Department Of Mechanical Engineering

MODULE 7

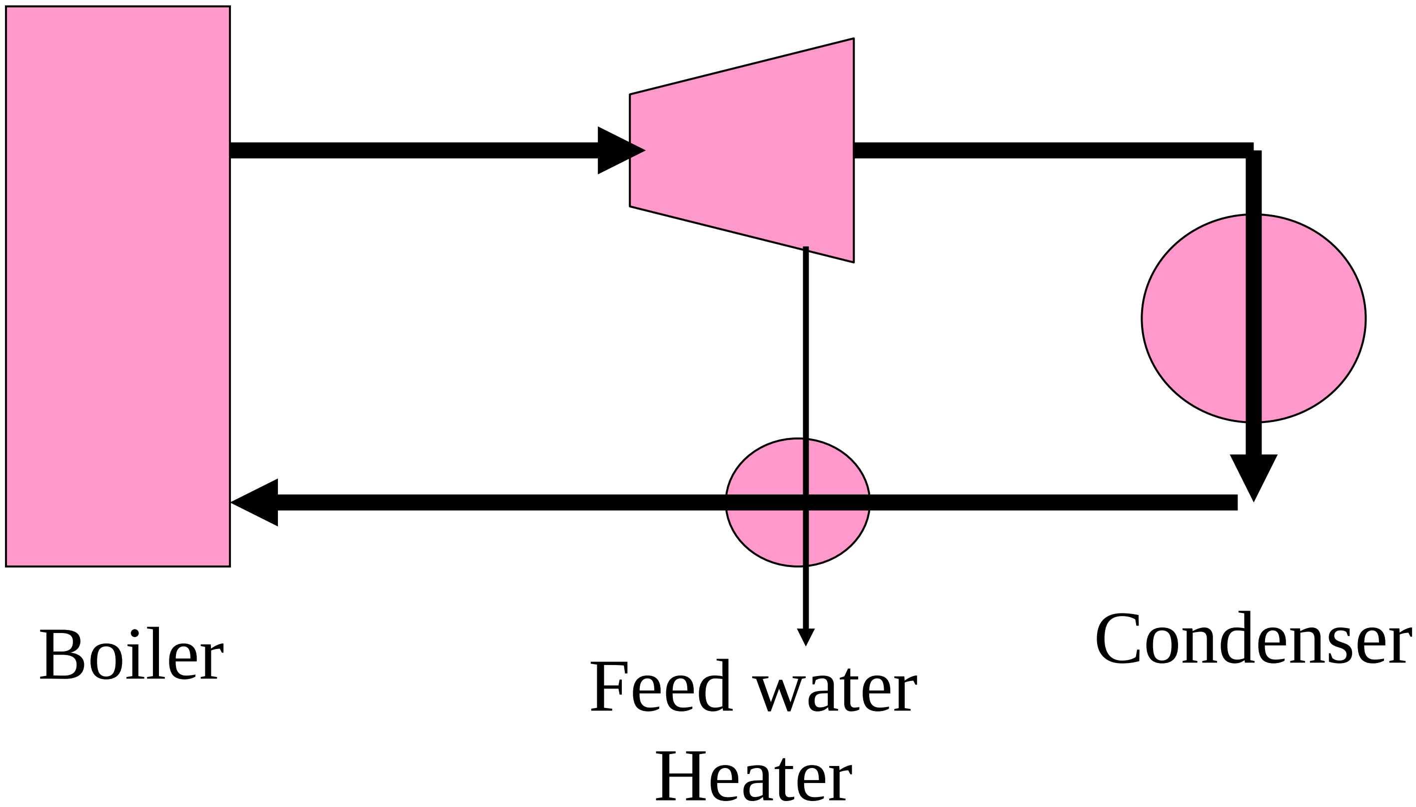
Introduction to Heat Exchangers

What are heat exchangers for?

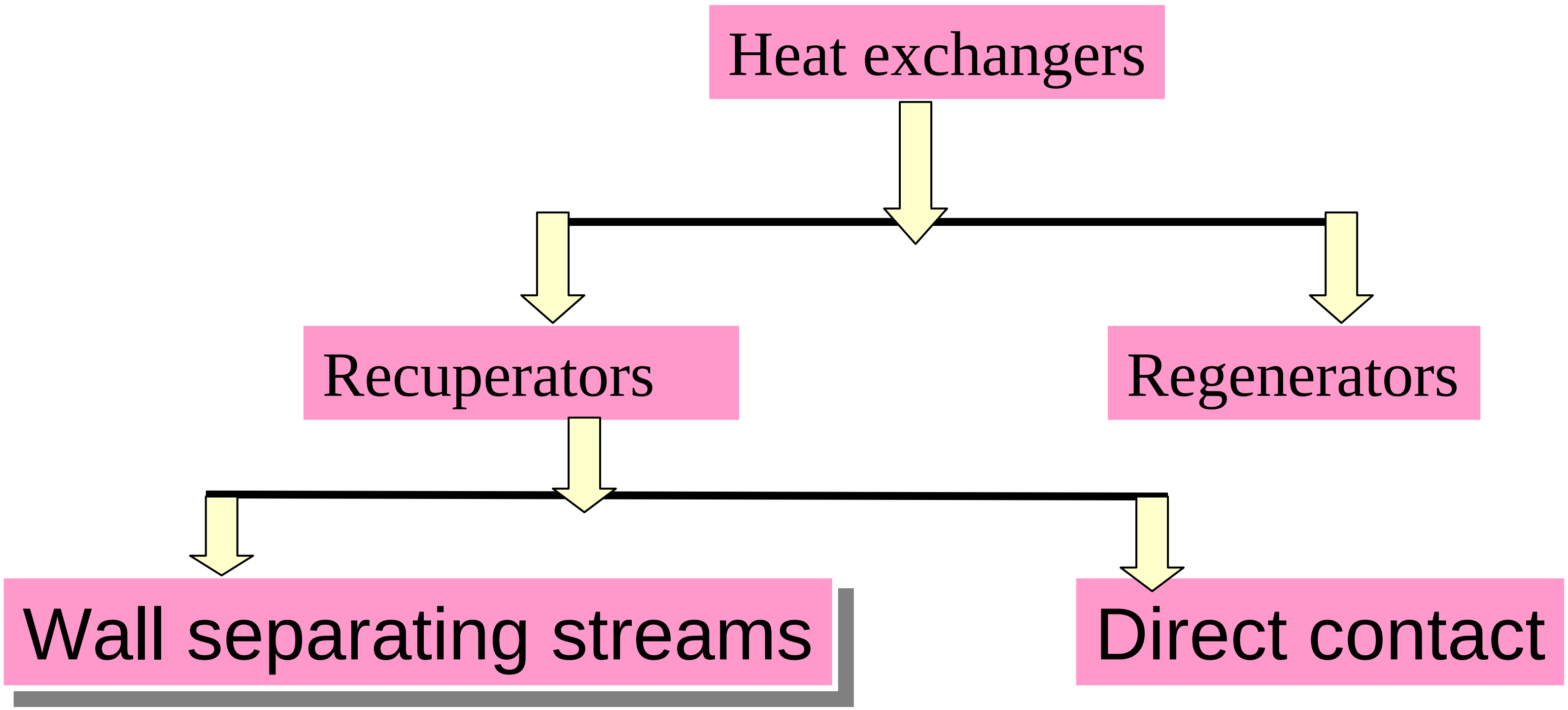
- Heat exchangers are practical devices used to transfer energy from one fluid to another
- To get fluid streams to the right temperature for the next process
  - reactions often require feeds at high temp.
- To condense vapours
- To evaporate liquids
- To recover heat to use elsewhere
- To reject low-grade heat
- To drive a power cycle

Application: Power cycle

Steam Turbine



Main Categories Of Exchanger

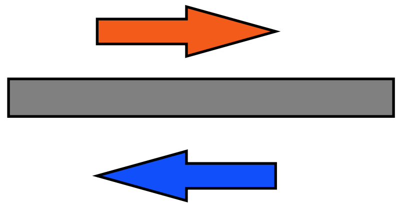


- Most heat exchangers have two streams, *hot* and *cold*, but some have more than two

Recuperators/Regenerators

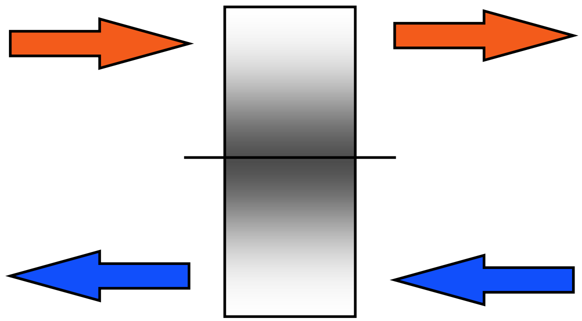
- **Recuperative:**

  Has separate flow paths for each fluid which flow simultaneously through the exchanger transferring heat between the streams



- **Regenerative**

  Has a single flow path which the hot and cold fluids alternately pass through.

