Equipment Fundamentals: Heat Exchangers

Chapter 3
Topics

Equipment – heat exchangers
- Combines information about fluid flow & heat transfer across internal boundaries
- Considerations
  • When do I need to know the specifics of the heat exchange configuration?
  • How is the heat transfer coefficient related to the outlet temperatures?
  • What is an approach temperature?

Fundamentals of heat transfer & exchange
- Heat transfer across boundaries
  • Conduction
  • Convection
  • Radiation
- Coupled with internal energy changes
  • Sensible heat effects
  • Phase change
Topics

Fundamentals of heat transfer & exchange

- Heat transfer across boundaries
  - Conduction
  - Convection
  - Radiation
- Coupled with internal energy changes
  - Sensible heat effects
  - Phase change
- Area-averaged temperature difference

Equipment – heat exchangers

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Fundamentals
Heat Transfer – Modes of heat transfer

Conduction

- Flow of heat through material with no bulk movement of the material itself
- Usually thought of through solid, but can also be through a stagnant fluid
- For a flat solid:
  \[
  \frac{\dot{Q}}{A} = k \frac{T_{\text{hot}} - T_{\text{cold}}}{\Delta x}
  \]
- Through a circular pipe:
  \[
  \frac{\dot{Q}}{L} = \frac{2\pi}{\ln(D_o/D_i)} k (T_{\text{hot}} - T_{\text{cold}})
  \]
- Through a sphere:
  \[
  \dot{Q} = \frac{2\pi}{\frac{1}{D_i} + \frac{1}{D_o}} k (T_{\text{hot}} - T_{\text{cold}})
  \]
Heat Transfer – Modes of heat transfer

Convection

- Flow of heat associated with fluid movement – natural & forced convection

\[
\frac{\dot{Q}}{A} = h(T_{\text{hot}} - T_{\text{cold}})
\]

Radiation

- Heat transferred via electromagnetic radiation

\[
\frac{\dot{Q}}{A} = \varepsilon \sigma \left( T_{\text{hot}}^4 - T_{\text{cold}}^4 \right)
\]

\[
= \left[ \varepsilon \sigma \left( T_{\text{hot}}^2 + T_{\text{cold}}^2 \right)(T_{\text{hot}} + T_{\text{cold}}) \right] (T_{\text{hot}} - T_{\text{cold}})
\]
Heat Exchangers – Some Basics

Focus is on the system to have heat flow from the hot fluid(s) to the cold fluid(s) usually without direct contact

- Use bulk flow parameters to relate the heat conduction across the flow barrier to the change in energy of the hot & cold fluids
- Account for the series of resistances to heat transfer between the hot & cold fluids

Heat exchangers

- Heat to & from flowing fluids through impermeable barrier(s)
- Driving force for heat through barriers is the temperature difference between the two fluids on opposite sides of the barrier
- Relate the heat effects in the flowing fluids to the change in enthalpy
  - Often this can be related to the difference in the inlet & outlet temperatures for the fluids

\[
\dot{Q}_H = \dot{m}_H \left( \hat{H}_{H,in} - \hat{H}_{H,out} \right) \quad \Rightarrow \quad \dot{Q}_H = \dot{m}_H \hat{C}_{p,H} \left( T_{H,in} - T_{H,out} \right) \quad \text{for constant } \hat{C}_{p,H}
\]

\[
\dot{Q}_C = \dot{m}_C \left( \hat{H}_{C,out} - \hat{H}_{C,in} \right) \quad \Rightarrow \quad \dot{Q}_C = \dot{m}_C \hat{C}_{p,C} \left( T_{C,out} - T_{C,in} \right) \quad \text{for constant } \hat{C}_{p,C}
\]
Heat Exchangers – Some Basics

- Relate the heat across the barrier to the temperature difference across the barrier

\[
\frac{d(Q/L)}{dx} = U(T_h - T_c) \Rightarrow \dot{Q} = (UA)[T_h - T_c]_{\text{AREA AVERAGED}}
\]

- It can be shown that for many typical configurations the AREA AVERAGED temperature difference is the LMTD (Log Mean Temperature Difference)

\[
\dot{Q} = (UA)(\overline{\Delta T})_{LM} \quad \text{where} \quad (\overline{\Delta T})_{LM} \equiv \frac{(T_{H,0} - T_{C,0})(T_{H,1} - T_{C,1})}{\ln\left(\frac{T_{H,0} - T_{C,0}}{T_{H,1} - T_{C,1}}\right)}
\]
Heat Exchangers – Some Basics

LMTD is a prescribed calculation – calculating the LMTD from the procedure is always correct.

\[
LMTD = \frac{(\Delta T)_1 - (\Delta T)_2}{\ln\left[\frac{(\Delta T)_1}{(\Delta T)_2}\right]} \quad \text{and} \quad \lim_{(\Delta T)_1 \to (\Delta T)_2}(LMTD) = \frac{(\Delta T)_1 + (\Delta T)_2}{2}
\]

LMTD is appropriate for use as the area averaged temperature difference when temperature vs. heat released/absorbed is a straight line

- 1-1 co-current & counter-current flow and ...
- Both hot & cold sides have a constant heat or ...
- Only pure component phase change on one side or the other (no subcooling and/or superheating)
Heat Transfer – Some Basics

