Effectively Design Shell-and-Tube Heat Exchangers

To make the most of exchanger design software, one needs to understand STHE classification, exchanger components, tube layout, baffling, pressure drop, and mean temperature difference.

Rajiv Mukherjee,
Engineers India Ltd.

Thermal design of shell-and-tube heat exchangers (STHEs) is done by sophisticated computer software. However, a good understanding of the underlying principles of exchanger design is needed to use this software effectively.

This article explains the basics of exchanger thermal design, covering such topics as: STHE components; classification of STHEs according to construction and according to service; data needed for thermal design; tubeside design; shellside design, including tube layout, baffling, and shellside pressure drop; and mean temperature difference. The basic equations for tubeside and shellside heat transfer and pressure drop are well-known; here we focus on the application of these correlations for the optimum design of heat exchangers. A followup article on advanced topics in shell-and-tube heat exchanger design, such as allocation of shellside and tubeside fluids, use of multiple shells, overdesign, and fouling, is scheduled to appear in the next issue.

Components of STHEs

It is essential for the designer to have a good working knowledge of the mechanical features of STHEs and how they influence thermal design. The principal components of an STHE are:

- shell;
- shell cover;
- tubes;
- channel;
- channel cover;
- tubesheet;
- baffles; and
- nozzles.

Other components include tie-rods and spacers, pass partition plates, impingement plate, longitudinal baffle, sealing strips, supports, and foundation.

The Standards of the Tubular Exchanger Manufacturers Association (TEMA) *(1)* describe these various components in detail.

An STHE is divided into three parts: the front head, the shell, and the rear head. Figure 1 illustrates the TEMA nomenclature for the various construction possibilities. Exchangers are described by the letter codes for the three sections — for example, a BFL exchanger has a bonnet cover, a two-pass shell with a longitudinal baffle, and a fixed-tubesheet rear head.

Classification based on construction

Fixed tubesheet. A fixed-tubesheet heat exchanger (Figure 2) has straight tubes that are secured at both ends to tubesheets welded to the shell. The construction may have removable channel covers (*e.g.,* AEL), bonnet-type channel covers (*e.g.,* BEM), or integral tubesheets (*e.g.,* NEN).

The principal advantage of the fixed-tubesheet construction is its low cost because of its simple construction. In fact, the fixed tubesheet is the least expensive construction type, as long as no expansion joint is required.

Other advantages are that the tubes can be cleaned mechanically after removal of

 ©Copyright 1997 American Institute of Chemical Engineers. All rights reserved. Copying and downloading permitted with restrictions.

