will be used to cool a hot stream from 350°F to 250°F by heating a cold stream from 80°F to 120°F The hot stream will flow in the inner pipe, which is 2-in. schedule 40 carbon steel with a thermal conductivity of 26 Btu/h. ft ^{2}. °F Fouling factors of 0.001 h. ft ^{2}. °F. should be provided for each stream. The heat-transfer coefficients are estimated to be h_i= 200 and h_o = 350 Btu/h. ft 2. °F and the heat load is 3.5 x 10 ^{6} Btu/h.

a) For counter-current operation, what surface area is required?

b) For co-current operation, what surface area is required?

Solution

- *Counter-current operation*

$$A = \frac{q}{U_D \Delta T_{ln}} \qquad \Delta T = 230°F \left\{ \begin{array}{l} 350°F \longrightarrow 250°F \\ 120°F \longleftarrow 80°F \end{array} \right\} \Delta T = 170°F$$

$$A = \frac{3.5 \times 10^6}{U_D \Delta T_{ln}} \qquad \Delta T_{ln} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)} = \frac{230 - 170}{\ln(230/170)} = 198.5°F$$

Find D_o and D_i for 2-in. schedule 40 pipe, from tables

$D_i = 2.067$ in. and $D_o = 2.375$ in

$$U_D = \left[\frac{D_o}{h_i D_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o} + \frac{R_{Di} D_o}{D_i} + R_{Do}\right]^{-1}$$

$$U_D = \left[\frac{2.375}{200 \times 2.067} + \frac{(2.375/12) \times \ln(2.375/2.067)}{2 \times 26} + \frac{1}{350} + \frac{0.001 \times 2.375}{2.067} + 0.001\right]^{-1}$$

$$U_D = [0.0057 + 0.0005 + 0.0029 + 0.0011 + 0.001]^{-1}$$

$$U_D = 88.65\,\text{Btu/h} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

$$A = \frac{3.5 \times 10^6}{88.65 \times 198.5} = 198.9\,\text{ft}^2 \cong 199\,\text{ft}^2$$

- *Co-current operation 'Parallel flow'*

$$\Delta T = 270°\text{F} \begin{cases} 350°\text{F} \longrightarrow 250°\text{F} \\ 80°\text{F} \longrightarrow 120°\text{F} \end{cases} \Delta T = 130°\text{F}$$

$$\Delta T_{\ln} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} = \frac{270 - 130}{\ln(270/130)} = 191.5°\text{F}$$

$$A = \frac{3.5 \times 10^6}{88.65 \times 191.5} = 206.2 \cong 206\ \text{ft}^2$$

- Comments

The T-x diagram

- Pure counter current seems the best heat exchanger configuration.
- T-x diagram: this diagram shows the variation of temperature a long the exchanger.