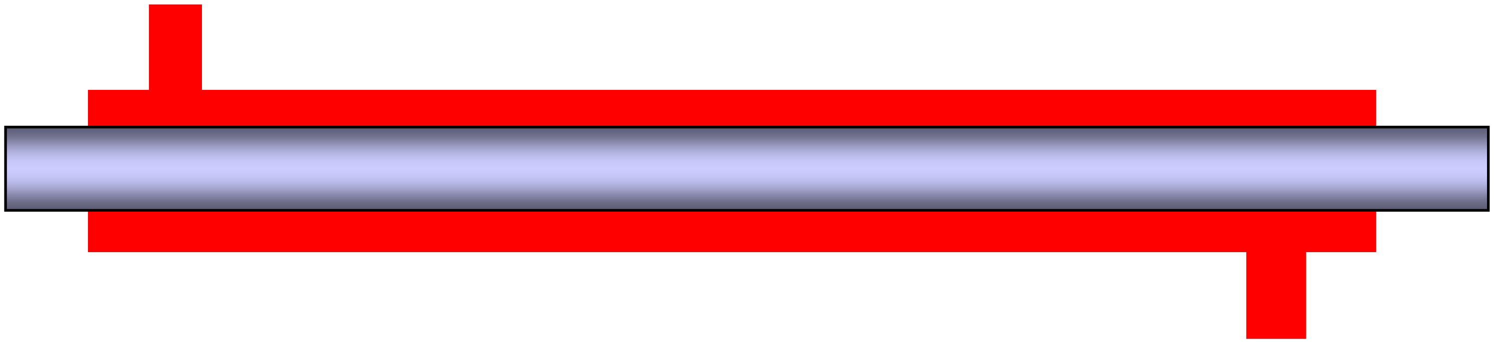


Compactness

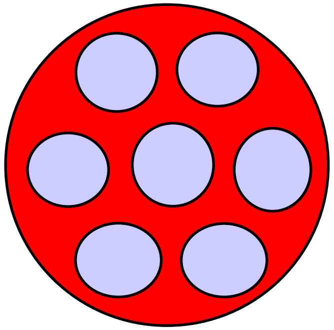
- Can be measured by the heat-transfer area per unit volume or by channel size
- Conventional exchangers (shell and tube) have channel size of 10 to 30 mm giving about $100 m^2/m^3$
- Plate-type exchangers have typically 5mm channel size with more than $200 m^2/m^3$
- More compact types available

Double Pipe

- Simplest type has one tube inside another - inner tube may have longitudinal fins on the outside

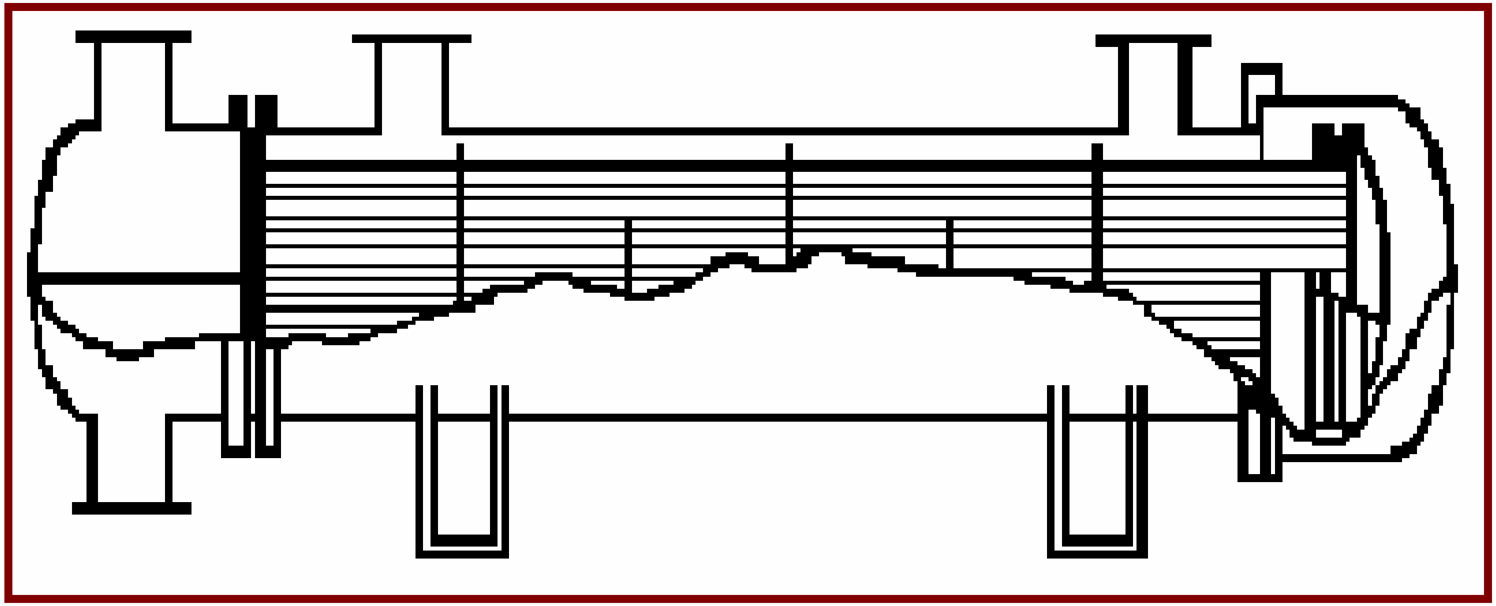


- However, most have a number of tubes in the outer tube - can have very many tubes thus becoming a shell-and-tube



