Equipment Sizing and Specification: Shell and Tube Heat Exchangers

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• Safety Topic
• Heat Exchanger Geometry Fundamentals for Process Engineers
• Shell and Tube Heat Exchanger Design Software
• Process Engineering Workflow throughout the Project Cycle
• Demonstration
Safety Topic:
Don’t Let History Repeat Itself
On Jan. 29, 2016, the U.S. Chemical Safety and Hazard Investigation Board (CSB) issued a report and video animation of an April 17, 2013, explosion in an agricultural chemical storage facility in West, TX (Photos 1–3). The explosion caused 15 fatalities, more than 260 injuries, total destruction of the plant, and widespread destruction of the surrounding community.

A few days later, on Feb. 5, 2016, the Chinese government released a report on an Aug. 12, 2015, explosion in a chemical warehouse in Tianjin, China. That explosion caused more than 170 fatalities, over 700 injuries, and over a billion dollars in financial loss.

Both of these incidents occurred in warehouses that stored ammonium nitrate (AN), a common fertilizer, as well as a variety of other chemicals. And in both incidents, a fire exposed AN to high temperatures, causing the explosion. The CSB report explains some of the dangers associated with AN: “AN exhibits three main hazards in fire situations: uncontrollable fire, decomposition with formation of toxic gases, and explosion.”
**Did you know?**

- The CSB report on the West, TX, explosion identifies 32 other explosions involving AN that date back to 1916 (including the 2015 Tianjin, China, explosion). In total, these explosions caused nearly 1,500 fatalities and thousands of injuries.
- The CSB list of AN explosions includes an April 16, 1947, explosion on the ship *Grandcamp* in Texas City, TX, which caused approximately 500 fatalities and 3,000 injuries. This incident is considered to be the deadliest industrial disaster in U.S. history.

**What can you do?**

- You may not handle AN or other materials with the potential to cause catastrophic damage in your plant, but if you use any hazardous materials or operate at hazardous process conditions, you should be aware of and understand past incidents related to those materials or process conditions.
- Ask other engineers, managers, and veteran employees to share information about past incidents at your plant and at other plants like yours. Understand what is being done to prevent similar incidents.
- Search the Internet for past incidents related to the materials and processes in your plant.
- For other examples of repeat incidents, see the February 2014 and February 2016 Beacons.
Heat Exchanger Geometry Fundamentals for Process Engineers
• Resources for nomenclature/diagrams/guidelines
  – GPSA Databook Section 9
  – Perry’s Section 11 (Heat Transfer Equipment)
  – AIChe CEP or e-library
  – Company or plant specific design guides
Perry’s Chemical Engineers’ Handbook, 7th edition
FIG. 11-36  Heat-exchanger-component nomenclature. (a) Internal-floating-head exchanger with floating-head backing device. Type AES. (b) Fixed-tube-sheet exchanger. Type REM. (Standard of Tubular-Exchanger Manufacturers Association, 6th ed., 1978.)
Perry’s Chemical Engineers’ Handbook, 7th edition
FIG. 11-40  Baffle cuts. (a) Baffle cuts for single segmental baffles. (b) Baffle cuts for double segmental baffles. (c) Baffle cuts for triple segmental baffles.
Figure 2.16  Baffle plates.
**Effectively Design Shell and Tube Heat Exchangers, CEP Feb 1998, Mukherjee**

![Tube layout patterns](image)

*Figure 6. Tube layout patterns.*

Ford, Bacon & Davis, LLC 13
COMMON TUBE PASS LAYOUTS

Quadrant or Segment

Ribbon

H-banded
• Leakage streams
  – A stream
    • Flow between the tube and the tube hole in the baffle. Not detrimental but B stream is better
  – B stream
    • Not a “leakage stream”. This is where you want most of the flow
  – C stream
    • Bundle bypass stream
    • Hard to visualize. Flows around outer edge of the baffle.
  – E stream
    • Baffle to shell leakage. Flow that slips between the baffle and the shell
  – F stream
    • Pass partition leakage. Flow down/across the pass partition
Figure 11. Shellside flow distribution.

Effectively Design Shell and Tube Heat Exchangers, CEP Feb 1998, Mukherjee
Fouling

- Usually accounted for in a fouling factor
  - Fouling resistance on tube and shell
- Can be combined as a Total Equivalent Fouling Resistance (TEFR)
- Sometimes an “oversurface” factor is applied to area for fouling
- Carefully choose fouling factors to prevent oversizing
- Multiple fouling mechanisms but in general higher velocity leads to less fouling
Shell and Tube Heat Exchanger Design Software
• Software can be packaged as a suite of products.
  • Shell and Tube design and rating
  • Tube vibration analysis
  • Air Cooler design and rating
  • Others
    – Plate and frame, plate-fin, spiral plate, hairpin, jacketed pipe, and fired heater, etc.