Heat exchangers – Co-Current vs. Counter-Current vs. Cross-Current flows

- Counter-current flow allows the outlet temperatures to approach more closely to the inlet temperature of the other fluid
- Cross-current flow is complicated & requires knowledge of the actual flow patterns

Heat exchangers – Industrial Heat Exchangers

- Industrial heat exchangers have a combination of heat transfer through multiple barriers and a combination of counter-current & co-current flow
  - LMTD must be “corrected” to give the actual area-averaged temperature difference (i.e., driving force) – this is the source for one type of “F” factor
Heat Exchanger – Example 1

Heat 291,800 lb/hr cold C2+ NGL feed from 80°F to 105°F using 191,600 lb/hr hot C3+ bottoms @ 240°F

- Assume only sensible heat effects
  - C2+ NGL feed heat capacity – 0.704 Btu/lb F
  - C3+ Bottoms heat capacity – 0.830 Btu/lb F

Determine

- C3+ Bottoms outlet temperature
- Exchanger duty
- (UA) for the exchanger
Heat Exchanger – Example 1

Exchanger duty & C3+ Bottoms outlet temperature determined from energy balance around exchanger

\[
\dot{Q} = \dot{m}_c \hat{C}_{p,c} (T_{c,\text{out}} - T_{c,\text{in}}) = (291800)(0.704)(145 - 80) = 13,353,000 \text{ Btu/hr}
\]

\[
T_{h,\text{out}} = T_{h,\text{in}} - \frac{\dot{Q}}{\dot{m}_h \hat{C}_{p,h}} = 240 - \frac{13353000}{(191600)(0.828)} = 155.8^\circ\text{F}
\]

Determination of UA requires configuration information

- 1-1 counter-current flow

\[
(\Delta T)_{LMTD} = \frac{(240 - 145) - (155.8 - 80)}{\ln \left( \frac{240 - 145}{155.8 - 80} \right)} = 85.1^\circ\text{F}
\]

\[
UA = \frac{\dot{Q}}{(\Delta T)_{LMTD}} = \frac{13353000}{85.1} = 157,000 \frac{\text{Btu}}{\text{hr}^\circ\text{F}}
\]

- 1-1 co-current flow

\[
(\Delta T)_{LMTD} = \frac{(240 - 80) - (155.8 - 145)}{\ln \left( \frac{240 - 80}{207.7 - 105} \right)} = 55.4^\circ\text{F}
\]

\[
UA = \frac{\dot{Q}}{(\Delta T)_{LMTD}} = \frac{13353000}{55.4} = 241,000 \frac{\text{Btu}}{\text{hr}^\circ\text{F}}
\]
Heat Exchanger – Example 1

Determination of UA requires configuration information

- 1-2 (1 shell & 2 tube passes) combines both counter & co-current flow

The fluid in the shell pass transfers heat separately to the two tube banks

Ref: GPSA Data Book, 13th ed.
Heat Exchanger – Example 1

- 1-2 exchanger calculations require a configuration correction to relate temperatures to the UA
- Does not include crossflow effects across the tubes

\[ F_1 = \frac{\sqrt{R^2 + 1} \ln \frac{1-P}{1-RP}}{(R-1)\ln \frac{2-P(R+1-\sqrt{R^2+1})}{2-P(R+1+\sqrt{R^2+1})}} \]


Ref: GPSA Data Book, 13th ed.
Heat Exchanger – Example 1

- 1-2 exchanger

\[
(\Delta T)_{LMTD} = \frac{(240 - 145) - (155.8 - 80)}{\ln\left(\frac{240 - 145}{155.8 - 80}\right)} = 85.1^\circ F
\]

\[
P = \frac{145 - 80}{240 - 80} = 0.4
\]

\[
R = \frac{240 - 155.8}{145 - 80} = 1.3
\]

\[
F_2 = 0.86 \text{ (from chart)}
\]

\[
UA = \frac{\dot{Q}}{F_2 (\Delta T)_{LMTD}} = \frac{13353000}{0.86(85.1)} = 182,500 \text{ Btu/hr}\degree F
\]

Ref: GPSA Data Book, 13th ed.
Heat Exchanger – Example 1
Heat Exchanger – Example 1

Representation of temperature profiles with combined flow becomes more complicated.
Heat Exchanger – Example 2

Heat 291,800 lb/hr cold C2+ NGL feed starting from 80°F using 191,600 lb/hr hot C3+ bottoms @ 240°F. Drive the exchanger to a 10°F approach temperature

- For 1-1 Counter-Current flow, what are the outlet temperatures?
  - The C2+ NGL Feed is either heated to 230°F (approach on the hot inlet side) or ...
  - the C3+ Bottoms is cooled to 90°F (approach on the cold inlet side)

- Assume only sensible heat effects
  - C2+ NGL feed heat capacity – 0.704 Btu/lb°F
  - C3+ Bottoms heat capacity – 0.830 Btu/lb°F

Determine

- The outlet temperature that is not controlled by the approach
- Exchanger duty
- (UA) for the exchanger
Heat Exchanger – Example 2

Exchanger duty & “other” outlet temperature determined from energy balance around exchanger

- If the hot side inlet has the approach temperature

\[ T_{c,\text{out}} = T_{h,\text{in}} - 10 = 230^\circ\text{F} \]

\[ Q = \dot{m}_c \hat{C}_p,c \left( T_{c,\text{out}} - T_{c,\text{in}} \right) = (291800)(0.704)(230 - 80) = 30,814,000 \text{ Btu/hr} \]

\[ T_{h,\text{out}} = T_{h,\text{in}} - \frac{Q}{\dot{m}_h \hat{C}_{p,h}} = 240 - \frac{30814000}{(191600)(0.828)} = 45.8^\circ\text{F} \]

This has a temperature crossover – this is not the controlling side!