Shell and Tube

- Typical shell and tube exchanger as used in the process industry



Shell-Side Flow

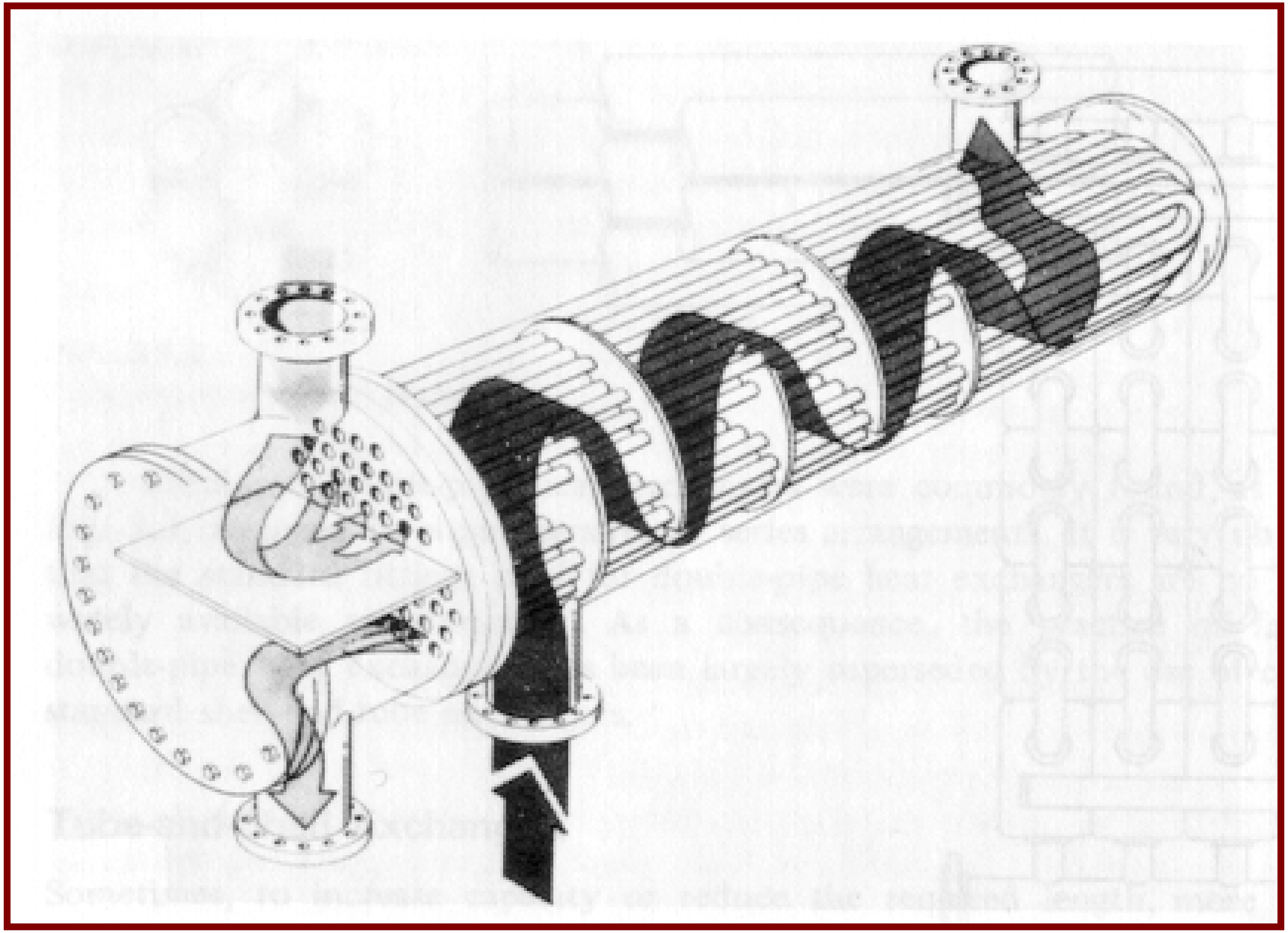
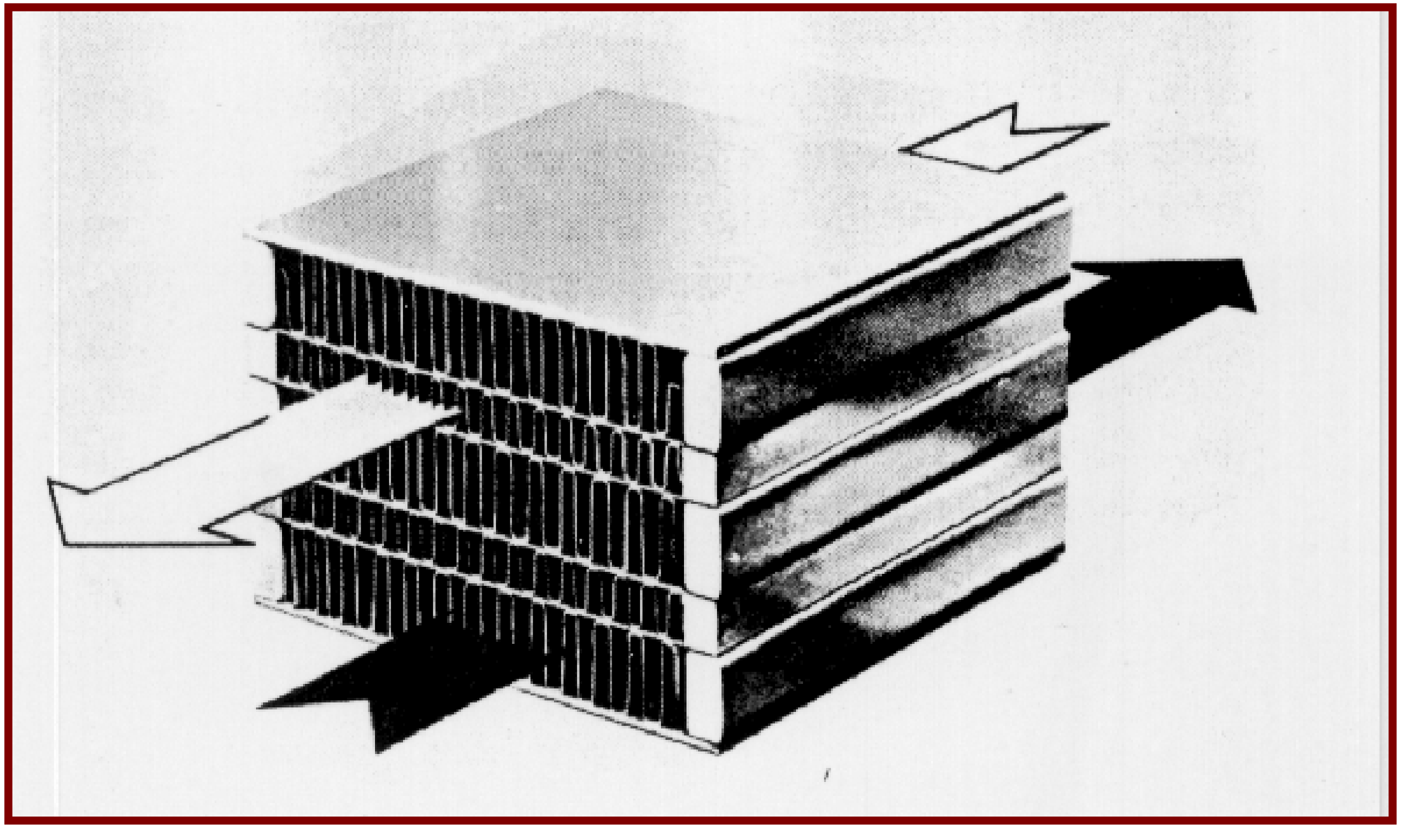
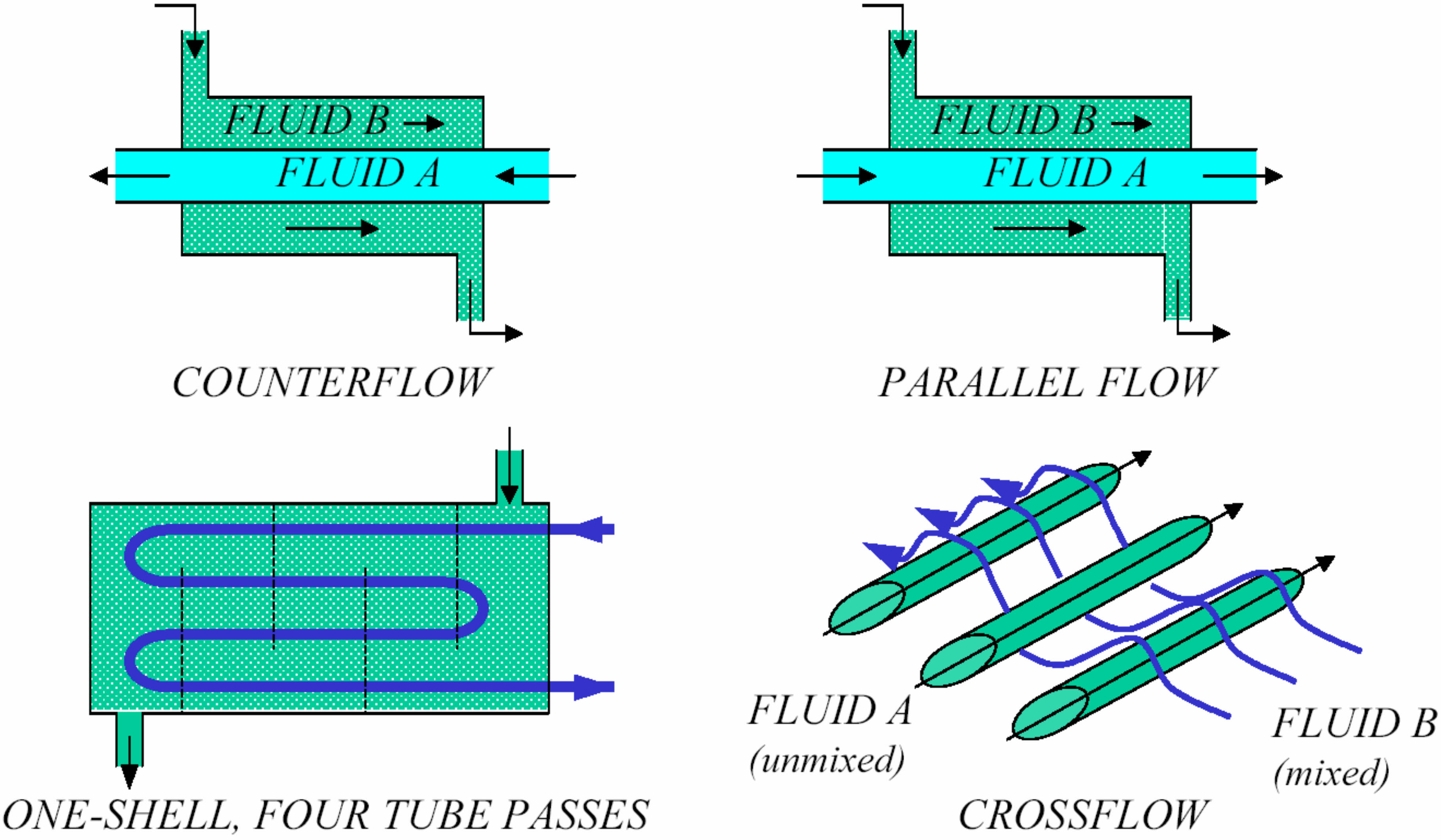