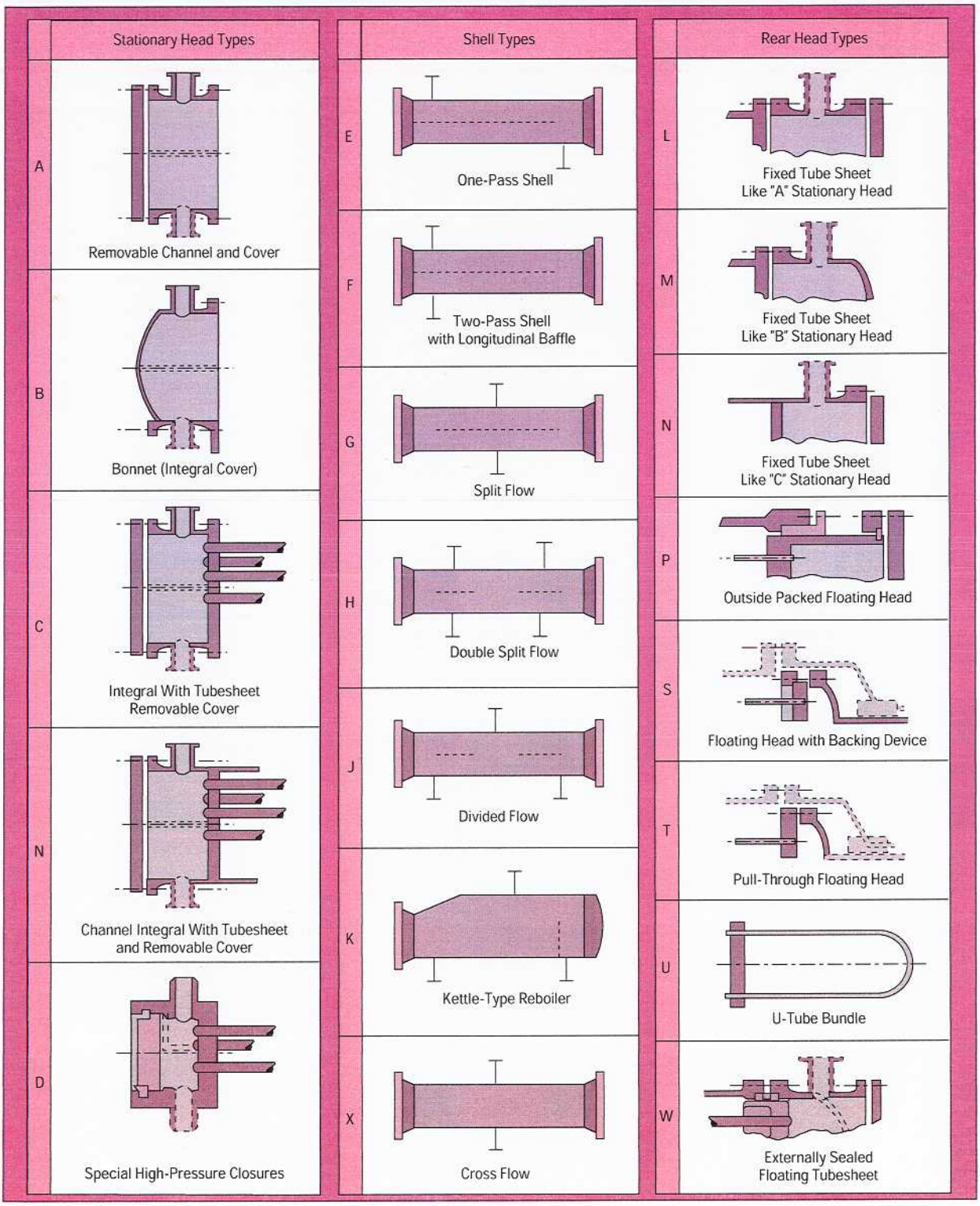


Figure 1. TEMA designations for shell-and-tube heat exchangers.

the channel cover or bonnet, and that leakage of the shellside fluid is minimized since there are no flanged joints.

A disadvantage of this design is that since the bundle is fixed to the shell and cannot be removed, the outsides of the tubes cannot be cleaned mechanically. Thus, its application is limited to clean services on the shellside. However, if a satisfactory chemical cleaning program can be employed, fixed-tubesheet construction may be selected for fouling services on the shellside.

In the event of a large differential temperature between the tubes and the shell, the tubesheets will be unable to absorb the differential stress, thereby making it necessary to incorporate an expansion joint. This takes away the advantage of low cost to a significant extent.

U-tube. As the name implies, the tubes of a U-tube heat exchanger (Figure 3) are bent in the shape of a U. There is only one tubesheet in a U-tube heat exchanger. However, the lower cost for the single tubesheet is offset by the additional costs incurred for the bending of the tubes and the somewhat larger shell diameter (due to the minimum U-bend radius), making the cost of a U-tube heat exchanger comparable to that of a fixed-tubesheet exchanger.

The advantage of a U-tube heat exchanger is that because one end is free, the bundle can expand or contract in response to stress differentials. In addition, the outsides of the tubes can be cleaned, as the tube bundle can be removed.

The disadvantage of the U-tube construction is that the insides of the tubes cannot be cleaned effectively, since the U-bends would require flexible-end drill shafts for cleaning. Thus, U-tube heat exchangers should not be used for services with a dirty fluid inside tubes.