- If the cold side inlet has the approach temperature:

\[ T_{h,\text{out}} = T_{c,\text{in}} + 10 = 90^\circ\text{F} \]

\[ Q = \dot{m}_h \hat{C}_{p,h} \left( T_{h,\text{in}} - T_{h,\text{out}} \right) = (191600)(0.828)(240 - 90) = 23,797,000 \text{ Btu/hr} \]

\[ T_{c,\text{out}} = T_{c,\text{in}} + \frac{Q}{\dot{m}_c \hat{C}_p,c} = 80 + \frac{23797000}{(291800)(0.704)} = 195.8^\circ\text{F} \]
Heat Exchanger – Example 2

Determination of UA for 1-1 Counter-Current flow using the cold & hot outlet temperatures of 195.8°F & 90°F, respectively

\[
(\Delta T)_{LMTD} = \frac{(240 - 195.8) - (90 - 80)}{\ln\left(\frac{240 - 195.8}{90 - 80}\right)} = 23.0°F
\]

\[
UA = \frac{Q}{(\Delta T)_{LMTD}} = \frac{23797000}{23.0} = 1,035,000 \text{ Btu/hr°F}
\]
Heat Exchanger – Example 3

Heat 291,800 lb/hr cold C2+ NGL feed from 80°F using 191,600 lb/hr hot C3+ bottoms @ 240°F. 1-1 Counter-Current heat exchanger from Example #1 designed with 25% excess heat transfer area (UA=196,000 Btu/hr °F)

- Assume only sensible heat effects
  - C2+ NGL feed heat capacity – 0.704 Btu/lb °F
  - C3+ Bottoms heat capacity – 0.830 Btu/lb °F

Determine

- Both outlet temperatures
- Exchanger duty

Need to couple all three equations relating heat exchanger duty find the three unknowns
Heat Exchanger – Example 3

Even though it looks like you’ll have to solve the three equations in an iterative manner, it can be shown that the heat transfer duty is:

\[
\dot{Q} = \frac{(\Lambda - 1)(T_{H,in} - T_{C,in})}{\Lambda \frac{1}{m_c C_{p,C}} + \frac{1}{m_H C_{p,H}}} \text{where } \Lambda \equiv \exp \left[ UA \left( \frac{1}{m_c C_{p,C}} - \frac{1}{m_H C_{p,H}} \right) \right] \text{ for } m_c C_{p,C} \neq m_H C_{p,H}
\]

In the limiting case where the \(mCp\) terms are equal:

\[
\dot{Q} = \frac{T_{H,in} - T_{C,in}}{1 + \frac{UA}{m C_p}} \text{ if } m_c C_{p,C} = m_H C_{p,H}
\]
Heat Exchanger – Example 3

Even though it looks like you’ll have to solve the three equations in an iterative manner, it can be shown that the heat transfer duty is:

\[ \dot{Q} = \frac{(\Lambda - 1)(T_{H,\text{in}} - T_{C,\text{in}})}{\Lambda} - \frac{1}{\dot{m}_c C_{p,c} \dot{m}_H C_{p,H}} \]

where \( \Lambda \equiv \exp \left[ UA \left( \frac{1}{\dot{m}_c C_{p,c}} - \frac{1}{\dot{m}_H C_{p,H}} \right) \right] \) for \( \dot{m}_c C_{p,c} \neq \dot{m}_H C_{p,H} \)

So:

\[ \Lambda = \exp \left[ (196000) \left( \frac{1}{(291800)(0.704)} - \frac{1}{(191600)(0.828)} \right) \right] = 0.7548 \]

\[ \dot{Q} = \frac{(0.7548 - 1)(240 - 80)}{0.7548} = \frac{1}{(291800)(0.704)} - \frac{1}{(191600)(0.828)} \]

\[ = 14,924,000 \text{ Btu/hr} \]

\[ T_{h,\text{out}} = T_{h,\text{in}} - \frac{\dot{Q}}{\dot{m}_h \hat{C}_{p,h}} = 240 - \frac{14924000}{(191600)(0.828)} = 145.9^\circ F \]

\[ T_{c,\text{out}} = T_{c,\text{in}} + \frac{Q}{\dot{m}_c \hat{C}_{p,c}} = 80 + \frac{14924000}{(291800)(0.704)} = 152.6^\circ F \]
Heat Exchange with Phase Change

Can get significant heat exchange with little to no change in temperature

Ref: GPSA Data Book, 13th ed.
Heat Exchanger – Example 4

Condense 10,000 lb/hr saturated vapor propane at 120°F using 95°F air. Figure a 10°F approach temperature, so heat the air up to 110°F.

