Heat Transfer equipment - (Chpt. 22)

Heat Exchangers

Open - Closed - Heaters
Heat Transfer Equipment

• Double-pipe exchanger, used for cooling or heating.
• Shell and tube heat exchangers, used for all applications.
• Plate-fin exchangers.
• Spiral heat exchangers.
• Air cooled: coolers and condensers.
• Direct contact: cooling and quenching.
• Agitated vessels.
• Fired heaters.
Heat Transfer Equipment

Usual terminology:

- **Exchanger**: heat exchange between two process streams.
- **Heater or Cooler**: a process stream is heated/cooled by a utility stream.
- **Vaporizer**: a process stream is completely vaporized.
- **Reboiler**: vaporizer associated with a distillation column.
- **Evaporator**: used to concentrate a solution.
- **Fired heater**: heating is done by combustion.
Heat Transfer Equipment – What do we want?

**Design:**

- Duty (how much heat/energy is exchanged)
- Stream conditions (T, flow rate, pressures, phase)
- Configuration (size, material of construction etc.)

**Need:** physical properties, need U (h and k)

**Heat transport:**

\[ q = U A \Delta T_{tot} \]

Overall resistance, \( R = 1/UA \)
Overall Heat Transfer Coefficient

Resistances in series:
Overall resistance = Sum of resistances

In our case:

\[
\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o/d_i)}{2k_w} + \frac{d_o}{d_i h_i} + \frac{d_o}{d_i h_{id}}
\]

\(U_o\): overall heat transfer coefficient based on the outside area
\(h_o, h_i\): outside/inside film heat transfer coefficient
\(d_o, d_i\): outside/inside pipe diameter
\(k_w\): wall thermal conductivity
\(h_{od}, h_{id}\): outside/inside fouling heat transfer coefficient (Table 22.1)
Shell and Tube Heat Exchangers

Most commonly used heat exchangers.

Advantages:

- Large surface area in a small volume.
- Good mechanical layout.
- Well-established fabrication methods.
- Can be constructed from a wide variety of materials.
- Easily cleaned and maintained.
- Well-established design procedures.
Shell and Tube Heat Exchangers

Single pass, co-current and countercurrent flow.
Heat Transfer Equipment

Tube and shell heat exchanger:

Figure 12.4. U-tube (based on figures from BS 3274: 1960)
## Heat Transfer Equipment

### Tube and shell heat exchanger:

#### Nomenclature

<table>
<thead>
<tr>
<th>Part number</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1.</td>
<td>Shell</td>
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<tr>
<td>2.</td>
<td>Shell cover</td>
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<tr>
<td>3.</td>
<td>Floating-head cover</td>
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<tr>
<td>4.</td>
<td>Floating-tube plate</td>
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<td>5.</td>
<td>Clamp ring</td>
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<td>6.</td>
<td>Fixed tube sheet (tube plate)</td>
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<td>7.</td>
<td>Channel (end-box or header)</td>
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<tr>
<td>8.</td>
<td>Channel cover</td>
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<tr>
<td>9.</td>
<td>Branch (nozzle)</td>
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<tr>
<td>10.</td>
<td>Tie rod and spacer</td>
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<tr>
<td>11.</td>
<td>Cross baffle or tube-support plate</td>
</tr>
<tr>
<td>12.</td>
<td>Impingement baffle</td>
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<tr>
<td>13.</td>
<td>Longitudinal baffle</td>
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<tr>
<td>14.</td>
<td>Support bracket</td>
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<tr>
<td>15.</td>
<td>Floating-head support</td>
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<tr>
<td>16.</td>
<td>Weir</td>
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<tr>
<td>17.</td>
<td>Split ring</td>
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<tr>
<td>18.</td>
<td>Tube</td>
</tr>
<tr>
<td>19.</td>
<td>Tube bundle</td>
</tr>
<tr>
<td>20.</td>
<td>Pass partition</td>
</tr>
<tr>
<td>21.</td>
<td>Floating-head gland (packed gland)</td>
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<tr>
<td>22.</td>
<td>Floating-head gland ring</td>
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<tr>
<td>23.</td>
<td>Vent connection</td>
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<tr>
<td>24.</td>
<td>Drain connection</td>
</tr>
<tr>
<td>25.</td>
<td>Test connection</td>
</tr>
<tr>
<td>26.</td>
<td>Expansion bellows</td>
</tr>
<tr>
<td>27.</td>
<td>Lifting ring</td>
</tr>
</tbody>
</table>
Heat Transfer Equipment

Cross-flow & compact H.E.:  

Welty et al., Fig 22-2

Welty et al., Fig 22-4
Single phase streams with constant $C_p$ and no pressure effect on enthalpy:

$$q = \dot{m}C_p\Delta T$$

Pure components undergoing phase change:

$$q = \dot{m}\lambda$$
The T-Q diagram reveals two important truths regarding heat transfer:

(1) T-lines for counter-current flows do not cross! It is impossible.
(2) T-lines should not approach each other too closely: As they approach, the area required for heat transfer goes to infinity. The point of closest approach is called **pinch point**.
(a) A single-phase stream is heated from 100 to 200°C by condensing saturated steam to saturated liquid at 250°C in a countercurrent heat exchanger.