Plate-Fin Exchanger



- Made up of flat plates (parting sheets) and corrugated sheets which form fins
- Brazed by heating in vacuum furnace

Configurations



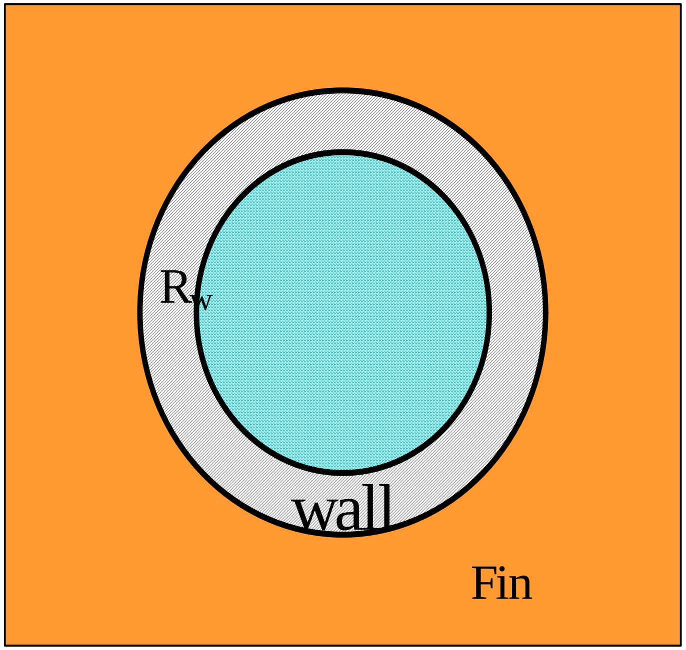
Heat Transfer Considerations:

Overall heat transfer coefficient

- Internal and external thermal resistances in series

$$\frac{1}{UA} = \frac{1}{(UA)_c} = \frac{1}{(UA)_h}$$

$$\frac{1}{UA} = \frac{1}{(h\eta_o A)_c} + \frac{R''_{f,c}}{(\eta_o A)_c} + R_w + \frac{1}{(h\eta_o A)_h} + \frac{R''_{f,h}}{(\eta_o A)_h}$$



- *A* is wall total surface area on hot or cold side
- R''_f is fouling factor (m^2K/W)
- η_o is overall surface efficiency (if finned)

Heat Transfer Considerations (contd…):

- ❑Fouling factor

Material deposits on the surfaces of the heat exchanger tube may add further resistance to heat transfer in addition to those listed above. Such deposits are termed fouling and may significantly affect heat exchanger performance.

- ❑ Scaling is the most common form of fouling and is associated with inverse solubility salts. Examples of such salts are $CaCO_3$, $CaSO_4$, $Ca_3(PO_4)_2$, $CaSiO_3$, $Ca(OH)_2$, $Mg(OH)_2$, $MgSiO_3$, Na_2SO_4, $LiSO_4$, and Li_2CO_3.

- ❑ Corrosion fouling is classified as a chemical reaction which involves the heat exchanger tubes. Many metals, copper and aluminum being specific examples, form adherent oxide coatings which serve to passivity the surface and prevent further corrosion.

Heat Transfer Considerations (contd…):

- Chemical reaction fouling involves chemical reactions in the process stream which results in deposition of material on the heat exchanger tubes. When food products are involved this may be termed scorching but a wide range of organic materials are subject to similar problems.

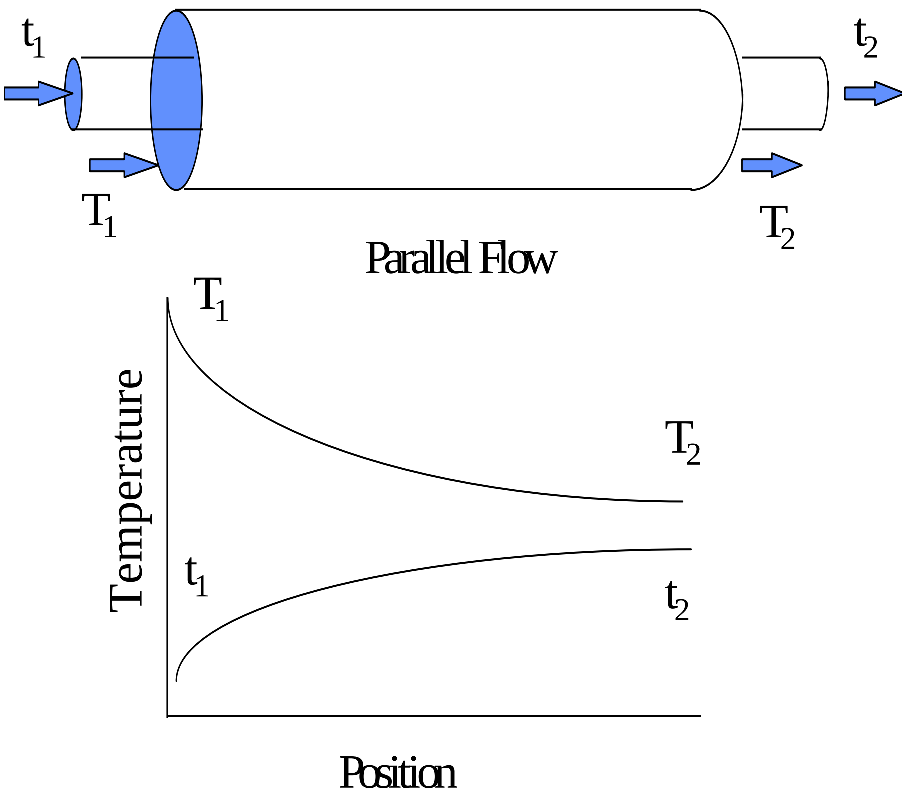
- Freezing fouling is said to occur when a portion of the hot stream is cooled to near the freezing point for one of its components. This is most notable in refineries where paraffin frequently solidifies from petroleum products at various stages in the refining process, obstructing both flow and heat transfer.