- Needed physical properties
  - Air heat capacity – 0.24 Btu/lb F
  - Propane heat of vaporization @ 120°F – 1,236 Btu/lb

Determine

- Exchanger duty
- Flow rate of air needed
- Exchanger UA
Heat Exchanger – Example 4

Duty determined from the propane energy balance. No sensible heat effect.

\[ \dot{Q} = \dot{m}_h \lambda_{vap} = (10000)(1236) = 12,360,000 \text{ Btu/hr} \]

Air flowrate from its energy balance:

\[ \dot{m}_c = \frac{\dot{Q}}{\dot{C}_{p,c}(T_{c,\text{out}} - T_{c,\text{in}})} = \frac{12,360,000}{(0.24)(110 - 95)} = 3,430,000 \text{ lb/hr} \]

Calculate UA knowing the terminal temperatures

\[ (\Delta T)_{\text{LMTD}} = \frac{(120 - 110) - (120 - 95)}{\ln\left(\frac{120 - 110}{120 - 95}\right)} = 16.4^\circ F \]

\[ UA = \frac{\dot{Q}}{(\Delta T)_{\text{LMTD}}} = \frac{12360000}{16.4} = 755,000 \frac{\text{Btu}}{\text{hr}^\circ F} \]
Heat Exchanger – Example 4

Calculating the UA is essentially the same as when there is no phase change since the temperature profiles with heat release are still straight lines. The hot stream’s profile just happens to be a constant temperature.
Heat Exchanger – Example 5

Condense 10,000 lb/hr propane vapor that is superheated to 160°F (but still with 120°F vapor pressure) using 95°F air heated up to 110°F.

- Needed physical properties
  - Air heat capacity – 0.24 Btu/lb F
  - Propane vapor heat capacity – 0.52 Btu/lb F
  - Propane heat of vaporization @ 120°F – 1236 Btu/lb

Determine

- Exchanger duty
- Flow rate of air needed
- Exchanger UA
Heat Exchanger – Example 5

Duty determined from the propane balance. Combine sensible heat & latent heat effects

\[
\dot{Q} = \dot{m}_h \left[ \lambda_{vap} + \dot{C}_{p,c} (T_{h,in} - T_{h,BP}) \right] = (10000) \left[ (1236) + 0.52(160 - 120) \right]
\]
\[
= (10000)(1236 + 20.8)
\]
\[
= 125,680,000 \text{ Btu/hr}
\]

Air flowrate from its energy balance:

\[
\dot{m}_c = \frac{\dot{Q}}{\dot{C}_{p,c} (T_{c,out} - T_{c,in})} = \frac{125,680,000}{(0.24)(110 - 95)} = 34,900,000 \text{ lb/hr}
\]

Just using terminal temperatures gives an incorrect result!

\[
(\Delta T)_{LMTD} = \frac{(160 - 110) - (120 - 95)}{\ln \left( \frac{160 - 110}{120 - 95} \right)} = 36.1^\circ \text{F} \quad \Rightarrow \quad UA = \frac{\dot{Q}}{(\Delta T)_{LMTD}} = \frac{125680000}{36.1} = 3,480,000 \frac{\text{Btu}}{\text{hr}^\circ \text{F}}
\]
Heat Exchanger – Example 5

Calculating the UA is more complicated than just using the terminal temperatures since there is a drastic break in the temperature profile for the condensing propane.
Heat Exchanger – Example 5

Determine the intermediate air temperature between the sensible & latent heat zones

\[ \dot{Q}_{\text{cond}} = \dot{m}_h \lambda_{\text{vap}} = 123,600,000 \text{ Btu/hr} \]

\[ T_{c,\text{mid}} = T_{c,\text{in}} + \frac{\dot{Q}_{\text{cond}}}{\dot{m}_c \hat{C}_p,c} = 95 + \frac{123,600,000}{(34,900,000)(0.24)} = 109.8^\circ\text{F} \]

Calculate the UA values for the two zones

\[ (\Delta T)_{\text{LMTD}} = \frac{(120 - 109.8) - (120 - 95)}{\ln \left(\frac{120 - 109.8}{120 - 95}\right)} = 16.5^\circ\text{F} \]

\[ (\Delta T)_{\text{LMTD}} = \frac{(160 - 110) - (120 - 109.8)}{\ln \left(\frac{160 - 110}{120 - 109.8}\right)} = 25.0^\circ\text{F} \]

\[ UA = \frac{\dot{Q}}{(\Delta T)_{\text{LMTD}}} = \frac{123600000}{36.1} = 3,420,000 \frac{\text{Btu}}{\text{hr}^\circ\text{F}} \]

\[ UA = \frac{\dot{Q}}{(\Delta T)_{\text{LMTD}}} = \frac{2080000}{25.0} = 83,000 \frac{\text{Btu}}{\text{hr}^\circ\text{F}} \]

The total UA is the sum of these two contributions.
Heat Exchanger – Example 6

Can we condense 10,000 lb/hr propane vapor that is superheated to 160°F (but still with 120°F vapor pressure) using 95°F air heated up to 140°F? This still gives an apparent 20°F approach temperature?

The answer is NO! It is not apparent from the terminal temperatures but there is an internal pinch point to the temperature profiles & there would be a temperature crossover. The air’s outlet temperature is constrained by this internal pinch point.