(b) A single-phase stream is heated from 120 to 220°C by condensation of saturated steam at 250°C and by subcooling the liquid to 225°C in a countercurrent heat exchanger.
Single pass heat exchangers: Analysis

- A T-A diagram is another visual representation of the energy transfer in a heat exchanger.

Energy balance (1\textsuperscript{st} thermo law): \[ q = mC_p \Delta T \]

For a differential area

\[ dq = (mc_p)_H dT_H = C_H dT_H \]
\[ dq = (mc_p)_c dT_c = C_c dT_c \]
Single pass heat exchangers: Analysis

\[ dq = U dA (T_H - T_c) \]

Temperature difference: \( \Delta T = (T_H - T_c) \)

Differential \( d(\Delta T) = dT_H - dT_c \)

Substitute

\[ d(\Delta T) = dq \left( \frac{1}{C_H} - \frac{1}{C_c} \right) = \frac{dq}{C_H} \left( 1 - \frac{C_H}{C_c} \right) \]

Heat lost from hot fluid is taken by cold fluid, so:

\[ \frac{C_H}{C_c} = \frac{T_{c2} - T_{c1}}{T_{H2} - T_{H1}} \]
Recall: \( dq = U (dA) \Delta T \), and \( q = C_H (T_{H2} - T_{H1}) \)

Then:

\[
\int_{\Delta T_1}^{\Delta T_2} \frac{d(\Delta T)}{\Delta T} = \frac{U}{q} (\Delta T_2 - \Delta T_1) \int_0^A dA
\]
Integrate:

\[ \ln \frac{\Delta T_2}{\Delta T_1} = \frac{UA}{q} (\Delta T_2 - \Delta T_1) \]

And, by rearranging:

\[ q = UA \frac{\Delta T_2 - \Delta T_1}{\Delta T_2 \ln \frac{\Delta T_2}{\Delta T_1}} \]

So that

\[ q = UA \Delta T_{lm} \]
Single pass heat exchangers: Analysis

Log-mean temperature difference

\[ q = UA \Delta T_{lm} \]

Important Assumptions:

**U** constant
No heat losses to ambient environment

Can be used with **U** calculated at average conditions in the exchanger
Heat Exchangers - Typical design

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties ($\rho$, $\mu$, $k$).
3) Decide on the type of exchanger.
4) Select a trial value for $U$.
5) Calculate the mean temperature difference, $\Delta T_m$.
6) Calculate area required.
7) Decide on the exchanger layout.
8) Calculate individual coefficients.
9) Calculate $U$. If significant difference from step (4), substitute in (4) and repeat.
10) Calculate the pressure drop. If it is not satisfactory, back to (7) or (4) or (3).
11) Optimise: repeat (4) to (10) to determine cheapest solution (usually smaller area).
(4) Use first order approximations for $U$, such as table 22-2 pg. 385 in Welty et al.

$$q = UA \Delta T_m$$
Overall Heat Transfer Coefficient

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(5) Mean temperature difference for counter-current flow:

$$\Delta T_m = \Delta T_{lm} = \frac{(T_{H-in} - t_{c-out}) - (T_{H-out} - t_{c-in})}{\ln \left( \frac{T_{H-in} - t_{c-out}}{T_{H-out} - t_{c-in}} \right)}$$

In reality, combination of co-current, countercurrent and cross flow.

What do we do? Use a correction factor, $F_t$, (see figs 22-9 and 22-10 in Welty et al.)

$$\Delta T_m = F_t \Delta T_{lm}$$

Parameters:

$$Z = R = \frac{(T_{H-in} - T_{H-out})}{(t_{c-out} - t_{c-in})}, \quad Y = S = \frac{(t_{c-out} - t_{c-in})}{(T_{H-in} - t_{c-in})}$$
Heat Transfer Equipment

Correction factor:

\[ \frac{T_{H1} - T_{H2}}{T_{c2} - T_{c1}} \]

Correction factor plot for exchanger with one shell pass and two, four, or any multiple of tube passes.

