1.4. Construction of Shell and Tube Heat Exchangers

1.4.1. Why a Shell and Tube Heat Exchanger?

Shell and tube heat exchangers in their various construction modifications are probably the most widespread and commonly used basic heat exchanger configuration in the process industries. The reasons for this general acceptance are several. The shell and tube heat exchanger provides a comparatively large ratio of heat transfer area to volume and weight. It provides this surface in a form which is relatively easy to construct in a wide range of sizes and which is mechanically rugged enough to withstand normal shop fabrication stresses, shipping and field erection stresses, and normal operating conditions. There are many modifications of the basic configuration, which can be used to solve special problems. The shell and tube exchanger can be reasonably easily cleaned, and those components most subject to failure - gaskets and tubes – can be easily replaced. Finally, good design methods exist, and the expertise and shop facilities for the successful design and construction of shell and tube exchangers are available throughout the world.

1.4.2. Basic Components of Shell and Tube Heat Exchangers.

While there is an enormous variety of specific design features that can be used in shell and tube exchangers, the number of basic components is relatively small. These are shown and identified in Fig. 1.34.

1. **Tubes.** The tubes are the basic component of the shell and tube exchanger, providing the heat transfer surface between one fluid flowing inside the tube and the other fluid flowing across the outside of the tubes. The tubes may be seamless or welded and most commonly made of copper or steel alloys. Other alloys of nickel, titanium, or aluminum may also be required for specific applications.

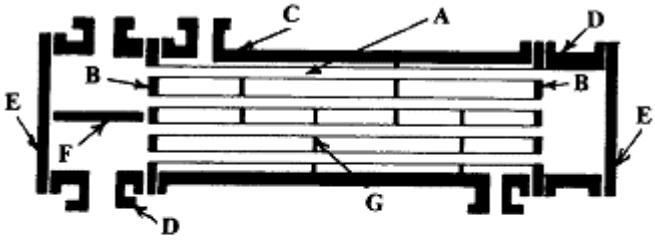

Fig. 1.34 Diagram of a Typical (Fixed Tube Sheet) Shell and Tube Heat Exchanger, Showing the Components. A. Tubes; B. Tube Sheets; C. Shell and Shell-Side Nozzles; D. Tube-Side Channels and Nozzles; E. Channel Covers; F. Pass Divider; G. Baffles.

The tubes may be either bare or with extended or enhanced surfaces on the outside. A typical Trufin Tube with extended surface is shown in Fig. 1.35. Extended or enhanced surface tubes are used when one fluid has a substantially lower heat transfer coefficient than the other fluid. Doubly enhanced tubes, that is, with enhancement both inside and outside are available that can reduce the size and cost of the exchanger. Extended surfaces, (finned tubes) provide two to four times as much heat transfer area on the outside as the corresponding bare tube, and this area ratio helps to offset a lower outside heat transfer coefficient.

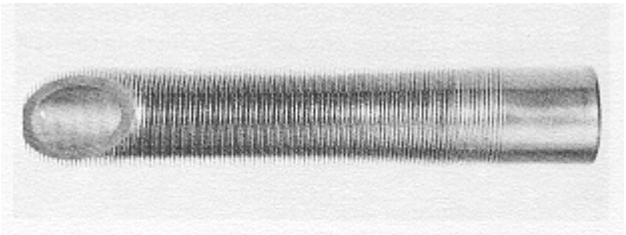

Fig. 1.35 Low-Fin Tube (Trufin Type S/T) for Use in Shell and Tube Heat Exchangers.

More recent developments are: a corrugated tube which has both inside and outside heat transfer enhancement, a finned tube which has integral inside turbulators as well as extended outside surface, and tubing which has outside surfaces designed to promote nucleate boiling. These and other developments are treated in detail in the last chapter of this book.

2. **Tube Sheets.** The tubes are held in place by being inserted into holes in the tube sheet and there either expanded into grooves cut into the holes or welded to the tube sheet where the tube protrudes from the surface. The tube sheet is usually a single round plate of metal that has been suitably drilled and grooved to take the tubes (in the desired pattern), the gaskets, the spacer rods, and the bolt circle where it is fastened to the shell. However, where mixing between the two fluids (in the event of leaks where the tube is sealed into the tube sheet) must be avoided, a double tube sheet such as is shown in Fig. 1.36 may be provided.