![Heat Flow Diagram](image-url)
More air flow is needed to accomplish this cooling. Using a 10°F internal approach temperature shows that the air’s outlet temperature is constrained to 112.5°F. The required air mass flow would be calculated accordingly.
Heat Transfer – Some Basics

Thermal resistances are added when in series

- Can be combined into an overall heat transfer coefficient
- Across a flat plate (i.e., constant cross sectional area)

\[
\frac{1}{U} = \frac{1}{h_i} + \frac{L}{k} + \frac{1}{h_o}
\]

- For radial heat transfer (e.g., through the wall of a tube) must also take into account the change is area with respect to radius
  - Overall heat transfer coefficient must also be related to a reference area / diameter

\[
\frac{1}{U_o A_o} = \frac{1}{h_i A_i} + \frac{L}{k A_{ave}} + \frac{1}{h_o A_o}
\]

\[
\frac{1}{U_o} = \frac{1}{h_i A_i} + \frac{L}{k A_{ave}} + \frac{1}{h_o} = \frac{1}{h_i D_i} + \frac{2D_o}{k} \ln\left(\frac{D_o}{D_i}\right) + \frac{1}{h_o}
\]
Heat Transfer – Correlations for Film Coefficients

Flow in tubes with no phase change

\[ N_{Nu} = 0.023 \, N_{Re}^{0.8} \, N_{Pr}^{0.4} \Rightarrow \left( \frac{hD}{k} \right) = 0.023 \left( \frac{D \nu \rho}{\mu} \right)^{0.8} \left( \frac{C_p \mu}{k} \right)^{0.4} \]

When there is a significant difference between wall & bulk fluid

\[ N_{Nu} = 0.023 \, N_{Re}^{0.8} \, N_{Pr}^{0.33} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \Rightarrow \left( \frac{hD}{k} \right) = 0.023 \left( \frac{D \nu \rho}{\mu} \right)^{0.8} \left( \frac{C_p \mu}{k} \right)^{0.33} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \]

Stirred liquids, heat transfer from coil ...

\[ N_{Nu} = 0.9 \, N_{Re,i}^{0.62} \, N_{Pr}^{0.33} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \Rightarrow \left( \frac{hD}{k} \right) = 0.9 \left( \frac{N_i D_i^2 \rho}{\mu} \right)^{0.62} \left( \frac{C_p \mu}{k} \right)^{0.33} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \]

... from tank jacket

\[ N_{Nu} = 0.36 \, N_{Re,i}^{0.66} \, N_{Pr}^{0.33} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \Rightarrow \left( \frac{hD}{k} \right) = 0.36 \left( \frac{N_i D_i^2 \rho}{\mu} \right)^{0.67} \left( \frac{C_p \mu}{k} \right)^{0.33} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \]
Typical Overall Heat Transfer Coefficients

Heat transfer coefficients are drastically different for conditions of boiling and/or condensation versus when there is sensible heat change.

- Bubbles break up the films along the wall
- Also dependent upon the temperature difference across the wall

Ref: GPSA Data Book, 13th ed.

Typical Overall Heat Transfer Coefficients

**FIG. 9-9**
Typical Heat Transfer Coefficients, U, and Fouling Resistances, \( r_f \)

<table>
<thead>
<tr>
<th>Service and ( \tau_f )</th>
<th>U</th>
<th>Service and ( \tau_f )</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (0.002)/100 psi Gas (0.001)</td>
<td>35-40</td>
<td>Rich (0.001)/Lean Oil (0.002)</td>
<td>80-100</td>
</tr>
<tr>
<td>300 psi Gas (0.001)</td>
<td>40-50</td>
<td>C(_2) Liq/C(_2) Liq (0.001)</td>
<td>110-130</td>
</tr>
<tr>
<td>700 psi Gas (0.001)</td>
<td>60-70</td>
<td>MEA/MEA (0.002)</td>
<td>120-130</td>
</tr>
<tr>
<td>1000 psi Gas (0.001)</td>
<td>80-100</td>
<td>100 psi Gas/500 psi Gas</td>
<td>50-70</td>
</tr>
<tr>
<td>Kerosene (0.001)</td>
<td>80-90</td>
<td>1000 psi Gas/1000 psi Gas</td>
<td>60-80</td>
</tr>
<tr>
<td>MEA (0.002)</td>
<td>130-150</td>
<td>1000 psi Gas/Cond. C(_2) (0.001)</td>
<td>60-80</td>
</tr>
<tr>
<td>Air (0.002)</td>
<td>20-25</td>
<td>Steam (0.0005) Reboilers</td>
<td>140-160</td>
</tr>
<tr>
<td>Water (0.001)</td>
<td>180-200</td>
<td>Hot Oil (0.002) Reboilers</td>
<td>90-120</td>
</tr>
<tr>
<td>Condensing with water (0.002)/C(_2) or C(_4) (0.001)</td>
<td>125-135</td>
<td>Heat Transfer Fluid (0.001) Reboilers</td>
<td>80-110</td>
</tr>
<tr>
<td>Naphtha (0.001)</td>
<td>70-80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Still Overhead (0.001)</td>
<td>70-80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amine (0.002)</td>
<td>100-110</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

U in Btu/(hr • sq ft • °F)
\( r_f \) in (hr • sq ft • °F)/Btu

**TABLE 3.2**
Typical Orders of Magnitude for Heat Transfer Coefficients

<table>
<thead>
<tr>
<th>Fluid</th>
<th>( h ), Btu/ft(^2)-h-°F (W/m(^2)-°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gases in forced convection</td>
<td>2–20 (10–100)</td>
</tr>
<tr>
<td>Liquids in forced convection</td>
<td>10–100 (50–500)</td>
</tr>
<tr>
<td>Water</td>
<td>100–2,000 (500–10,000)</td>
</tr>
<tr>
<td>Boiling water</td>
<td>200–4,000 (1,000–20,000)</td>
</tr>
<tr>
<td>Condensing vapors</td>
<td>200–20,000 (1,000–100,000)</td>
</tr>
</tbody>
</table>