(b) Shell fluid

(b) Tube fluid

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Heat Transfer Equipment

Correction factor:

\[ z = \frac{T_{H_1} - T_{H_2}}{T_{c_2} - T_{c_1}} \]

\[ Y = \frac{T_{c_2} - T_{c_1}}{T_{H_1} - T_{c_1}} \]

(a)

(b)
Heat Transfer Equipment

Correction factor:


Figure 12.20. Temperature correction factor: two shell passes; four or multiples of four tube passes
Heat Transfer Equipment

Correction factor:


Figure 12.21. Temperature correction factor: divided-flow shell; two or more even-tube passes
Heat Transfer Equipment

Correction factor:


Figure 12.22. Temperature correction factor, split flow shell, 2 tube pass
Heat Transfer Equipment

Correction factor:


Figure 12.19. Temperature correction factor: one shell pass; two or more even tube 'passes
Heat Exchangers - Typical design

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties ($\rho$, $\mu$, $k$).
3) Decide on the type of exchanger.
4) Select a trial value for $U$.
5) Calculate the mean temperature difference, $\Delta T_m$.
6) Calculate area required.
7) Decide on the exchanger layout.
8) Calculate individual coefficients.
9) Calculate $U$. If significant difference from step (4), substitute in (4) and repeat.
10) Calculate the pressure drop. If it is not satisfactory, back to (7) or (4) or (3).
11) Optimise: repeat (4) to (10) to determine cheapest solution (usually smaller area).
Step (7): Shell and Tube Heat Exchangers

*Tube size:*
Length is standard, commonly 8, 12 or 16 ft.
Diameter: most common 3/4 or 1 in OD

*Tube pitch and clearance:*
Pitch is the shortest center-to-center distance between adjacent tubes. Commonly 1.25 to 1.5 time the tube diameter.

Clearance is the distance between tubes. It should be larger than 25% of the tube diameter.

Triangular or square arrangement of tubes are quite common.

*Baffles:*
Baffles are usually spaced between 20% and 80% of the ID of the shell.
Step (7): Shell and Tube Heat Exchangers

**Tube pitch and clearance:**

Triangular or square arrangement of tubes are quite common.

Sinnott & Towler, Chemical Engineering Design, Elsevier, 5\textsuperscript{th} edition, 2009

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Shell and Tube Heat Exchangers

Shell:
Up to 24 in nominal size, use standard pipes.

Passes:
Most usual pass is one (type E according to TEMA – Tubular Exchangers Manufacturing Association standards).
Split flow arrangement (types G and J) are used for pressure drop reduction, when the pressure drop is the controlling factor in the design.
Shell and Tube Heat Exchangers

Shell - baffles

Shell and Tube Heat Exchangers

**Fluid location:**
Corrosive fluids flow inside the tubes.
Fluid with higher fouling tendency inside the tubes.
High pressure fluid inside the tubes (if everything else the same).
Hot fluid inside the tubes.

**Typical velocities:**
Liquids: 1-2 m/s in tubes, max 4 m/s to reduce fouling.
  0.3 to 1 m/s in shell
Vapors: 50-70 m/s (vacuum), 10-30 m/s (1 bar),
  5-10 m/s (high P)
Shell and Tube Heat Exchangers - Design

- Tube side: Configuration (pitch, number of tubes, dimensions).
  - Heat transfer coefficient.
  - Pressure drop.

- Shell side: Configuration (dimensions, baffles).
  - Heat transfer coefficient.
  - Pressure drop.

Cost influenced by:
- Heat transfer area
- Tube diameter and length
- Pressure
- Material of construction
- Baffle type
- Special features, such as U bends, floating heads, fins etc.
Tube Side

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties ($\rho$, $\mu$, $k$).
4) Select a value for $U$.
5) Calculate the mean temperature difference, $\Delta T_m$. Use the correction factor, $F_t$.
6) Calculate area required.
7) Decide on the exchanger layout. Select one of the standard tube lengths and tube diameters. Calculate the number of tubes needed from the area estimated in (6). Decide on pitch.

Calculate bundle diameter from the following:

$$N_t = K_1 \left( \frac{D_b}{d_o} \right)^{n_1} \quad D_b = d_o \left( \frac{N_t}{K_1} \right)^{1/n_1}$$
Tube Side

$N_t$ is the number of tubes
$D_b$ is the bundle diameter
$d_o$ is the tube outside diameter

$$D_b = d_o \left( \frac{N_t}{K_1} \right)^{1/n_1}$$

Constants:

| Triangular pitch, $p_t = 1.25d_o$ |  |  |  |  |  |  |
|----------------------------------|---|---|---|---|---|
| No. passes | 1 | 2 | 4 | 6 | 8 |
| $K_1$     | 0.319 | 0.249 | 0.175 | 0.0743 | 0.0365 |
| $n_1$     | 2.142 | 2.207 | 2.285 | 2.499 | 2.675 |