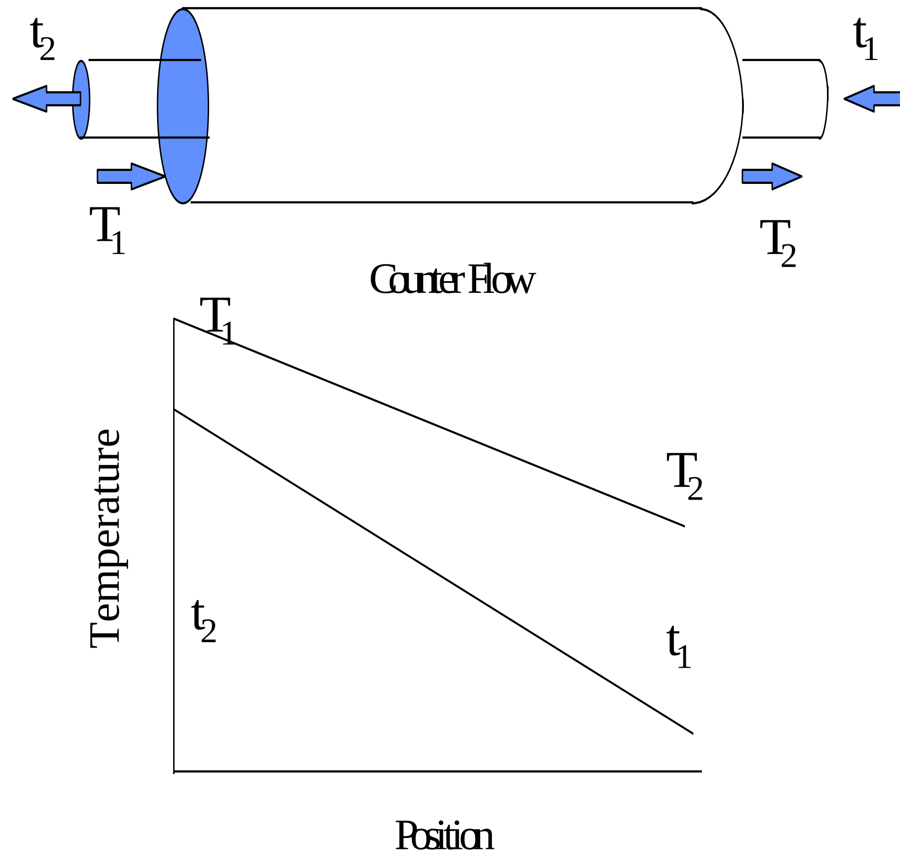
- Biological fouling is common where untreated water is used as a coolant stream. Problems range from algae or other microbes to barnacles.

Heat Transfer Considerations (contd…):

Fluid	R”, $m^2K/Watt$
Seawater and treated boiler feedwater (below 50^oC)	0.0001
Seawater and treated boiler feedwater (above 50^oC)	0.0002
River water (below 50^oC)	0.0002-0.001
Fuel Oil	0.0009
Regrigerating liquids	0.0002
Steam (non-oil bearing)	0.0001

Basic flow arrangement in tube in tube flow





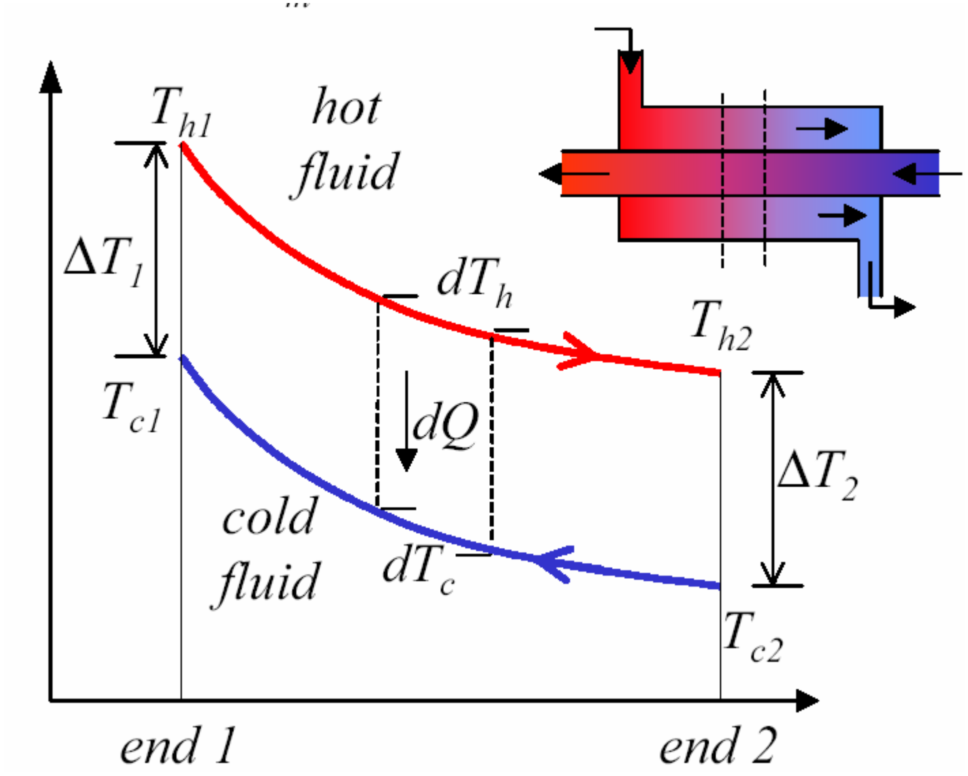
Heat Exchanger Analysis

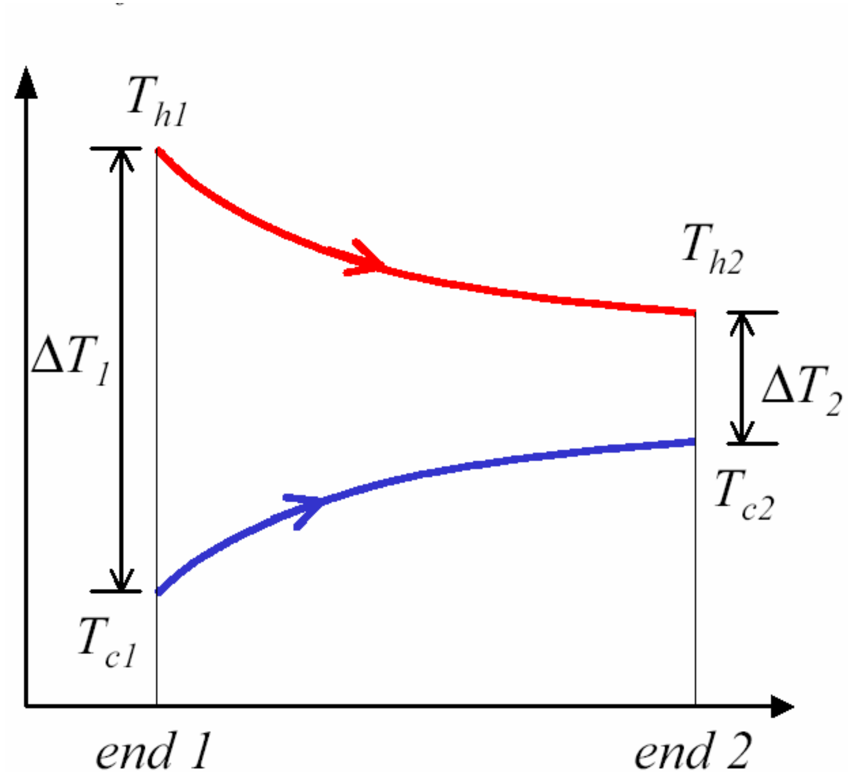
Log mean temperature difference (LMTD) method

Want a relation $\dot{Q} = UA\Delta T_m$

Where ΔT_m is some mean ΔT between hot and cold fluid

Heat Exchanger Analysis(contd…)





Counterflow

Note $T_{h,out}$ can be < $T_{c,out}$

Parallel flow

$T's$, cannot cross

Heat Exchanger Analysis (contd…)

Energy balance (counterflow) on element shown

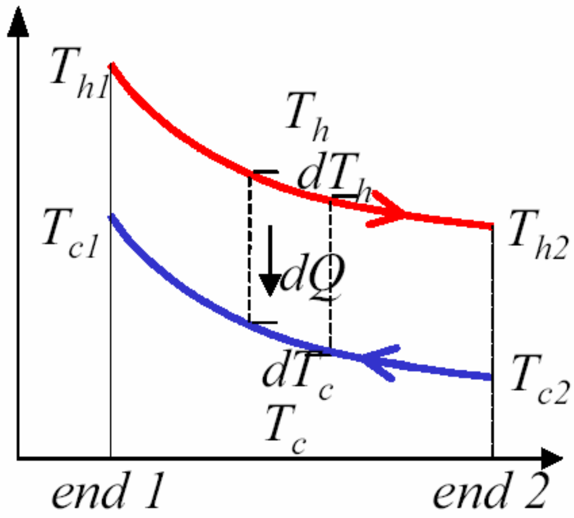
$$d\dot{Q} = -\dot{m}_h c_h dT_h = -\dot{m}_c c_c dT_c \qquad (1)$$