Ref: GPSA Data Book, 13\(^{th}\) ed.
Typical Fouling Factors

Add these resistances to the reciprocal of the “clean” overall heat transfer coefficient

![Typical Fouling Factors for PHEs](image)

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Fouling Factor Sq ft·°F·Hr/Btu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Demineralized or distilled</td>
<td>0.00001</td>
</tr>
<tr>
<td>Municipal supply (soft)</td>
<td>0.00002</td>
</tr>
<tr>
<td>Municipal supply (hard)</td>
<td>0.00005</td>
</tr>
<tr>
<td>Cooling tower (treated)</td>
<td>0.00004</td>
</tr>
<tr>
<td>Sea (coastal) or estuary</td>
<td>0.00005</td>
</tr>
<tr>
<td>Sea (ocean)</td>
<td>0.00003</td>
</tr>
<tr>
<td>River, canal, borehole, etc.</td>
<td>0.00005</td>
</tr>
<tr>
<td>Engine jacket</td>
<td>0.00006</td>
</tr>
<tr>
<td>Oils, lubricating</td>
<td>0.00002 to 0.00005</td>
</tr>
<tr>
<td>Solvents, organic</td>
<td>0.00001 to 0.00003</td>
</tr>
<tr>
<td>Steam</td>
<td>0.00001</td>
</tr>
<tr>
<td>Process fluids, general</td>
<td>0.00001 to 0.00006</td>
</tr>
</tbody>
</table>

Ref: GPSA Data Book, 13th ed.
Equipment
Gas Processing Applications

Common heat exchangers

- Shell and Tube
- Kettle reboiler
- Aerial coolers
- Plate Frame
- Plate-Fin (Brazed Aluminum)
- Hairpin
- Tank Heaters

Shell & Tube Heat Exchangers

Workhorses of the gas processing industry

Shell side
- Baffles used in the shell side to minimize channeling

Tube side
- Manifolds allow for even distribution of fluids into the tubes & collection/mixing of fluids out of the tubes
- Multiple tube passes make it easier to pull the tube bundle for maintenance/cleaning and...
- ... have better allowance for thermal expansion effects

Fig. 3.6, Fundamentals of Natural Gas Processing, 2nd ed., Kidnay, Parrish, & McCartney, 2011
Shell and Tube Heat Exchangers (Types)

Ref: GPSA Data Book, 13th ed.

Updated: January 29, 2019
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# Shell and Tube Heat Exchangers (Selection)

![Shell and Tube Exchanger Selection Guide](image)

**FIG. 9-24**

Shell and Tube Exchanger Selection Guide (Cost Increases from Left to Right)

<table>
<thead>
<tr>
<th>Type of Design</th>
<th>“U” Tube</th>
<th>Fixed Tubesheet</th>
<th>Floating Head Outside Packed</th>
<th>Floating Head Split Backing Ring</th>
<th>Floating Head Pull-Through Bundle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provision for differential expansion</td>
<td>individual tubes free to expand</td>
<td>expansion joint in shell</td>
<td>floating head</td>
<td>floating head</td>
<td>floating head</td>
</tr>
<tr>
<td>Removeable bundle</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Replacement bundle possible</td>
<td>yes</td>
<td>not practical</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Individual tubes replaceable</td>
<td>only those in outside row</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Tube interiors cleanable</td>
<td>difficult to do mechanically, can do chemically</td>
<td>yes, mechanically or chemically</td>
<td>yes, mechanically or chemically</td>
<td>yes, mechanically or chemically</td>
<td>yes, mechanically or chemically</td>
</tr>
<tr>
<td>Tube exteriors with triangular pitch cleanable</td>
<td>chemically only</td>
<td>chemically only</td>
<td>chemically only</td>
<td>chemically only</td>
<td>chemically only</td>
</tr>
<tr>
<td>Tube exteriors with square pitch cleanable</td>
<td>yes, mechanically or chemically</td>
<td>chemically only</td>
<td>yes, mechanically or chemically</td>
<td>yes, mechanically or chemically</td>
<td>yes, mechanically or chemically</td>
</tr>
<tr>
<td>Number of tube passes</td>
<td>any practical even number possible</td>
<td>normally no limitations</td>
<td>normally no limitations</td>
<td>normally no limitations</td>
<td>normally no limitations</td>
</tr>
<tr>
<td>Internal gaskets eliminated</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Ref: *GPSA Data Book*, 13th ed.
Kettle Reboiler

Shell & tube heat exchanger with the tubes submerged in boiling liquid on the shell side

- Main resistance to heat transfer is on the tube side since boiling is occurring on the shell side

Fig. 3.7, *Fundamentals of Natural Gas Processing, 2nd ed.*, Kidnay, Parrish, & McCartney, 2011
Plate Frame Heat Exchangers

Positives

- Low cost
- Compact – high area per weight & volume
- Can get very close approach temperatures (5°F or lower)
- Can be disassembled to clean

Negative considerations

- Limited maximum allowable working pressure
- Susceptible to plugging

http://www.cheresources.com/content/articles/heat-transfer/plate-heat-exchangers-preliminary-design

Fig. 3.9, Fundamentals of Natural Gas Processing, 2nd ed., Kidnay, Parrish, & McCartney, 2011
Tank Heaters

Integrated into existing equipment (i.e., tanks or vessels)

FIG. 9-32
Prefabricated Tank Heater

Ref: GPSA Data Book, 13th ed.