<table>
<thead>
<tr>
<th>Square pitch, $p_t = 1.25d_o$</th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No. passes</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>$K_1$</td>
<td>0.215</td>
<td>0.156</td>
<td>0.158</td>
<td>0.0402</td>
<td>0.0331</td>
<td></td>
</tr>
<tr>
<td>$n_1$</td>
<td>2.207</td>
<td>2.291</td>
<td>2.263</td>
<td>2.617</td>
<td>2.643</td>
<td></td>
</tr>
</tbody>
</table>
Heat Transfer Equipment

Figure 12.10. Shell-bundle clearance

Heat Exchangers - Typical design

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties ($\rho$, $\mu$, $k$).
3) Decide on the type of exchanger.
4) Select a trial value for $U$.
5) Calculate the mean temperature difference, $\Delta T_m$
6) Calculate area required.
7) Decide on the exchanger layout.
8) Calculate individual coefficients.
9) Calculate $U$. If significant difference from step (4),
   substitute in (4) and repeat.
10) Calculate the pressure drop. If it is not satisfactory, back
    to (7) or (4) or (3).
11) Optimise: repeat (4) to (10) to determine cheapest solution
    (usually smaller area).
Tube Side

Use of the heat transfer factor, $j_h$, for transition and laminar flow:

$$Nu = j_h \text{ Re} \text{ Pr}^{0.33} \left( \frac{\mu}{\mu_w} \right)^{0.14}$$

See correlations in Chapter 20 of Welty et al. for internal forced convection.

9) Calculate pressure drop.
Use the friction factor, as for pipe flows, in the Fanning equation.
Heat Transfer Factor

Figure 12.23. Tube-side heat-transfer factor

9) Calculate pressure drop \((Peters & Timmerhaus, 4^{th}\, edition,\, 1991)\).

\[ \Delta P_i = \frac{B_i 2 f_i G^2 L n_p}{g_c \rho_i d_i \phi_i} \]

\(f_i\) is the friction factor for isothermal flow at the mean temperature

\(n_p\) is the number of tube passes

\(g_c\) is the unit conversion factor

\(\phi_i\) is a correction factor for non-isothermal flow

\[ \phi_i = 1.1 (\mu_i / \mu_w)^{0.25} \quad \text{for } Re < 2100 \]

\[ \phi_i = 1.02 (\mu_i / \mu_w)^{0.14} \quad \text{for } Re > 2100 \]

\(B_i\) is a correction factor for friction due to contraction, expansion and reversal of flow direction \((B_i > 1,\, \text{can use } 1.2)\)

\(G\) is the mass velocity inside the tube \((\text{mass/area time})\)
Shell Side

From the bundle diameter we have the shell diameter (step 7)!

10) Calculate shell side heat transfer coefficient. For turbulent flow outside the tubes:

\[
Nu = \frac{a_0}{F_s} \left( \frac{Re}{Pr} \right)^{0.6} \left( \frac{Pr}{Re} \right)^{0.33}
\]

\(Nu\) is the Nusselt number, \(Nu = h_o d_o / k_f\)

\(Re\) is the shell side Reynolds number, \(Re = G_s d_o / \mu\)

\(Pr\) is the shell side Prandtl number, \(Pr = C_p \mu / k_f\)

\(a_o = 0.33\) if the tubes are staggered and 0.26 if they are in line

\(F_s\) is a safety factor to account for bypassing (usually 1.6)

\(G_s\) is the mass velocity across tubes, based on the minimum free area between baffles.

Also see: Kern, “Process heat transfer”, McGraw Hill, 1950
11) Calculate pressure drop.

\[ \Delta P_o = \frac{B_o \cdot 2 f_o G_s^2 N_r}{g_c \rho_o} \]

\( f_o \) is the friction factor for the shell side

\[ f_o = b_o \left( \frac{d_o G_s}{\mu} \right)^{-0.15} \]

\( N_r \) is the number of rows of tubes
\( B_o \) is a correction factor for friction due to reversal of flow direction. It can be equal to the number of tube crossings (e.g., one when there are no baffles).

12) Now we can recalculate \( U \) and make a decision.
**HEAT EXCHANGERS- ON THE WEB!**

Tubular Exchanger Manufacturing Association (TEMA), Standards for H.E. design

http://www.tema.org/

Log-mean temperature difference

https://www.youtube.com/watch?v=AivvyYrPvtM

And:

https://www.youtube.com/watch?v=3DedKWNfM7Q

Also, other sites on YouTube.
MAIN POINTS

Heat transfer equipment

Concepts: Shell and tube heat exchangers
          Log-mean temperature difference
          T-Q heat exchanger diagrams
          Design steps

Chapter 22