$\dot{m}$ = mass flow rate of fluid

c = specific heat

Rate Equation

$$d\dot{Q} = UdA(T_h - T_c) \qquad (2)$$



(dT in direction $1 \rightarrow 2$)

Now from (1) $\quad dT_h = \dfrac{-d\dot{Q}}{\dot{m}_h c_h} \qquad dT_c = \dfrac{-d\dot{Q}}{\dot{m}_c c_c}$

$$\therefore d(T_h - T_c) = d\dot{Q}\left(\frac{1}{\dot{m}_c c_c} - \frac{1}{\dot{m}_h c_h}\right)$$

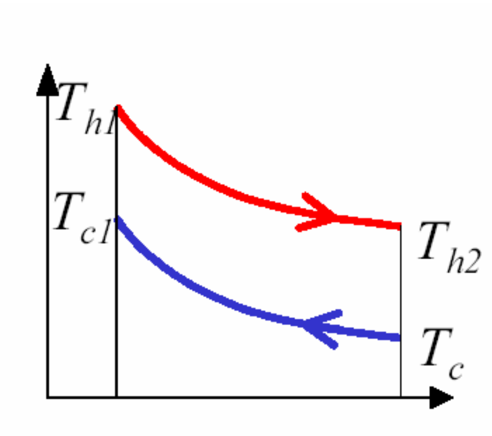
Heat Exchanger Analysis (contd…)

Subtract $d\dot{Q}$ from (2),

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

Integrate $1 \rightarrow 2$

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



Total heat transfer rate

$$\dot{Q} = \dot{m}_h c_h\left(T_{h1} - T_{h2}\right) \text{ and } \dot{Q} = \dot{m}_c c_c\left(T_{c1} - T_{c2}\right)$$

Heat Exchanger Analysis (contd…)

Substitute for $\dot{m}c$ and put

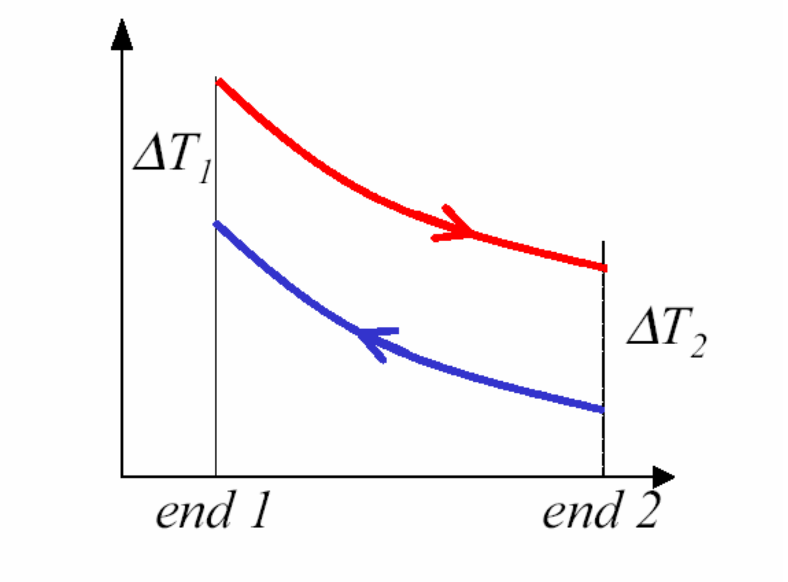
$$\Delta T_1 = T_{h1} - T_{c1} \qquad END\ 1$$

$$\Delta T_2 = T_{h2} - T_{c2} \qquad END\ 2$$

$$\dot{Q} = UA\left[\frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2 / \Delta T_1)}\right]$$

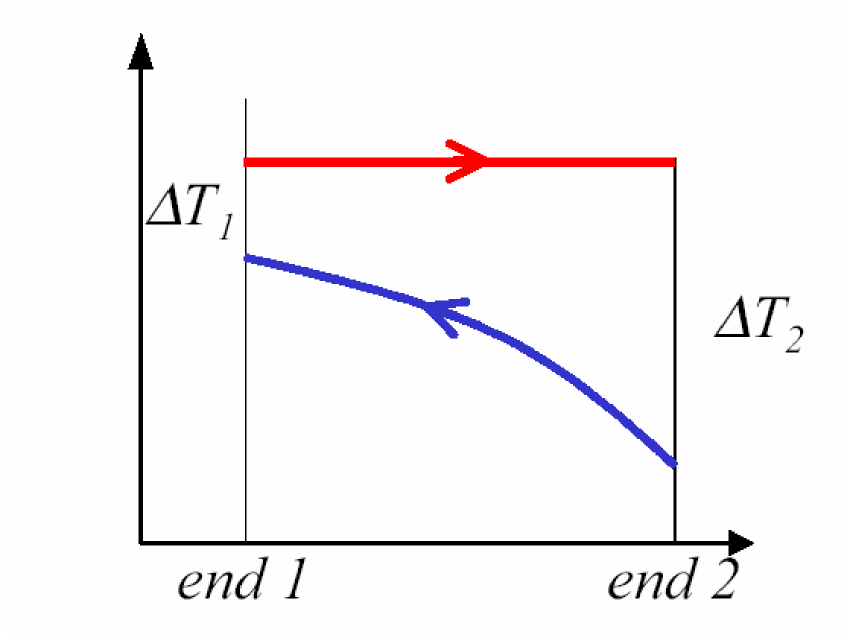
$$\dot{Q} = UA(\text{LMTD})$$

LMTD is Log Mean Temperature Difference

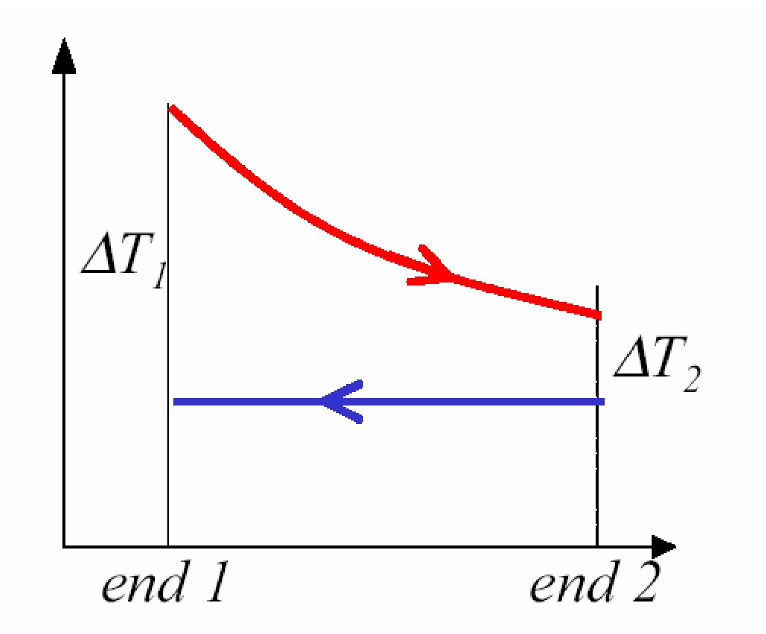


- Remember – 1 and 2 are ends, not fluids
- Same formula for parallel flow (but ΔT's are different)
- Counterflow has highest LMTD, for given T's therefore smallest area for Q.