The space between the tube sheets is open to the atmosphere so any leakage of either fluid should be quickly detected. Triple tube sheets (to allow each fluid to leak separately to the atmosphere without mixing) and even more exotic designs with inert gas shrouds and/or leakage recycling systems are used in cases of extreme hazard or high value of the fluid.

The tube sheet, in addition to its mechanical requirements, must withstand corrosive attack by both fluids in the heat exchanger and must be electrochemically compatible with the tube and all tube-side material. Tube sheets are sometimes made from low carbon steel with a thin layer of corrosion-resisting alloy metallurgically bonded to one side.

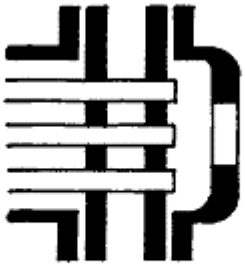

Fig. 1.36 Schematic Diagram of a Double Tube Sheet.
(COURTESY OF PATTERSON-KELLEY CO.)

3. **Shell and Shell-Side Nozzles.** The shell is simply the container for the shell-side fluid, and the nozzles are the inlet and exit ports. The shell normally has a circular cross section and is commonly made by rolling a metal plate of the appropriate dimensions into a cylinder and welding the longitudinal joint ("rolled shells"). Small diameter shells (up to around 24 inches in diameter) can be made by cutting pipe of the desired diameter to the correct length ("pipe shells"). The roundness of the shell is important in fixing the maximum diameter of the baffles that can be inserted and therefore the effect of shell-to-baffle leakage. Pipe shells are more nearly round than rolled shells unless particular care is taken in rolling, In order to minimize out-of-roundness, small shells are occasionally expanded over a mandrel; in extreme cases, the shell is cast and then bored out on a boring mill.

In large exchangers, the shell is made out of low carbon steel wherever possible for reasons of economy, though other alloys can be and are used when corrosion or high temperature strength demands must be met.

The inlet nozzle often has an impingement plate (Fig. 1.37) set just below to divert the incoming fluid jet from impacting directly at high velocity on the top row of tubes. Such impact can cause erosion, cavitations, and/or vibration. In order to put the impingement plate in and still leave enough flow area between the shell and plate for the flow to discharge without excessive pressure loss, it may be necessary to omit some tubes from the full circle pattern. Other more complex arrangements to distribute the entering flow, such as a slotted distributor plate and an enlarged annular distributor section, are occasionally employed.

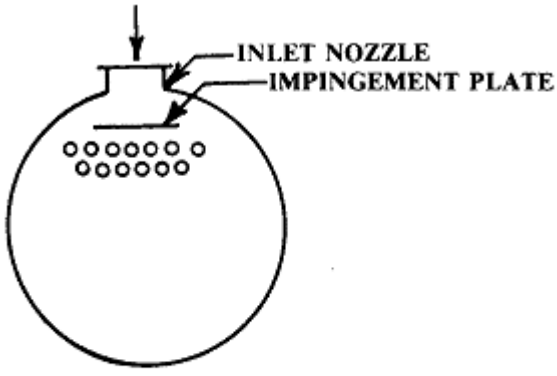

Fig. 1.37 Schematic Diagram of Placement of an Impingement Plate Under the Entrance Nozzle.

4. **Tube-Side Channels and Nozzles.** Tube-side channels and nozzles simply control the flow of the tube-side fluid into and out of the tubes of the exchanger. Since the tube-side fluid is generally the more corrosive, these channels

and nozzles will often be made out of alloy materials (compatible with the tubes and tube sheets, of course). They may be clad instead of solid alloy.

5. **Channel Covers.** The channel covers are round plates that bolt to the channel flanges and can be removed for tube inspection without disturbing the tube-side piping. In smaller heat exchangers, bonnets with flanged nozzles or threaded connections for the tube-side piping are often used instead of channels and channel covers.

