Shell-and-Tube Heat Exchanger Design

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A lot has been written about designing heat exchangers, and specifically, shell-and-tube heat exchangers. For example, the book by Kern (1) published in 1950 details basic design procedures for a variety of heat exchangers. Since the publication of that book, with the advent of computers, design procedures have become sophisticated even though the basic goals of design remain the same. Because it is possible to specify an infinite number of different heat exchangers that would perform the given service (heat load), we have to identify the specific heat exchanger that would do it subject to certain constraints. These constraints can be based on allowable pressure drop considerations either on the shell-side or on the tube-side or both, and usually include that of minimizing the overall cost. An article in 1979 by Taborek (2) outlines how heat exchanger design techniques evolved over the years since the appearance of the book by Kern. More recent developments are discussed in numerous articles in the magazine "Chemical Engineering."

Here is a step-by-step approach to specifying a new shell-and-tube heat exchanger. We shall focus on sensible heat transfer, and make extensive use of Chapter 11 in Perry's Handbook (3). From hereon, references to page numbers, table numbers, and equation numbers are from Perry's Handbook.

Usually, the flow rates and the physical properties of the two streams involved are specified, and the temperatures at which the fluids are available are known. If the outgoing temperature of one of the streams is not specified, usually a constraint (e.g. the temperature of the cooling water cannot exceed $99^\circ C$) is given. Then, by an energy balance, the outgoing temperature of the second stream can be calculated along with the heat duty.

Size

1. The heat duty Q is usually fixed by the required service. The selected heat exchanger has to meet or exceed this requirement.

2. Make an approximate estimate of the size of the heat exchanger by using a reasonable guess for the overall heat transfer coefficient. For typical shell-and-tube heat exchangers in a chemical process or a refinery, Tables 11-3 and 11-4 can be used as a starting point for the estimate. Using this estimate, calculate the heat transfer area A. This will give you an idea of the approximate size of the heat exchanger, and therefore its cost. Based on the cost, a determination is made on how much time is worth investing in a detailed design.

3. Select the stream that should be placed on the tube side. The tube side is used for the fluid that is more likely to foul the walls, more toxic or more corrosive, or for the fluid with the higher pressure. Cleaning of the inside of the tubes is easier than cleaning the outside. When a gas or vapor is used as a heat exchange fluid, it is typically introduced on the shell side. Also, high

viscosity liquids, for which the pressure drop for flow through the tubes might be prohibitively large, can be introduced on the shell side.

4. The next step is to determine the approximate number of tubes N_t needed to do the job. Because we have an idea of the approximate heat transfer area, we can write

$$A = N_t \left(\pi D_o \right) L$$

where D_o is the OD of a tube, and L is its length. Both of these are only available in discrete increments. For example, the length is selected as 8, 10, 12, 16, or 20 feet. Likewise, the OD is specified as $\frac{1}{4}, \frac{3}{8}, \frac{1}{2}, \frac{5}{8}, \frac{3}{4}, 1, 1\frac{1}{4}$, or $1\frac{1}{2}$ inch. The tubes are typically specified to be 14 BWG. The most common tube lengths are 16 and 20 feet and the most common tube OD values are 3/4 and 1 inch. So, selecting one of the values in each set will get you started in estimating the approximate number of tubes. Check the velocity through a single tube; it should not exceed roughly 10 *ft/s* for liquids, to keep the pressure drop under reasonable constraints, but it should be at least 1 to 3 *ft/s* (the specific choice depends on the viscosity as well) to maintain turbulent flow, and minimize fouling. If necessary, adjust the number of tube passes to get the velocity to fall in this range. You can learn more about tubes and the tube-side construction from pages 11-40 to 11-41.