Heat Exchanger Analysis (contd…)



Condenser

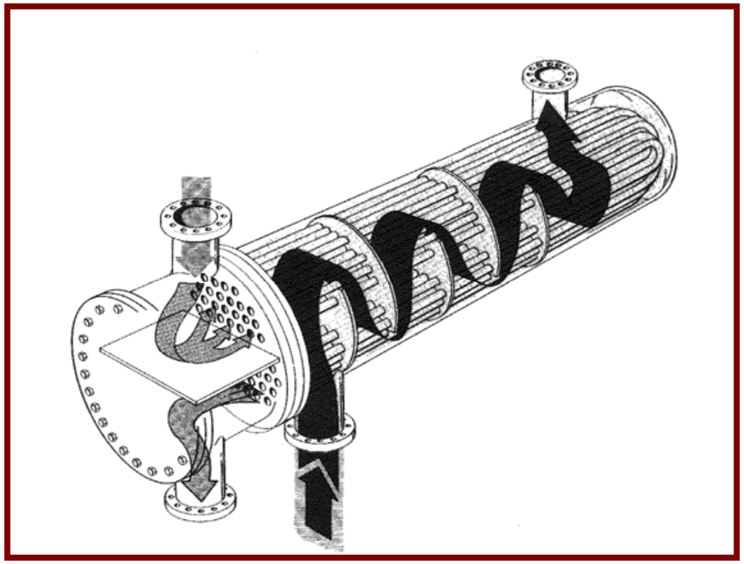


Evaporator

Multipass HX Flow Arrangements

- In order to increase the surface area for convection relative to the fluid volume, it is common to design for multiple tubes within a single heat exchanger.

- With multiple tubes it is possible to arrange to flow so that one region will be in parallel and another portion in counter flow.



1-2 pass heat exchanger, indicating that the shell side fluid passes through the unit once, the tube side twice. By convention the number of shell side passes is always listed first.

Multipass HX Flow Arrangements (contd…)

- The LMTD formulas developed earlier are no longer adequate for multipass heat exchangers. Normal practice is to calculate the LMTD for counter flow, $LMTD_{cf}$, and to apply a correction factor, F_T, such that

$$\Delta\theta_{eff} = F_T \cdot LMTD_{CF}$$

- The correction factors, F_T, can be found theoretically and presented in analytical form. The equation given below has been shown to be accurate for any arrangement having 2, 4, 6, ...,2n tube passes per shell pass to within 2%.

Multipass HX Flow Arrangements (contd…)

$$F_T = \frac{\sqrt{R^2+1}\,\ln\left[\dfrac{1-P}{1-R\cdot P}\right]}{(R-1)\ln\left[\dfrac{2-P\left(R+1-\sqrt{R^2+1}\right)}{2-P\left(R+1+\sqrt{R^2+1}\right)}\right]}$$

Effectiveness: $P = \dfrac{1-X^{1/N_{shell}}}{R-X^{1/N_{shell}}}, \quad \text{for} R \neq 1$

$$P = \frac{P_o}{N_{shell} - P_o\cdot\left(N_{shell}-1\right)}, \quad \text{for } R = 1$$

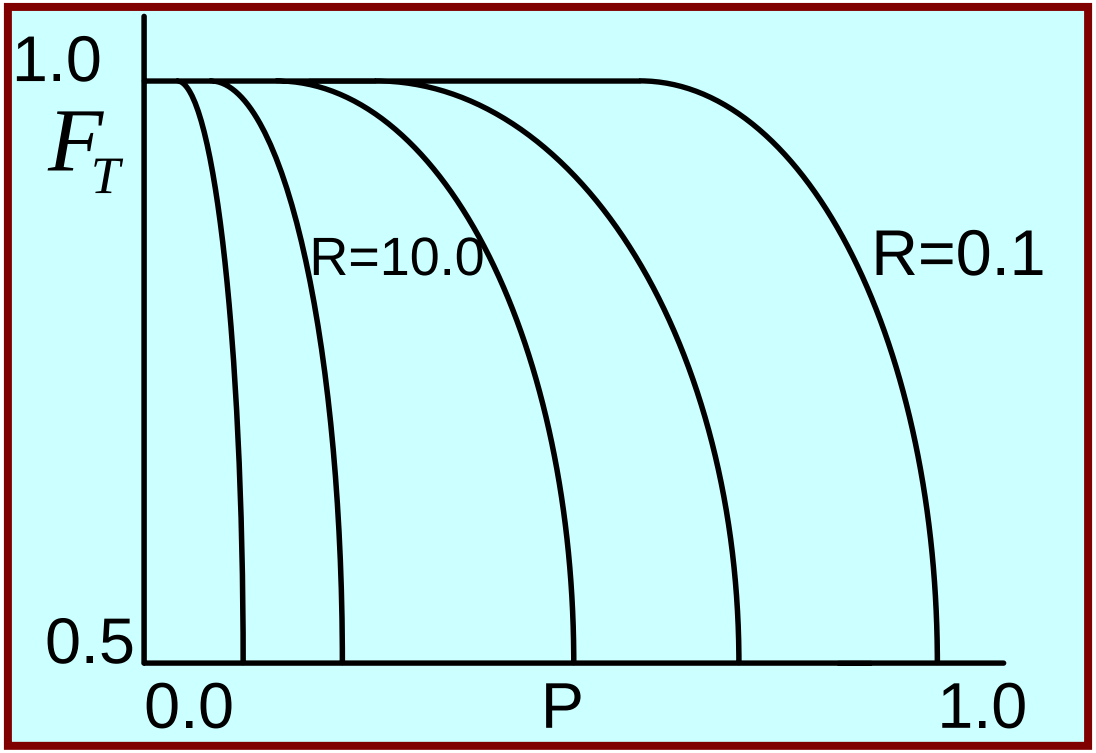
$$P_o = \frac{t_2 - t_1}{T_1 - t_1}$$

$$X = \frac{P_o\cdot R - 1}{P_o - 1}$$

Capacity ratio $R = \dfrac{T_1 - T_2}{t_2 - t_1}$

T,t = Shell / tube side; 1, 2 = inlet / outlet

Multipass HX Flow Arrangements (contd…)



Effectiveness-NTU Method

How will existing H.Ex. perform for given inlet conditions?

Define effectiveness: $\varepsilon = \dfrac{\dot{Q}_{actual}}{\dot{Q}_{\max}}$

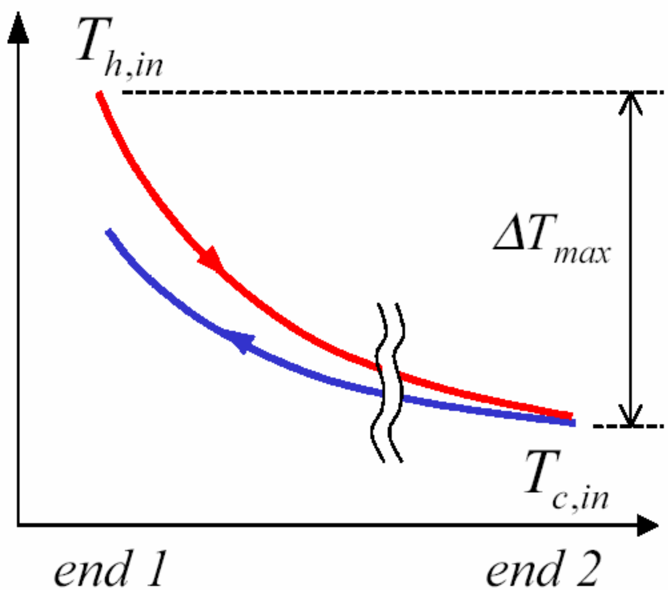
where $\dot{Q}_{\max}$ is for an infinitely long H.Ex.