Air-Cooled Exchangers – Fundamentals

Air cooled exchangers cool fluids with ambient air

- Seasonal variation can greatly impact performance

Utilize finned tube in increase heat transfer surface area

www.hudsonproducts.com
Aerial Coolers

Fans either push air through (forced draft) or pull air through (induced draft) tube bundle

- Can control the air flow rate either with a variable speed motor or with louviers

Fig. 3.8, *Fundamentals of Natural Gas Processing*, 2nd ed., Kidnay, Parrish, & McCartney, 2011

http://spxcooling.com/products/detail/air-cooled-heat-exchangers
Aerial Cooler Design Considerations

Typically a small number of diameter tubes (e.g., 1in OD) with fins on the air side (e.g., 1/2 or 5/8 in)

Design considerations

- Process side – pressure drop for flow inside of tubes
- Air side
  - Required air flow
    - May need high air flow to prevent temperature crossover, but...
    - High air flow gives higher pressure drop & fan power
- Mechanical considerations
  - Total number of tubes
  - Tube layout: number of passes, number of rows, pitch
  - Bay size: typically 45 ft X 15 ft max

Ref: GPSA Data Book, 14th ed.
Air-Cooled Exchangers – Types

Forced Draft:
Advantages:
- Slightly lower horsepower
- Better maintenance accessibility
- Easily adaptable for warm air recirculation
- Most common in gas industry

Induced Draft:
Advantages
- Better distribution of air
- Less possibility of air recirculation
- Less effect of sun, rain, or hail
- Increased capacity in the event of fan failure
Air-Cooled Exchanger – Thermal Design (Δ Temperature – CMTD Figs 10-8 & 9)

FIG. 10-9

MTD Correction Factors (2 Pass — Cross Flow, Both Fluids Unmixed)

Nomenclature:
T_1 = inlet temperature, tube side
T_2 = outlet temperature, tube side
t_1 = inlet temperature, air side
t_2 = outlet temperature, air side

F \sim 1.0

for 3+ Over/Under Passes
Summary
Summary

Common types of heat exchangers used in the gas processing industry

- Shell & tube
- Kettle reboiler
- Air cooled exchangers
- Plate Frame
- Plate-Fin (Brazed Aluminum)
- Hairpin
- Tank Heaters

Heat exchange basics

- Coupling of fluid energy balances with heat transfer across barrier
- Common heat exchanger configurations
- Typical heat transfer coefficients
- Example process calculations involving heat exchangers
Supplemental Slides
LMTD as Area-Averaged Temperature Difference

If the temperature curves are linearly related to the duty then the temperature difference will also be linearly related to duty

$$\Delta T = (\Delta T)_0 + \left[ \frac{(\Delta T)_1 - (\Delta T)_0}{Q} \right] q \quad \Rightarrow \quad d(\Delta T) = \frac{(\Delta T)_1 - (\Delta T)_0}{Q} dq$$

Can put into differential form of heat transfer equation & integrate

$$dq = U(\Delta T) \, d\alpha \quad \Rightarrow \quad \frac{Q}{(\Delta T)_1 - (\Delta T)_0} \, d(\Delta T) = U(\Delta T) \, d\alpha$$

$$\frac{d(\Delta T)}{\Delta T} = U \frac{(\Delta T)_1 - (\Delta T)_0}{Q} d\alpha$$

$$\int_{(\Delta T)_0}^{(\Delta T)_1} \frac{d(\Delta T)}{\Delta T} = U \frac{(\Delta T)_1 - (\Delta T)_0}{Q} \int_0^A d\alpha$$

$$\ln \left[ \frac{(\Delta T)_1}{(\Delta T)_0} \right] = U \frac{(\Delta T)_1 - (\Delta T)_0}{Q} A \quad \Rightarrow \quad \dot{Q} = UA \left( \frac{(\Delta T)_1 - (\Delta T)_0}{Q} \right) = UA \left( \frac{(\Delta T)_1}{(\Delta T)_0} \right)$$
Shell & Tube Heat Exchangers

Tubes
Available in Copper 90/10 CuNi, 316 Stainless Steel, Admiralty or Carbon Steel. Tubes are roller expanded.

Shells
Rugged shell available in Steel and 316 Stainless Steel. Minimum clearances between shell and baffles reduce by-pass and maximize heat transfer.

Heads
Heads available in Cast Iron, Brass, 316 Stainless Steel or Fabricated Carbon Steel.

Supports
Moveable, fabricated Carbon Steel available on all sizes.

Tubesheets
Thick Carbon Steel, 316 Stainless Steel or 90/10 CuNi tubesheets.

