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

Boiler

Feed water

Heater

Condenser
Main Categories Of Exchanger

- Heat exchangers
  - Recuperators
    - Wall separating streams
  - Regenerators
    - Direct contact

- 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 100m²/m³
- Plate-type exchangers have typically 5mm channel size with more than 200m²/m³
- 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
Plate-Fin Exchanger

- Made up of flat plates (parting sheets) and corrugated sheets which form fins
- Brazed by heating in vacuum furnace
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 (m²K/W)
- \(\eta_o\) 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$_2$SO$_4$, LiSO$_4$, and Li$_2$CO$_3$.

- **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...):

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$R''$, m²K/Watt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater and treated boiler feedwater (below 50°C)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Seawater and treated boiler feedwater (above 50°C)</td>
<td>0.0002</td>
</tr>
<tr>
<td>River water (below 50°C)</td>
<td>0.0002-0.001</td>
</tr>
<tr>
<td>Fuel Oil</td>
<td>0.0009</td>
</tr>
<tr>
<td>Refrigerating liquids</td>
<td>0.0002</td>
</tr>
<tr>
<td>Steam (non-oil bearing)</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
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 $\Delta T_m$ is some mean $\Delta T$ 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

\[ d\dot{\mathcal{Q}} = -n_h c_h dT_h = -n_c c_c dT_c \quad (1) \]

\( n_h \) = mass flow rate of fluid

\( c \) = specific heat

Rate Equation

\[ d\dot{\mathcal{Q}} = U dA (T_h - T_c) \quad (2) \]

Now from (1)

\[ dT_h = \frac{-d\dot{\mathcal{Q}}}{n_h c_h} \quad dT_c = \frac{-d\dot{\mathcal{Q}}}{n_c c_c} \]

\[ \therefore d(T_h - T_c) = d\dot{\mathcal{Q}} \left( \frac{1}{n_h c_h} - \frac{1}{n_c c_c} \right) \]
Heat Exchanger Analysis (contd...)

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

$$\frac{d(T_h - T_c)}{T_h - T_c} = U \left( \frac{1}{n_h c_h} - \frac{1}{n_c c_c} \right) dA$$

Integrate $1 \rightarrow 2$

$$\ln\left(\frac{T_{h2} - T_{c2}}{T_{h1} - T_{c1}}\right) = UA \left( \frac{1}{n_h c_h} - \frac{1}{n_c c_c} \right)$$

Total heat transfer rate

$$\mathcal{Q} = n_h c_h (T_{h1} - T_{h2}) \quad \text{and} \quad \mathcal{Q} = n_c c_c (T_{c1} - T_{c2})$$
Heat Exchanger Analysis (contd...) 

Substitute for $\Delta T$ and put 

$$
\Delta T_1 = T_{h1} - T_{c1} \quad END 1 \\
\Delta T_2 = T_{h2} - T_{c2} \quad END 2 \\

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

\mathcal{Q} = UA(LMTD) 

LMTD is Log Mean Temperature Difference

• Remember – 1 and 2 are ends, not fluids
• Same formula for parallel flow (but $\Delta T$’s are different)
• Counterflow has highest LMTD, for given $T$’s therefore smallest area for $Q$. 
Heat Exchanger Analysis (contd...)
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.
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…)

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

Effectiveness: \[ P = \frac{1 - X^{1/N_{shell}}}{R - X^{1/N_{shell}}} \], for \( R \neq 1 \)

\[ P = \frac{P_0}{N_{shell} - P_0 \cdot (N_{shell} - 1)} \], for \( R = 1 \)

\[ P_0 = \frac{t_2 - t_1}{T_1 - t_1} \]

\[ X = \frac{P_0 \cdot R - 1}{P_0 - 1} \]

\[ T,t = \text{Shell / tube side}; \ 1, 2 = \text{inlet / outlet} \]

Capacity ratio \( R = \frac{T_1 - T_2}{t_2 - t_1} \)
Multipass HX Flow Arrangements (contd...)
Effectiveness-NTU Method

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

Define effectiveness: \[
\varepsilon = \frac{\dot{Q}_{actual}}{\dot{Q}_{max}}
\]

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 \[
\dot{Q} = (n \& c_A) \Delta T_A = (n \& c_B) \Delta T_B
\]

\[
= C_A \Delta T_A = C_B \Delta T_B
\]

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. \( \dot{Q}_{\text{max}} = C_{\text{min}} \Delta T_{\text{max}} \) and \( \varepsilon = \frac{\dot{Q}}{C_{\text{min}} (T_{\text{h.in}} - T_{\text{c.in}})} \)

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

Want expression for \( \varepsilon \) which does not contain outlet T's

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

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

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

and No. of transfer units (size of HEx.) \( NTU = \frac{UA}{C_{\text{min}}} \)
Charts for each Configuration

Procedure:
Determine $C_{\text{max}}$, $C_{\text{min}}/C_{\text{max}}$
Get $UA/C_{\text{min}}$, $\varepsilon$ from chart

$$Q = \varepsilon C_{\text{min}} (T_{h.in} - T_{c.in})$$
Effectiveness-NTU Method (contd…)

\[ NTU_{\text{max}} = \frac{UA}{C_{\text{min}}} \quad \Rightarrow \quad A = \frac{NTU_{\text{max}} C_{\text{min}}}{U} \]

- \( NTU_{\text{max}} \) can be obtained from figures in textbooks/handbooks

First, however, we must determine which fluid has \( C_{\text{min}} \).