General Description

You have been tasked to design a new shell-and-tube heat exchanger for the chemical plant in which you work. The heat exchanger will utilize cooling water to cool Syltherm 800 (a heat transfer fluid).

The Syltherm 800 is used in a certain process as a cooling medium, as the process operates at too high of a temperature to use water. The flow rate of Syltherm is 1,000,000 $\frac{\text{lb}_\text{m}}{\text{hr}}$, and it exits the process at 500 °F. It must be cooled to 180 °F before being recycled to the process.

The cooling water used to cool the Syltherm 800 is available at 65 °F. For safety reasons, the maximum allowable water effluent temperature is 120 °F.

As a minimum, the following will need to be determined for this heat exchanger:

- Which fluid is on shell-side/tube-side
- Number of shell passes
- Number of tube passes
- Number of tubes
- Tube pitch (center-to-center distance between tubes)
- Tube size (ID and OD)
- Shell size (ID only)
- Total heat transfer area required
- Length of the tube passes (can't be too long!)

When designing your heat exchanger, keep in mind the following:

- It must be reasonably sized. If you get a tube length required of 1.5 km, something is very wrong in your design (perhaps add more tubes?). Conversely, if you get a length of 5 cm, you probably have too many tubes.
- Pay attention to the pressure drop through both the shell side and tube side. Part of your analysis will need to be the cost of the electricity for the pumps to pump the fluid through the heat exchanger.
- Don't forget to add in some fouling allowances in your overall heat transfer coefficient calculation

As heat exchangers can be rather expensive to purchase and cooling water isn't free, your boss would like you to try to optimize the design, both in terms of capital cost (i.e. the purchase cost of the heat exchanger) and operating costs (cooling water and electricity to drive both the shell-side and tube-side pumps).

Shell-and-Tube Heat Exchanger Costs

Installed equipment cost = $3.8822 * C_p^o$
where $\log_{10}\left(C_p^o\right) = 4.3247 - 0.303\log_{10}(A) + 0.1634\left[\log_{10}(A)\right]^2$
A = heat exchanger area in m^2 ($10 < A < 1000$)
Note, this is *per shell pass*. So a heat exchanger with 2 shell passes and a total area of $100\,m^2$ would calculate C_p^o for A=$50\,m^2$, and multiply the cost by 2.

Utility Costs

- Electricity - $0.06 per kWh
- Cooling water - $0.12 per thousand gallons
  - Note that the water is being recycled. This is the cost of cooling it back down to 65 °F

Some Useful Information

- **Shell-and-Tube Correction Factor**
  The correction factor for shell-and-tube heat exchangers may be calculated analytically instead of using the charts. The formulas are (F_{1-2} is for 1 shell pass, F_{2-4} is for 2 shell pass):

$$F_{1-2} = \frac{\left[\frac{\sqrt{R^2+1}}{R-1}\right]\ln\left(\frac{1-P}{1-PR}\right)}{\ln\left[\frac{A+\sqrt{R^2+1}}{A-\sqrt{R^2+1}}\right]}$$

$$F_{2-4} = \frac{\left[\frac{\sqrt{R^2+1}}{2(R-1)}\right]\ln\left(\frac{1-P}{1-PR}\right)}{\ln\left[\frac{A+B+\sqrt{R^2+1}}{A+B-\sqrt{R^2+1}}\right]}$$

where $A = \frac{2}{P} - 1 - R$, $\quad B = \frac{2}{P}\sqrt{(1-P)(1-PR)}$

- **Shell Side Heat Transfer Coefficient**
  The heat transfer coefficient for the shell side can be found using:

$$Nu = \frac{h_o D_o}{k} = C \, \mathrm{Re}^n \, \mathrm{Pr}^{1/3}$$

The Reynolds number $\mathrm{Re} = \frac{D_o V_{max} \rho}{\mu}$, where D_o is the outside diameter of a tube. V_{max} is the "maximum" velocity of the fluid through the tube bank. To find it, first, the cross-flow area must be evaluated. This is given as $\text{Cross flow area} = \text{Shell ID} \times \text{Baffle spacing} \times \frac{\text{clearance}}{\text{pitch}}$

The clearance $l = S_n - D_o$. When the volumetric flow rate of the shell-side fluid is divided by the cross-flow area defined here, it yields the "maximum velocity" through the tube bank, V_{max}. The symbols k, ρ, and μ represent the thermal conductivity, density, and viscosity of the shell-side fluid, respectively, and all the properties should be evaluated at the arithmetic average temperature of that fluid between the two end temperatures. The symbol Pr stands for the Prandtl number of the shell-side fluid. The exponent n and the multiplicative constant C depend on the pitch to tube OD ratio, and are given in a table provided in Holman's book. An excerpt from the table for tubes on a rectangular pitch (in-line tube rows) is given below.