6. **Pass Divider.** A pass divider is needed in one channel or bonnet for an exchanger having two tube-side passes, and they are needed in both channels or bonnets for an exchanger having more than two passes. If the channels or bonnets are cast, the dividers are integrally cast and then faced to give a smooth bearing surface on the gasket between the divider and the tube sheet. If the channels are rolled from plate or built up from pipe, the dividers are welded in place.
The arrangement of the dividers in multiple-pass exchangers is somewhat arbitrary, the usual intent being to provide nearly the same number of tubes in each pass, to minimize the number of tubes lost from the tube count, to minimize the pressure difference across any one pass divider (to minimize leakage and therefore the violation of the MTD derivation), to provide adequate bearing surface for the gasket and to minimize fabrication complexity and cost. Some pass divider arrangements are shown in Fig. 1.38.

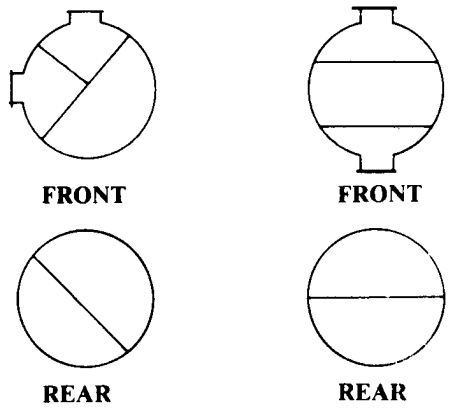

Fig. 1.38 Alternative Pass Divider Arrangements for Four Tube Passes.

7. **Baffles.** Baffles serve two functions: Most importantly, they support the tubes in the proper position during assembly and operation and prevent vibration of the tubes caused by flow-induced eddies, and secondly, they guide the shell-side flow back and forth across the tube field, increasing the velocity and the heat transfer coefficient.

The most common baffle shape is the single segmental, shown in Fig. 1.39. The segment sheared off must be less than half of the diameter in order to insure that adjacent baffles overlap at least one full tube row. For liquid flows on the shell side, a baffle cut of 20 to 25 percent of the diameter is common; for low pressure gas flows, 40 to 45 percent (i.e., close to the maximum allowable cut) is more common, in order to minimize pressure drop.

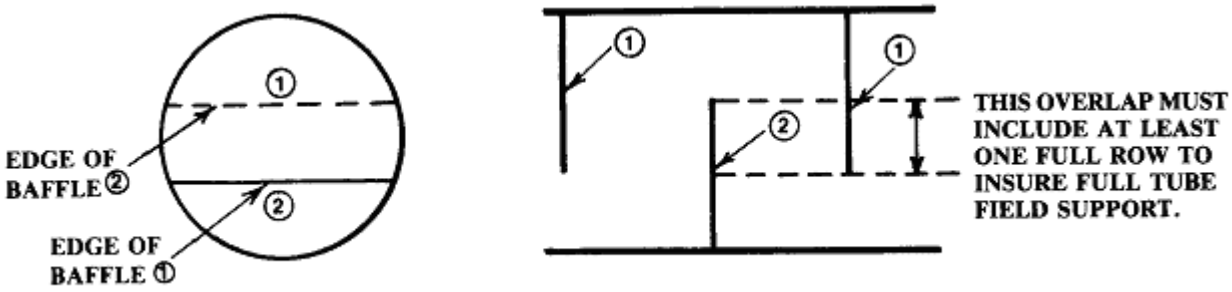

Fig. 1.39 Sketch of Typical Segmental Baffle Arrangements.

The baffle spacing should be correspondingly chosen to make the free flow areas through the "window" (the area between the baffle edge and shell) and across the tube bank roughly equal.

For many high velocity gas flows, the single segmental baffle configuration results in an undesirably high shell-side pressure drop. One way to retain the structural advantages of the segmental baffle and reduce the pressure drop (and,

regrettably, to some extent, the heat transfer coefficient, too) is to use the double segmental baffle, shown in Fig. 1.40. Exact comparisons must be made on a case-to-case basis, but the rough effect is to halve the local velocity and therefore to reduce the pressure drop by a factor of about 4 from a comparable size single segmental unit.