Baffles
Precision punched baffles assure effective circulation by providing minimum clearances between the tubes and tube holes. Baffle cuts and spacing for each diameter are consistent with best practices. Standard available material includes Carbon Steel, Brass and 316 Stainless Steel.

http://www.apiheattransfer.com/Product/54/Type-ST-U-Tube-Shell-Tube-Heat-Exchangers
Heat Exchanger – Example 7

Heat 291,800 lb/hr cold C2+ NGL feed from 80°F to 160°F using 191,600 lb/hr hot C3+ bottoms @ 240°F

- Assume only sensible heat effects
  - C2+ NGL feed heat capacity – 0.704 Btu/lb F
  - C3+ Bottoms heat capacity – 0.828 Btu/lb F

Determine

- C3+ Bottoms outlet temperature
- Exchanger duty
- (UA) for the exchanger
Heat Exchanger – Example 7

Exchanger duty & C3+ Bottoms outlet temperature determined from energy balance around exchanger

\[ \dot{Q} = \dot{m}_c \hat{C}_p,c \left( T_{c,\text{out}} - T_{c,\text{in}} \right) = (291800)(0.704)(160 - 80) = 16,434,000 \text{ Btu/hr} \]

\[ T_{h,\text{out}} = T_{h,\text{in}} - \frac{\dot{Q}}{\dot{m}_h \hat{C}_{p,h}} = 240 - \frac{16434000}{191600}(0.828) = 136.4^\circ \text{F} \]

Determination of UA requires configuration information

- 1-1 counter-current flow

\[ (\Delta T)_{\text{LMTD}} = \frac{(240 - 160) - (136.4 - 80)}{\ln\left(\frac{240 - 160}{136.4 - 80}\right)} = 67.5^\circ \text{F} \]

\[ UA = \frac{\dot{Q}}{(\Delta T)_{\text{LMTD}}} = \frac{16434000}{67.5} = 243,000 \frac{\text{Btu}}{\text{hr}^\circ \text{F}} \]

- 1-1 co-current flow cannot be done – crossover!
Heat Exchanger – Example 7

1-2 exchanger

\[
(\Delta T)_{\text{LMTD}} = \frac{(240 - 160) - (136.4 - 80)}{\ln \left( \frac{240 - 160}{136.4 - 80} \right)} = 67.5^\circ F
\]

\[
P = \frac{160 - 80}{240 - 80} = 0.5
\]

\[
R = \frac{240 - 136.4}{160 - 80} = 1.3
\]

\[
F_2 = 0.51 \text{ (from chart)}
\]

\[
UA = \frac{\dot{Q}}{F_2 (\Delta T)_{\text{LMTD}}}
\]

\[
= \frac{16434000}{0.51(67.5)} = 477,400 \text{ Btu/hr}^\circ F
\]

Ref: GPSA Data Book, 13th ed.
Heat Exchanger – Example 7

Correction factor below 0.8. Try 2-4 exchanger

\[ (\Delta T)_{\text{LMTD}} = \frac{(240 - 160) - (136.4 - 80)}{\ln\left(\frac{240 - 160}{136.4 - 80}\right)} = 67.5^\circ F \]

\[ P = \frac{160 - 80}{240 - 80} = 0.5 \]

\[ R = \frac{240 - 136.4}{160 - 80} = 1.3 \]

\[ F_2 = 0.925 \text{ (from chart)} \]

\[ UA = \frac{\dot{Q}}{F_2 (\Delta T)_{\text{LMTD}}} = \frac{16434000}{0.925(67.5)} = 263,200 \text{ Btu/hr}^\circ F \]

Ref: GPSA Data Book, 13th ed.
Cooling Tower Principles

Evaporative cooling (Psychrometry)

- Dry Bulb versus Wet Bulb Temperature
  - Contact dry air with water
  - Saturation of air (vaporization of some water) takes energy
  - Air is cooled below ambient – to “Wet Bulb” temperature
- Takes advantage of air below 100% humidity
  - Wet Bulb MUST be lower than Dry Bulb temperature
Evaporative cooling (Psychrometry)

- Wet bulb and dry bulb data for various locations around the world  Fig 11-3

![Figure 11-3: Dry Bulb/Wet Bulb Temperature Data for Selected Locations](image-url)
Example:

How cold can you get?
Air temperature: 95°F
RH = 65%
Temperature with cooling tower?
Temperature with air cooler?

Wet bulb = 84°F
Cooling Towers – Mechanical Induced Draft

Fig. 11-7
Mechanical Induced Draft Counterflow Tower

www.iklimnet.com

www.rjdesjardins.com
Cooling Towers – Wet Surface Air Cooler

FIG. 11-12
Wet Surface Air Cooler

Courtesy of Niagara Blower

www.niagarablower.com
Heat Exchanger – Example 1

Heat 291,800 lb/hr cold C2+ NGL feed from 80°F to 105°F using 191,600 lb/hr hot C3+ bottoms @ 240°F

- Assume only sensible heat effects
  - C2+ NGL feed heat capacity – 0.704 Btu/lb F
  - C3+ Bottoms heat capacity – 0.830 Btu/lb F

Determine

- C3+ Bottoms outlet temperature
- Exchanger duty
- (UA) for the exchanger
- Does the flow configuration in a 1-2 exchanger make a difference?
Heat Exchanger – Example 1

Determination of UA requires configuration information

- 1-2 (1 shell & 2 tube passes) combines both counter & co-current flow

Four possible flow configurations
Heat Exchanger – Example 1

Four possible flow configurations – all have the same exit temperatures but different internal profiles
Heat Exchanger – Example 7

I thought you said temperature crossovers weren’t possible???