• This presentation focuses on thermal and hydraulic design of shell and tube heat exchangers
• **Strengths**
  – Thermal rating/design
    • Calculate heat transfer coefficients (U) and film coefficients (h)
  – Hydraulic rating/design
  – Analyze temperature, pressure, velocity, $\rho v^2$ profiles/values in the exchanger
  – Quantify leakage streams
  – Conforming to TEMA standard
    • Defaults to TEMA standard for some inputs. Will warn if inputs don’t meet TEMA standards
  – Analyze boiling/condensation mechanisms
  – Analyze flow regimes in the exchanger
• Weaknesses (of the thermal/hydraulic module)
  – Mechanical
    • Do not trust mechanical calculations (tube, shell, nozzle, tubesheet thicknesses)
    • Have mechanical engineer check calculations
    • In general, these calculations and warnings seem to be conservative
  – Vibration
    • With a few exceptions, vibration analysis in shell and tube modules is conservative. If no warnings, then typically there is low risk of vibration issues.
    • Vibration warnings for existing exchangers should be investigated further (possibly FEA software).
  – Piping hydraulics (Reboilers only)
    • Recommend to check flow regimes and pressure drop calculations using other methods
• 3 different U values with different meanings

- \( U_{\text{SERVICE}} \)
  - Also called \( U_{\text{required}} \)
  - \( U_{\text{service}} = \frac{Q}{(A)(LMTD)(FT)} \)

- \( U_{\text{CALCULATED}} \) or \( U_{\text{ACTUAL}} \) or \( U_{\text{FOULED}} \)
  - \( U_{\text{calculated}} = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o} + \frac{1}{r_i} + \frac{1}{r_o} + \frac{x}{k}} \)

- \( U_{\text{CLEAN}} \)
  - \( U_{\text{clean}} = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o} + \frac{x}{k}} \)
• Typically, software can be run in different modes
  – Design Mode
    • Based on a minimum number of inputs, will vary shell diameter, baffle spacing, tubepasses, tube length, etc.
    • Will run short cut calculations on every possible combination and output a table with results
    • Pick the best option, and run rigorous calculations in Rating mode
Rating Mode

- Specify exchanger inlet conditions and outlet conditions of one side
  - Alternately, overall duty can be specified instead of outlet condition
- Used to evaluate existing exchanger or quantify new exchanger overdesign
- Based on a given geometry, calculates all three U values

\[
\text{Overdesign} = \left( \frac{U_{\text{calculated}}}{U_{\text{service}}} - 1 \right) \times 100\%
\]

- Note that overdesign and Total Equivalent Fouling Resistance (TEFR) are not the same.
Simulation Mode

• Specify exchanger inlet conditions
  – Has one less degree of freedom than Rating mode
• Used to estimate how exchanger will perform at a certain set of process conditions or degree of fouling
• Very useful for relief calculations
• Program will iterate until overdesign is zero
  – Usually converges to +/- 2% overdesign

\[ U_{\text{calculated}} = U_{\text{service}} \]

\[ \frac{Q}{(A)(LMTD)(FT)} = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o} + \frac{1}{r_i} + \frac{1}{r_o} + \frac{L}{k}} \]
• Specifying fluid and thermodynamic properties
  – User specified grid
    • Table of Properties vs. Temperature are given at multiple pressures.
    • Program will interpolate. Specify pressures and temperatures that bracket the operating conditions (both bulk and tube wall) to prevent extrapolation.
    • Manually type in properties
    • Copy/paste from Excel
    • Import from process simulation software
      – Input composition and generate properties through simulator Thermo engine
      – Select a stream from an existing simulation
  – Program Calculated
    • Composition is input into program
    • Choose between design software thermo or attach thermo from process simulation
    • Software will calculate all the properties it requires as the program is run
    • This option typically requires more calculation time.
• Vibration
  – For new exchanger, make sure software does not identify any potential vibration issues
  – For existing exchangers, perform further analysis if program gives warnings on:
    • Fluid-elastic instability
    • Critical velocity
    • Vortex shedding
    • Longest Unsupported Tube Span in U-Bend
    • High $\rho v^2$ (this is also an erosion issue)
  – Acoustic vibration is tricky to predict and to mitigate
Process Engineering Workflow throughout the Project Cycle
• **FEL-0 / FEL-1**
  – Estimate required surface area for cost estimate
  – May or may not use design software

• **FEL-2**
  – Estimate required surface area for cost estimate
  – Preliminary sizing (“rough-in” a design for development of P&IDs and other deliverables)
  – Use design mode

• **FEL-3**
  – Datasheet
  – Comparing technical offerings of multiple vendors
  – Evaluations of preliminary vendor information
  – Some clients request that EPC firms do rigorous sizing
  – Use rating mode