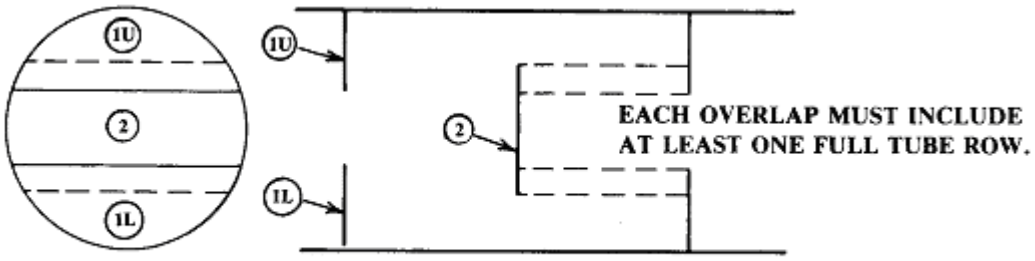

Fig. 1.40 Sketch of a Double Segmental Baffle Arrangement.

For sufficiently large units, it is possible to go to triple segmental arrangements and ultimately to strip and rod baffles, the important point being always to insure that every tube is positively constrained at periodic distances to prevent sagging and vibration. Special provisions must be made for supporting finned tubes passing through a baffle: 1) provide unfinned lands (of normal bare tube diameter) at the baffles; 2) use baffles thick enough that several fins fall within the baffle thickness and provide a solid bearing surface or 3) provide a thin metal wrap outside the fins in the vicinity of the baffle.

1.4.3. Provisions for Thermal Stress

1. **The Thermal Stress Problem**. Since, by its very purpose, the shell of the heat exchanger will be at a significantly different temperature than tubes, the shell will expand or contract relative to the tubes, resulting in stresses existing in both components and being transmitted through the tube sheets. The consequences of the thermal stress will vary with circumstances, but shells have been buckled or tubes pulled out of the tube sheet or simply pulled apart. The fixed tube sheet exchanger shown in Fig. 1.34 is especially vulnerable to this kind of damage because there is no provision made for accommodating differential expansion.

There is a rough rule of thumb that says a simple fixed tube sheet configuration can only be used for cases where the inlet temperatures of the two streams do not differ by more than 100 'F. Obviously, there must be many qualifications made to such a flat statement, recognizing the differences in materials and their properties, temperature level of operation, start-up and cycling operational procedures, etc.

2. **Expansion Joint on the Shell.** The most obvious solution to the thermal expansion problem is to put an expansion roll or joint in the shell, as shown in Fig. 1.41. This becomes less attractive for large diameter shells and/or increasing shell-side pressure. However, very large diameter, near-atmospheric pressure shells have been designed with a partial ball-joint in the shell designed to allow the shell to partially "rotate" to accommodate stresses.

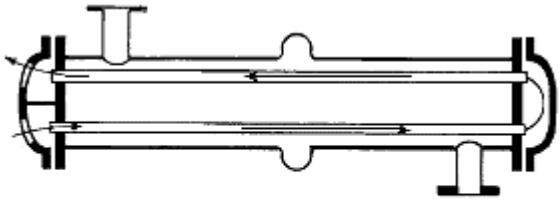

Fig. 1.41 Sketch of a Fixed Tube Sheet Design Incorporating an Expansion Joint.
(COURTESY OF PATTERSON-KELLEY CO.)

3. **Internal Bellows.** In recent years, an internal bellows design (Fig. 1.42) has become popular for such applications as waste heat vertical thermosiphon reboilers, where only one pass is permitted on the tube side. These bellows have been designed to operate successfully with high pressure boiling water on the tube side and high temperature reactor effluent gas on the shell.

4. **The U-Tube Exchanger.** One design variation that allows independent expansion of tubes and shell is the U-tube configuration shown schematically in Fig. 1.43. While this design solves the thermal expansion problem about as well as it can be solved, it has some drawbacks (e.g., inability to replace individual tubes except in the outer row, inability to clean around the bend) that render it unacceptable for some services.

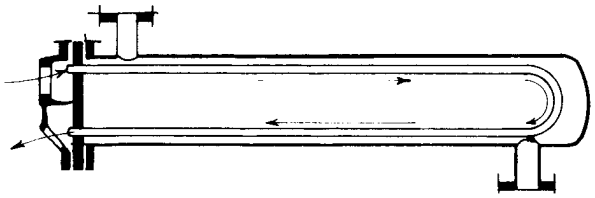

Fig. 1.43 Sketch of a U-Tube Shell and Tube Exchanger.
(COURTESY OF PATTERSON-KELLEY CO.)