Floating head. The floating-head heat exchanger is the most versatile type of STHE, and also the costliest. In this design, one tubesheet is fixed relative to the shell, and the other is free to "float" within the shell. This permits free expansion of the tube bundle, as well as cleaning of both the insides and outsides of the tubes. Thus, floating-head SHTEs can be used for services where both the shellside and the tubeside fluids are dirty — making this the standard construction type used in dirty services, such as in petroleum refineries.

There are various types of floating-head construction. The two most common are the pull-through with backing device (TEMA S) and pull-through (TEMA T) designs.

The TEMA S design (Figure 4) is the most common configuration in the chemical process industries (CPI). The floating-head cover is secured against the floating tubesheet by bolting it to an ingenious split backing ring. This floating-head closure is located beyond the end of the shell and contained by a shell cover of a larger diameter. To dismantle the heat exchanger, the shell cover is removed first, then the split backing ring, and then the floating-head cover, after which the tube bundle can be removed from the stationary end.

In the TEMA T construction (Figure 5), the entire tube bundle, including the floating-head assembly, can be removed from the stationary end, since the shell diameter is larger than the floating-head flange. The floating-head cover is bolted directly to the floating tubesheet so that a split backing ring is not required.

The advantage of this construction is that the tube bundle may be removed from the shell without removing either the shell or the floating-head cover, thus reducing maintenance time. This design is particularly suited to kettle reboilers having a dirty heating medium where U-tubes cannot be employed. Due to the enlarged shell, this construction has the highest cost of all exchanger types.

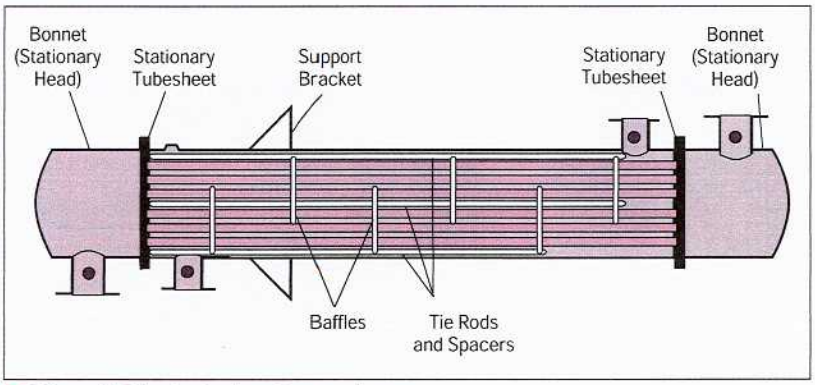


Figure 2. Fixed-tubesheet heat exchanger.

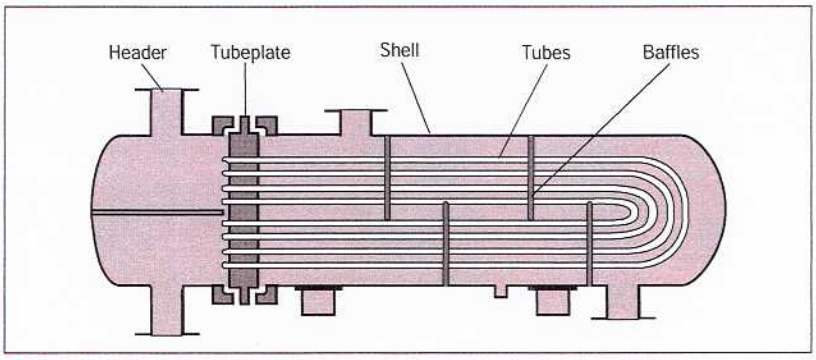


Figure 3. U-tube heat exchanger.

There are also two types of packed floating-head construction — outside-packed stuffing-box (TEMA P) and outside-packed lantern ring (TEMA W) (see Figure 1). However, since they are prone to leakage, their use is limited to services with shellside fluids that are nonhazardous and nontoxic and that have moderate pressures and temperatures (40 kg/cm^2 and 300°C).

Classification based on service

Basically, a service may be single-phase (such as the cooling or heating of a liquid or gas) or two-phase (such as condensing or vaporizing). Since there are two sides to an STHE, this can lead to several combinations of services.