• **Detailed Design**
  – Checking of vendor design and documents
• FEL-0 / FEL-1
  – Use heat and mass balance or simulation for duty and LMTD
  – Use tables in Perry’s, GPSA, etc. for typical U values
  – Calculate surface area
    • \(Q = UA(LMTD)\)
    • \[ A = \frac{Q}{(U)(LMTD)} \]
  – Alternately, use quick sizing tool in process simulation if typical value can’t be found
• FEL-2
  – For simple exchangers,
    • Fill out datasheet
    • Update any calculations from FEL-1 based on updated heat and mass balance, etc.
    • Can use the same typical U value as before or can run design software to get a better estimate
  – For more complex exchangers,
    • like thermosiphons, heat exchangers in networks, any fluids with skin temperature limits, applications with 2-phase flow, etc.,
    • Run a very preliminary design software calculation to start developing what the exchanger will look like on P&IDs (e.g. number of shells in parallel/series, temperature control scheme, etc.)
    • Run off-design cases in rating/simulation mode to troubleshoot possible issues
    • This can help to head off any issues that may come as a surprise later
• FEL-3/Detailed Design
  – For most clients, at this point the vendor does the heavy lifting and EPC firm reviews and check-rates the vendor drawings
  – Some clients prefer that the EPC firm process and/or mechanical engineers do extensive work on exchanger design to fully specify the exchanger (e.g. tubes, baffles, shell size, tie rods, sealing strips, skid bars, etc.). The vendor receives the design, develops drawings, and builds the exchanger. Be careful to explicitly state who, if anyone, will provide thermal or hydraulic guarantee
Demonstration
• Demonstration
  – Design of E-4 in HYSYS Example File “MODELING A CRUDE VACUUM SYSTEM WITH PREHEAT TRAIN.hsc”
  – Crude vs. Diesel Product Exchanger
  – TEMA Type AES
  – 1” BWG 12 tubes
  – Diesel fouling factor = 0.0015 hr-sqft-F/Btu
  – Crude fouling factor = 0.003 hr-sqft-F/Btu
<table>
<thead>
<tr>
<th>Liquid-liquid media</th>
<th>Shell side</th>
<th>Tube side</th>
<th>Design U</th>
<th>Includes total dirt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aroclor 1248</td>
<td>Water</td>
<td>Jet fuels</td>
<td>100–150</td>
<td>0.0015</td>
</tr>
<tr>
<td>Cutback asphalt</td>
<td>Water</td>
<td>10–20</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Demineralized water</td>
<td>Water</td>
<td>300–500</td>
<td></td>
<td>0.001</td>
</tr>
<tr>
<td>Ethanol amine (MEA or DEA) 10–25% solutions</td>
<td>Water or DEA, or MEA solutions</td>
<td>140–200</td>
<td>0.003</td>
<td></td>
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<tr>
<td>Fuel oil</td>
<td>Water</td>
<td>15–25</td>
<td></td>
<td>0.007</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>Oil</td>
<td>10–15</td>
<td></td>
<td>0.008</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Water</td>
<td>60–100</td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>Heavy oils</td>
<td>Heavy oils</td>
<td>10–40</td>
<td></td>
<td>0.004</td>
</tr>
<tr>
<td>Heavy oils</td>
<td>Water</td>
<td>15–50</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Hydrogen-rich reformer stream</td>
<td>Hydrogen-rich reformer stream</td>
<td>90–120</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Kerosene or gas oil</td>
<td>Water</td>
<td>25–50</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Kerosene or gas oil</td>
<td>Oil</td>
<td>20–35</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Kerosene or jet fuels</td>
<td>Trichlorethylene</td>
<td>40–50</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>Jacket water</td>
<td>Water</td>
<td>230–300</td>
<td></td>
<td>0.002</td>
</tr>
<tr>
<td>Lube oil (low viscosity)</td>
<td>Water</td>
<td>25–50</td>
<td></td>
<td>0.002</td>
</tr>
<tr>
<td>Lube oil (high viscosity)</td>
<td>Water</td>
<td>40–80</td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>Lube oil</td>
<td>Oil</td>
<td>11–20</td>
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<td>0.006</td>
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<tr>
<td>Naphtha</td>
<td>Water</td>
<td>50–70</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Naphtha</td>
<td>Oil</td>
<td>25–35</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Organic solvents</td>
<td>Water</td>
<td>50–150</td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>Organic solvents</td>
<td>Brine</td>
<td>35–90</td>
<td></td>
<td>0.003</td>
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<tr>
<td>Organic solvents</td>
<td>Organic solvents</td>
<td>20–60</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Tall oil derivatives, vegetable oil, etc.</td>
<td>Water</td>
<td>20–50</td>
<td></td>
<td>0.004</td>
</tr>
<tr>
<td>Water</td>
<td>Caustic soda solutions (10–30%)</td>
<td>100–250</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>Water</td>
<td>200–250</td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>Wax distillate</td>
<td>Water</td>
<td>15–25</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>Wax distillate</td>
<td>Oil</td>
<td>13–23</td>
<td></td>
<td>0.005</td>
</tr>
</tbody>
</table>
• Estimate area with typical U
  • U = 20 to 35 Btu/F-sqft-hr
    – Q=10.4 MMBTUH, LMTD=320 F
    – A= 929 to 1625 sq. ft (plus design margin)

• Use quick sizing tool

• Use design software in design mode
Questions, Comments, or Suggestions?
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