5. Determine the shell size. To do this, once the number of tubes is known, select a pitch and the number of passes. Typical initial guesses are 1 or 2 tube passes. A square pitch is chosen for reasons of convenience in cleaning the outside of the tubes; when the tubes are in-line, cleaning is relatively straightforward. The standard choice is a pitch equal to 1.25 inches for 1-inch OD tubes, and a pitch of 1 inch for 3/4 –inch OD tubes. Tubes on a triangular pitch cannot be cleaned by tools, but rather by passing a chemical solution through on the shell-side. Because triangular pitches allow for the packing of more tubes into a given space, they are more common when cleaning the outside is not a major issue. Rectangular pitches are uncommon. Knowing the number of tubes to be used and the number of passes, you can select the required shell size. You can use the tube count table I have posted on the course web page for settling on a suitable shell size. Note that you cannot find exactly the number of tubes you estimated in this table; so, you should use the next higher discrete number that is available for the tube count.

An alternative approach is to use the method discussed in Perry's Handbook. For this, you need to know about the clearance that must be allowed between the tube bundle and the shell inside diameter. The values of this clearance for different ranges of shell ID values are discussed in page 11-36. Then, you can use Equations (11.75a-d) on page 11-41 for a square pitch, or Equations (11.74a-d) on the same page for a triangular pitch. In either case, you need to specify the number of tube-side passes.

A 1-pass shell is the most common in use, but sometimes a 2-pass shell can be specified to improve thermal effectiveness. Shells are made from commercial steel pipes up to an outside diameter of 24 inches. Shells with a larger OD are made by rolling steel plate and welding.

6. You need to estimate the number of baffles to be used and the spacing among them. You can read about baffles from pages 11-42 and 11-43. Normally, baffles are equally spaced. The minimum baffle spacing is one-fifth of the shell diameter, but not less than 2 inches, and the maximum is determined by considerations involving supporting the tube bundle. A simple formula from Perry for estimating the maximum is $74\,D_o^{0.75}$ inches, where D_o is the OD of a tube measured in inches. The number of baffles is $\left(L/\text{Baffle Spacing}\right)-1$, where L stands for tube length; the number of baffles must, of course, be an integer.

7. Now, we are ready to check the thermal performance of the selected heat exchanger. Calculate the tube-side and shell-side heat transfer coefficients, the tube wall contribution to the resistance, and the appropriate fouling resistances. See if the calculated U_o matches the required U_o that you used for estimating the heat transfer area. If it is too small, start all over again! If it is too large, then the heat exchanger is over-specified for the required thermal duty.

If the calculated U_o is too small, you need to examine whether the tube-side or the shell-side resistance is controlling (sometimes they are comparable). Remember that the smaller the heat transfer coefficient, the larger the resistance to heat transfer. If you want to improve the shell-side heat transfer, try adjusting the baffle spacing and shell diameter to increase the shell-side mass velocity and therefore the Reynolds number. Also, for a given D_o, the pitch will play a role in influencing the Nusselt number. On the tube-side, the number of tubes and passes and the inside diameter can be varied to influence the Reynolds number and therefore the heat transfer coefficient.

Cost

This topic is discussed in my notes on "Shell-and-tube Heat Exchangers." Follow the procedure outlined there to evaluate the capital cost. Then, evaluate the pressure drop on the tube-side and that on the shell-side and work out the operating cost. You can use a figure of \$ 0.06/KWH for the cost of electricity needed. By writing off the capital cost over a reasonable lifetime for a heat exchanger, you can then work out a combined yearly cost and compare your alternate designs on a cost-basis.

References

1. Kern, D.Q. , *Process Heat Transfer*, McGraw-Hill, New York, 1950.

2. Taborek, J., Evolution of heat exchanger design techniques, *Heat Transfer Eng.* **1**, No. 1, 15-29 (1979).

3. Perry, R.H., Green, D.W., Eds. *Perry's Chemical Engineers' Handbook*, 7th Edition, McGraw-Hill, New York, 1997.

4. Phadke, P.S., Determining tube counts for shell-and-tube exchangers, *Chemical Engineering*, September 3, 1984, pp. 65-68.