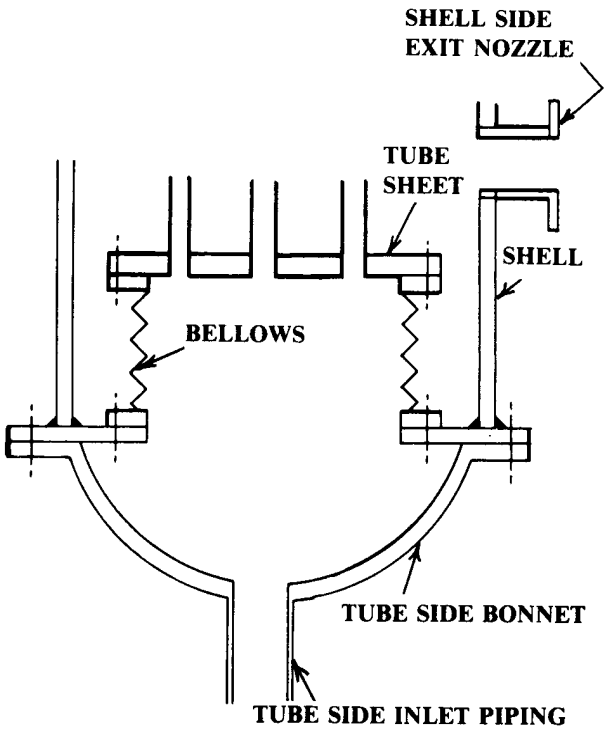

Fig. 1.42 Sketch of an Internal Bellows Configuration for a One-Tube-Pass Exchanger.

5. **Floating Head Designs.** Several different designs of "floating head" shell and tube exchangers are in common use. The goal in each case, of course, is to solve the thermal stress problem and each design does accomplish that goal. Inevitably, however, something must be given up, and each configuration has a somewhat different set of drawbacks to be considered when choosing one.

The simplest floating head design is the "pull-through bundle" type, shown in Fig. 1.44. One of the tube sheets is made small enough that it and its gasketed bonnet may be pulled completely through the shell for shell-side inspection and cleaning. The tube side may be cleaned and individual tubes may be replaced without removing the bundle from the shell. Unfortunately, many tubes must be omitted from the edge of the full bundle to allow for the bonnet flange and bolt circle.

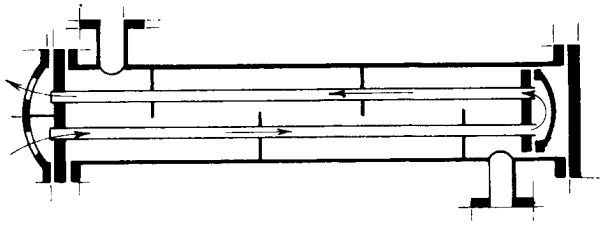

Fig. 1.44 Pull-Through Floating Head Design.
(COURTESY OF PATTERSON-KELLEY CO.)

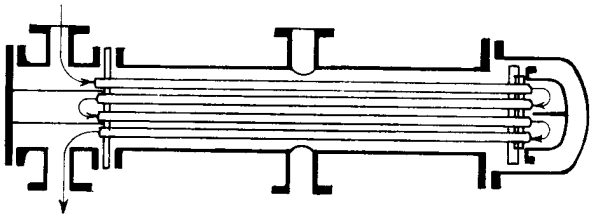

Fig. 1.45 Split Ring Floating Head Exchanger.
(COURTESY OF PATTERSON-KELLEY CO.)

This objection is met in the "split-ring floating head" type (Fig. 1.45) by bolting the floating head bonnet to a split backing ring rather than to the tube sheet. At some cost in added mechanical complexity, most of the tubes lost from the bundle in the pull-through design have been restored, and the other features retained.

Two other types, the "outside-packed lantern ring," (Fig. 1.46), and the "outside-packed stuffing box", (Fig. 1.47) are more prone to leakage to the atmosphere than the foregoing types and give up the advantage of positive sealing

so important in high pressure or hazardous fluid service. They have the advantage of allowing single tube side pass design.