One fluid $\Delta T \rightarrow \Delta T_{\max} = T_{h,in} - T_{c,in}$

and since $\dot{Q} = (\dot{m}c_A)\Delta T_A = (\dot{m}c_B)\Delta T_B$

$$= C_A \Delta T_A = C_B \Delta T_B$$

then only the fluid with lesser of C_A, C_B heat capacity rate can have $\Delta T_{\max}$



Effectiveness-NTU Method(contd…)

i.e. $\dot{Q}_{max} = C_{min}\Delta T_{max}$ and $\varepsilon = \dfrac{\dot{Q}}{C_{min}\left(T_{h.in} - T_{c.in}\right)}$

$$\text{or,} \quad \dot{Q} = \varepsilon C_{min}\left(T_{h.in} - T_{c.in}\right)$$

Want expression for ε which does not contain outlet T's

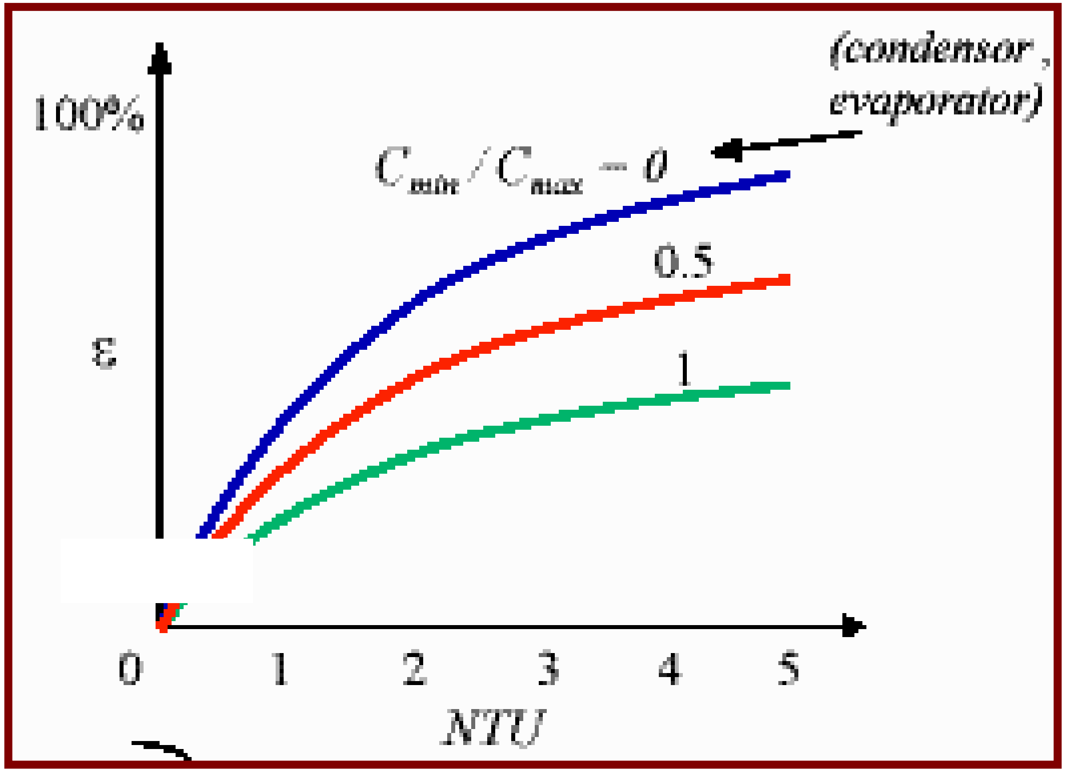
Substitute back into $\dot{Q} = UA(LMTD)$ ....

$$\varepsilon = \frac{1 - \exp\left[\dfrac{-UA}{C_{min}}\left(1 - \dfrac{C_{min}}{C_{max}}\right)\right]}{1 - \dfrac{C_{min}}{C_{max}}\exp\left[\dfrac{-UA}{C_{min}}\left(1 - \dfrac{C_{min}}{C_{max}}\right)\right]}$$

$$\therefore \varepsilon = \varepsilon\left(NTU, \frac{C_{min}}{C_{max}}\right)$$

and No. of transfer units (size of HEx.) $\quad NTU = \dfrac{UA}{C_{min}}$

Charts for each Configuration



<u>Procedure</u>:

Determine C_{max}, C_{min}/C_{max}

Get $UA/C_{min,}$ → ε from chart

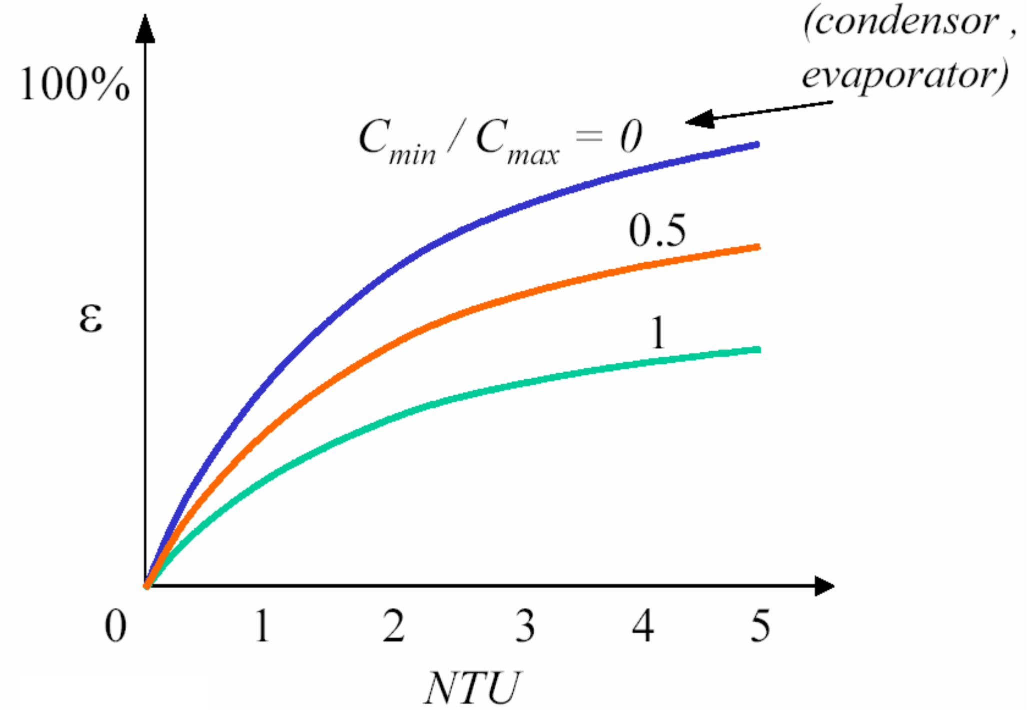
$$\dot{Q} = \varepsilon C_{\min}\left(T_{h.in} - T_{c.in}\right)$$

Charts for each Configuration

Procedure:

Determine C_{max}, C_{min}/C_{max}

Get UA/C_{min}, $\rightarrow$ ε from chart



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

Effectiveness-NTU Method(contd…)

$$NTU_{\max} = \frac{UA}{C_{\min}} \quad \Rightarrow \quad A = \frac{NTU_{\max} C_{\min}}{U}$$

- NTU_{max} can be obtained from figures in textbooks/handbooks

  First, however, we must determine which fluid has Cmin

- For the type of HEX used in this problem

$$\dot{m}_g c_{pg}(T_1 - T_2) = \dot{m}_w c_w (t_1 - t_2) \quad \Rightarrow \quad \dot{m}_g c_{pg} = \frac{\dot{m}_w c_w (t_1 - t_2)}{(T_1 - T_2)}$$

Examination of the last equation, subject to values given, indicated that gas will have C_{min}.

Effectiveness-NTU Method(contd…)

$$C_{\min} = \dot{m}g\; c_{pg} = \dot{m}g\; c_w \frac{t_2 - t_1}{T_1 - T_2} = \left(2.5\frac{kg}{s}\right)\left(4179\frac{J}{kg.°C}\right)\frac{85-35}{200-93} = \left(4{,}882\frac{W}{°C}\right)$$

$$C_{\max} = \dot{m}g\; c_w = \left(2.5\frac{kg}{s}\right)\left(4179\frac{J}{kg.°C}\right) = \left(10{,}448\frac{W}{°C}\right)$$

$$\frac{\quad}{\quad} = \frac{\quad}{\quad} =$$

Effectiveness can be calculated using

$$= \frac{-}{-} = \frac{-}{-} =$$

Effectiveness-NTU Method (contd…)

$$\left.\begin{array}{l}\dfrac{C_{min}}{C_{max}} = 0.467 \\ \varepsilon = 0.649\end{array}\right\} \rightarrow \qquad \rightarrow \; NTU_{max} = 1.4$$

$$A = \frac{NTU_{max} C_{min}}{U} = \frac{1.4\left(4{,}882\,\frac{W}{°C}\right)}{180\,\frac{W}{m^2 °C}} = 38.0\,m^2$$