Values of the constant C

S_n / D_o	1.25	1.5	2.0	3.0
S_p / D_o				
1.25	0.386	0.305	0.111	0.0703
1.5	0.407	0.278	0.112	0.0753
2.0	0.464	0.332	0.254	0.220
3.0	0.322	0.396	0.415	0.317

Values of the constant n

S_n / D_o	1.25	1.5	2.0	3.0
S_p / D_o				
1.25	0.592	0.608	0.704	0.752
1.5	0.586	0.620	0.702	0.744
2.0	0.570	0.602	0.632	0.648
3.0	0.601	0.584	0.581	0.608

Note: for this project, assume that $S_n = S_p$ (i.e. that the tubes are arranged in a square pitch)

- **Shell Side Pressure Drop**
  Assume that the viscosity ratio $\left(\frac{\mu}{\mu_s}\right)$ in the following equation is equal to 1.

The pressure drop on the shell-side is calculated using

$$\Delta P_{shell} = \frac{2 f G_s^2 D_s (N_B + 1)}{\rho D_e \left(\frac{\mu}{\mu_s} \right)^{0.14}}$$

In this equation, f is a Fanning friction factor for flow on the shell side given in Figure 8-10 of the book , G_s is the mass velocity on the shell side, D_s is the inside diameter of the shell, N_B is the number of baffles, ρ is the density of the shell-side fluid, and D_e is an equivalent diameter. The mass velocity $G_s = m / S_m$, where m is the mass flow rate of the fluid, and S_m is the crossflow area measured close to the central symmetry plane of the shell containing its axis. This area is defined as

$$\text{Cross flow area} = D_s\ L_B \times \frac{\text{clearance}}{\text{pitch}}$$

where L_B is the baffle spacing, and the clearance and pitch are defined in the notes on shell-and-tube heat exchangers. The equivalent diameter is defined as follows.

$$D_e = \frac{4\left(C_p S_n^2 - \frac{\pi D_0^2}{4} \right)}{\pi D_0}$$

Here, D_0 is the outside diameter of the tubes, and S_n is the pitch (center-to-center distance) of the tube assembly. The constant $C_p = 1$ for a square pitch, and $C_p = 0.86$ for a triangular pitch. The friction factor f is given in Figure 14-44 of the book as a function of the Reynolds number based on the equivalent diameter (Note the difference from the Reynolds number that we use for the heat transfer coefficient from Holman, which uses D_0 as the length scale). For the friction factor graph, we must use the Reynolds number Re defined as

$$\text{Re} = \frac{D_e G_s}{\mu}$$

where μ is the viscosity of the shell-side fluid.

- **Number of Tubes in Shell**
  Determining the maximum number of tubes of a certain size that can fit in a shell of a certain size can be a difficult process.[1] I suggest using the following website to determine the number of tubes that can fit in your heat exchanger's shell:
  http://www.engineeringtoolbox.com/smaller-circles-in-larger-circle-d_1849.html
  Remember that if your heat exchanger has n tubes and m passes, the number of tubes that must fit in the shell is $n * m$. (e.g. If you have a heat exchanger with 100 tubes and 2 passes, the shell must be able to fit 200 tubes)

[1] Google "Circle Packing" if you're interested in learning more about the process

Report Requirements

You should produce a short, but formal, report describing your results and summarizing the design parameters of the heat exchanger (number of passes, number of tubes, etc). A suggested format is given below. Your grade will be based on how well your heat exchanger is optimized as well as your justification and explanation of your design in your report.

Report Format

Your report should include (at a minimum):

- Title Page:

  Title of report
  Your name
  Date

- Table of contents
- Introduction
  - Charge (what you were told to do)
  - Scope (What you did, i.e. design a heat exchanger)
- Premises and Assumptions
  - Divide into project premises (what you were told) and design assumptions (what was assumed during design)
- Results, Conclusions, and Recommendations
  - Divide results into process (e.g. # of tubes, size of shell, etc) and economic (the heat exchanger costs this much to buy and this much to run each year). Explain how you came up with your recommended design.
  - Also discuss trade-offs you made in your design (e.g. more tubes make the initial cost more, but lower the electricity required by the tube-side pump)
  - Recommendations include additional work required
- Appendices
  - Any supporting calculations