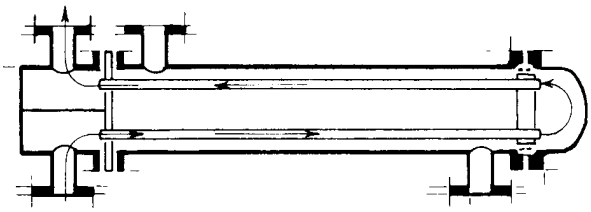

Fig. 1.46 Outside Packed Lantern Ring Floating Head Exchanger.
(COURTESY OF PATTERSON-KELLEY CO.)

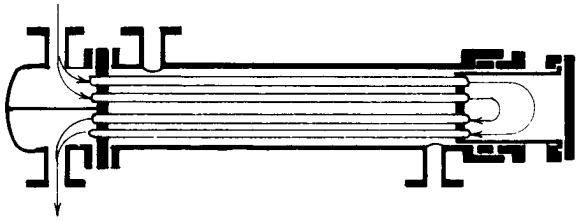

Fig. 1.47 Outside Packed Stuffing Box Floating Head Exchanger
(COURTESY OF PATTERSON-KELLEY CO.)

1.4.4. Mechanical Stresses

1. **Sources of Mechanical Stresses.** Every exchanger is subject to mechanical stresses from a variety of sources in addition to temperature gradients. There are mechanical stresses which result from the construction techniques used on the exchanger, e.g., tube and tube sheet stresses resulting from rolling in the tubes. During the manufacture, shipping and installation of the exchanger there are many, frequently unforeseen stresses imposed. There are stresses caused by the support structure reacting to the weight of the exchanger, and stresses from the connecting piping; these stresses are generally very different during normal plant operation than during construction or shutdown. Finally, there are the stresses arising within the exchanger as a result of the process stream conditions - especially pressure – during operation.

2. **Provision for Mechanical Stress.** To protect the ex changer from permanent deformation or weakening from these mechanical stresses, it is necessary to design the exchanger so that any stress that can be reasonably expected to occur will not strain or deform the metal beyond the point where it will spontaneously return to its original condition. And it is necessary to insure that stresses greater than the design values do not occur.

The analysis of stresses and strains in a heat exchanger is an extremely broad and complicated subject, and will not be developed in any detail here. The more obvious problems can be at least anticipated in a qualitative way by the thermal designer who can then seek the advice of a specialist in the subject.

1.4.5. The Vibration Problem

A very serious problem in the mechanical design of heat exchangers is flow - induced vibration of the tubes. There are several possible consequences of tube vibration, all of them bad. The tubes may vibrate against the baffles, which can eventually cut holes in the tubes. In extreme cases, the tubes can strike adjacent tubes, literally knocking holes in each other. Or the repeated stressing of the tube near a rigid support such as a tube sheet can result in fatigue cracking of a tube, loosening of the tube joint, and accelerated corrosion.

Vibration is caused by repeated unbalanced forces being applied to the tube. There are a number of such forces, but the most common one in heat exchangers is the eddying motion of the fluid in the wake of a tube as the fluid flows across the tube. The unbalanced forces are relatively small, but they occur tens, hundreds, or thousands of times a second, and their magnitudes increase rapidly with increased fluid velocity. Even so, these forces are ordinarily damped out with no damage to the tube. However, any body can vibrate much more easily at certain frequencies (called "natural frequencies") than at others. If the unbalanced forces are applied at "driving frequencies" that are at

or near these natural frequencies, resonance occurs; and even small forces can result in very strong vibration of the tube.

Although progress is being made, the prediction of whether or not a given heat exchanger configuration will adequately resist vibration is not yet a well-developed science. The two best ways to avoid vibration problems are to support the tubes as rigidly as possible (e.g., close baffle spacing) and to keep the velocities low. Both of these often conflict with the desire to keep the cost of the exchanger down. For the present, experience is the best guide in this area.

1.4.6. Erosion

Another essentially mechanical problem in heat exchanger design is that of erosion: the rapid removal of metal due to the friction of the fluid flowing in or across the tube. Erosion often occurs with and accelerates the effect of corrosion by stripping off the protective film formed on certain metals.