Broadly, services can be classified as follows:

- single-phase (both shellside and tubeside);
- condensing (one side condensing and the other single-phase);
- vaporizing (one side vaporizing and the other side single-phase); and
- condensing/vaporizing (one side condensing and the other side vaporizing).

The following nomenclature is usually used:

Heat exchanger: both sides single-phase and process streams (that is, not a utility).

Cooler: one stream a process fluid and the other cooling water or air.

Heater: one stream a process fluid and the other a hot utility, such as steam or hot oil.

Condenser: one stream a condensing vapor and the other cooling water or air.

Chiller: one stream a process fluid being condensed at sub-atmospheric temperatures and the other a boiling refrigerant or process stream.

Reboiler: one stream a bottoms stream from a distillation column and the other a hot utility (steam or hot oil) or a process stream.

This article will focus specifically on single-phase applications.

Design data

Before discussing actual thermal design, let us look at the data that must be furnished by the process licensor before design can begin:

1. flow rates of both streams.

2. inlet and outlet temperatures of both streams.

3. operating pressure of both streams. This is required for gases, especially if the gas density is not furnished; it is not really necessary for liquids, as their properties do not vary with pressure.

4. allowable pressure drop for both streams. This is a very important parameter for heat exchanger design. Generally, for liquids, a value of 0.5–0.7 kg/cm^2 is permitted per shell. A higher pressure drop is usually warranted for viscous liquids, especially in the tubeside. For gases, the allowed value is generally 0.05–0.2 kg/cm^2, with 0.1 kg/cm^2 being typical.

5. fouling resistance for both streams. If this is not furnished, the designer should adopt values specified in the TEMA standards or based on past experience.

6. physical properties of both streams. These include viscosity, thermal conductivity, density, and specific heat, preferably at both inlet and outlet temperatures. Viscosity data must be supplied at inlet and outlet temperatures, especially for liquids, since the variation with temperature may be considerable and is irregular (neither linear nor log-log).

7. heat duty. The duty specified should be consistent for both the shellside and the tubeside.

8. type of heat exchanger. If not furnished, the designer can choose this based upon the characteristics of the various types of construction described earlier. In fact, the designer is normally in a better position than the process engineer to do this.

9. line sizes. It is desirable to match nozzle sizes with line sizes to avoid expanders or reducers. However, sizing criteria for nozzles are usually more stringent than for lines, especially for the shellside inlet. Consequently, nozzle sizes must sometimes be one size (or even more in exceptional circumstances) larger than the corresponding line sizes, especially for small lines.

10. preferred tube size. Tube size is designated as O.D. × thickness × length. Some plant owners have a preferred O.D. × thickness (usually based upon inventory considerations), and the available plot area will determine the maximum tube length. Many plant owners prefer to standardize all three dimensions, again based upon inventory considerations.

11. maximum shell diameter. This is based upon tube-bundle removal requirements and is limited by crane capacities. Such limitations apply only to exchangers with removable tube bundles, namely U-tube and floating-head. For fixed-tubesheet exchangers, the only limitation is the manufacturer's fabrication capability and the availability of components such as dished ends and flanges. Thus, floating-head heat exchangers are often limited to a shell I.D. of 1.4–1.5 m and a tube length of 6 m or 9 m, whereas fixed-tubesheet heat exchangers can have shells as large as 3 m and tubes lengths up to 12 m or more.

12. materials of construction. If the tubes and shell are made of identical materials, all components should be of this material. Thus, only the shell and tube materials of construction need to be specified. However, if the shell and tubes are of different metallurgy, the materials of all principal components should be specified to avoid any ambiguity. The principal components are shell (and shell cover), tubes, channel (and channel cover), tubesheets, and baffles. Tubesheets may be lined or clad.

13. special considerations. These include cycling, upset conditions, alternative operating scenarios, and whether operation is continuous or intermittent.

Tubeside design

Tubeside calculations are quite straightforward, since tubeside flow