The erosion rate depends upon the metal (the harder the metal, the less the erosion if other factors are equal), the velocity and density of the fluid, and the geometry of the system. Thus, erosion is usually more severe at the entrance of a tube or in the bend of a U-tube, due to the additional shear stress associated with developing the boundary layer or turning the fluid. Other, more elusive effects are associated with the chemistry of the fluid and the tube metal, especially where corrosion is involved.

There are some commonly used upper velocity limits for flow inside tubes of a given metal. These limits are shown in Table 1. 1.

1.4.7. Cost of Shell and Tube Heat Exchangers

Some appreciation of the cost basis for shell and tube exchangers is essential to the proper selection of a configuration and allocation of streams. It is impossible to furnish here a precise and reasonably current correlation for estimating the cost of a given configuration, but we may at least identify the relative contributions to the total cost and how these change with certain design specifications.

The cost of a shell and tube exchanger f.o.b. the fabrication shop is composed of the costs of the individual components (shell, tubes, etc.), plus the assembly cost. The cost of each component is the sum of the material cost, plus gross fabrication (e.g., rolling the shell), plus machining. The final price to the customer will also include engineering and other overheads, the fabricator's profit and shipping. Some of these, e.g. the profit, are roughly proportional to the total cost, while the shipping is more nearly proportional to the total weight.

In order to arrive at the most economical unit (on a first cost basis), it is necessary to consider the effect of the special requirements of the unit on each of the component costs. For example, suppose one fluid requires a special alloy to resist corrosion. If that fluid is put in the shell, both the shell and the tubes must be made of that alloy; conversely, if the corrosive fluid is put in the tubes, only the tubes and tube side fittings must be alloy, and that cost can often be further reduced if the tube sheets and channels are only faced with the alloy.

The same total heat transfer area may be put in a shell that is of small diameter and relatively long, or in one that has a larger diameter and shorter length. The cost of a shell - often the largest single cost in the total exchanger cost - increases very rapidly with diameter but only linearly (at most) with length. Therefore, unless space or pressure drop limits dictate otherwise, the most economical exchanger is usually one of relatively large length to diameter ratio - up to perhaps 12 to I for a very rough rule of thumb.

For the exchanger as a whole, only a complete cost analysis of several different designs can establish which is in fact the least expensive in first cost. There are however, a number of rules, which will tend to select the more economical designs out of the multitude of possibilities. These will be discussed further.

1.4.8. Allocation of Streams in a Shell and Tube Exchanger

In principle, either stream entering a shell and tube ex changer may be put on either side-tube-side or shell-side -of the surface. However, there are four considerations, which exert a strong influence upon which choice will result in the most economical exchanger:

1. High pressure: If one of the streams is at a high pressure, it is desirable to put that stream inside the tubes. In this case, only the tubes and the tube-side fittings need be designed to withstand the high pressure, whereas the shell may be made of lighter weight metal. Obviously, if both streams are at high pressure, a heavy shell will be required and other considerations will dictate which fluid goes in the tube. In any case, high shell side pressure puts a premium on the design of long, small diameter exchangers.

2. Corrosion: Corrosion generally dictates the choice of material of construction, rather than exchanger design. However, since most corrosion - resistant alloys are more expensive than the ordinary materials of construction, the corrosive fluid will ordinarily be placed in the tubes so that at least the shell need not be made of corrosion - resistant material. If the corrosion cannot be effectively prevented but only slowed by choice of material, a design must be chosen in which corrodible components can be easily replaced (unless it is more economical to scrap the whole unit and start over.)

3. Fouling: Fouling enters into the design of almost every process exchanger to a measurable extent, but certain streams foul so badly that the entire design is dominated by features which seek a) to minimize fouling (e.g. high velocity, avoidance of dead or eddy flow regions) b) to facilitate cleaning (fouling fluid on tube-side, wide pitch and rotated square layout if shell-side fluid is fouling) or c) to extend operational life by multiple units.

4. Low heat transfer coefficient: If one stream has an inherently low heat transfer coefficient (such as low pressure gases or viscous liquids), this stream is preferentially put on the shell-side so that extended surface may be used to reduce the total cost of the heat exchanger.