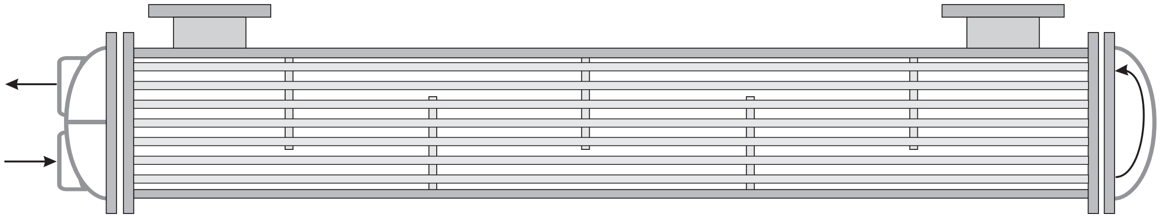
Basic Construction of Shell & Tube Heat Exchangers

Shell and tube heat exchangers represent the most widely used vehicle for the transfer of heat in industrial process applications. They are frequently selected for such duties as:

- Process liquid or gas cooling
- Process or refrigerant vapor or steam condensing
- Process liquid, steam or refrigerant evaporation
- Process heat removal and preheating of feed water
- Thermal energy conservation efforts, heat recovery
- Compressor, turbine and engine cooling, oil and jacket water
- Hydraulic and lube oil cooling
- Many other industrial applications

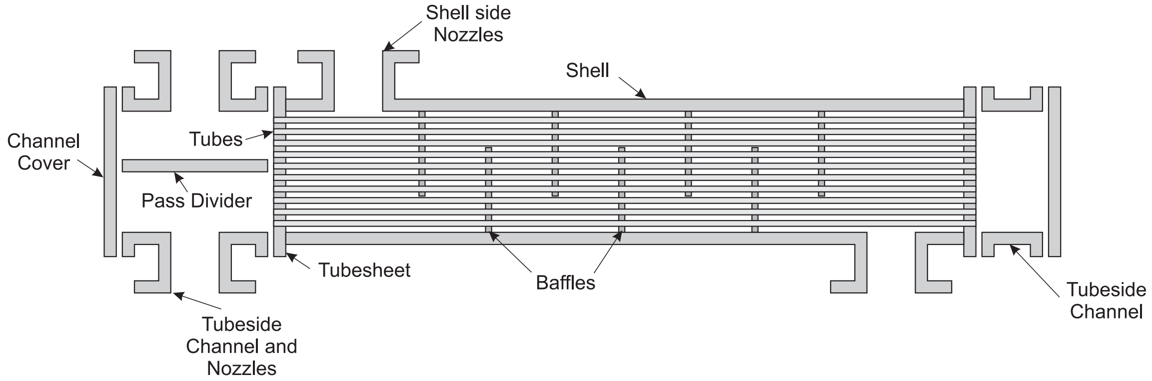
Shell and tube heat exchangers have the ability to transfer large amounts of heat in relatively low cost, servicable designs. They can provide large amounts of effective tube surface while minimizing the requirements of floor space, liquid volume and weight. Shell and tube exchangers are available in a wide range of sizes. They have been used in industry for over 150 years, so the thermal technologies and manufacturing methods are well defined and applied by modern competitive manufacturers. Tube surfaces from standard to exotic metals with plain or enhanced surface characteristics are widely available. They can help provide the least costly mechanical design for the flows, liquids and temperatures involved.



Fixed Tubesheet, 2-Pass Heat Exchanger

There are two distinct types of shell and tube heat exchangers, based in part on shell diameter. Designs from 2” to around 12” in shell diameter are available that feature shell constructions of low cost welded steel, brazed pipe with hub forgings, cast end bonnets and copper tubing rolled or brazed to the tube sheet. This mass production product has had great success with OEM’s of industrial machinery for oil cooling and water to water applications. As a result, there are a large number of this type of heat exchanger in the marketplace. Many manufacturers offer dimensionally interchangeable equipment to their competitors in order to minimize customer engineering resistance in winning OEM business. Models of this type generally use 1/4” and 3/8” tubing and are frequently 2 or 4 pass for general industrial use. While roller-expanding tubes to thick tube sheets is regarded as good practice, offering easier service, some manufacturers offer a low cost design that brazes the tubes to a thin tubesheet. By removing end bonnets or covers, most plant-water cooled heat exchangers can be readily serviced by mechanically cleaning the interior of the tubes. Failed tubes can merely be plugged or replaced, depending on the design. Some manufacturers offer products in this size range that have 1/8” tubes mechanically expanded to fins that fill the shell to greatly increase the effective surface and transfer rate. Many of the heat exchangers in the marketplace of this type construction are not ASME code qualified, nor is it generally required. A few manufacturers offer the equipment in a code version.

The other major type of shell and tube heat exchanger generally is seen in shell diameters from 10” to over 100”. Commonly available steel pipe is generally used up to 24” in diameter. Above 24”, manufactures use rolled and welded steel plate, which is more costly and roundness can become an issue. Heat exchangers of this type are commonly manufactured to the standards set forth by TEMA, the Tubular Exchangers Manufacturers Association. TEMA, in cooperation with users and manufacturers, establishes a common set of guidelines for the construction methods, tolerances and practices to be employed. This allows industrial consumers to obtain more than one manufacturers offerings and know that they are generally of similar design and construction. Additionally, it allows manufactures to establish industry approved designs and offer state of the art equipment that help to assure competitiveness and overall product reliability.



Although there exists a wide variety of designs and materials available, there are components common to all designs. Tubes are mechanically attached to tube sheets, which are contained inside a shell with ports for inlet and outlet fluid or gas. They are designed to prevent liquid flowing inside the tubes to mix with the fluid outside the tubes. Tube sheets can be fixed to the shell or allowed to expand and contract with thermal stresses by have one tube sheet float inside the shell or by using an expansion bellows in the shell. This design can also allow pulling the entire tube bundle assembly from the shell to clean the shell circuit of the exchanger.

Fluid Stream Allocations

There are a number of practical guidelines which can lead to the optimum design of a given heat exchanger. Remembering that the primary duty is to perform its thermal duty with the lowest cost yet provide excellent in service reliability, the selection of fluid stream allocations should be of primary concern to the designer. There are many trade-offs in fluid allocation in heat transfer coefficients, available pressure drop, fouling tendencies and operating pressure.

1. The higher pressure fluid normally flows through the tube side. With their small diameter and nominal wall thicknesses, they are easily able to accept high pressures

and avoids more expensive, larger diameter components to be designed for high pressure. If it is neccessary to put the higher pressure stream in the shell, it should be placed in a smaller diameter and longer shell.

2. Place corrosive fluids in the tubes, other items being equal. Corrosion is resisted by using special alloys and it is much less expensive than using special alloy shell materials. Other tube side materials can be clad with corrosion resistant materials or epoxy coated.

3. Flow the higher fouling fluids through the tubes. Tubes are easier to clean using common mechanical methods.

4. Because of the wide variety of designs and configurations available for the shell circuits, such as tube pitch, baffle use and spacing, multiple nozzles, it is best to place fluids requiring low pressure drops in the shell circuit.

5. The fluid with the lower heat transfer coefficient normally goes in the shell circuit. This allows the use of low-fin tubing to offset the low transfer rate by providing increased available surface.

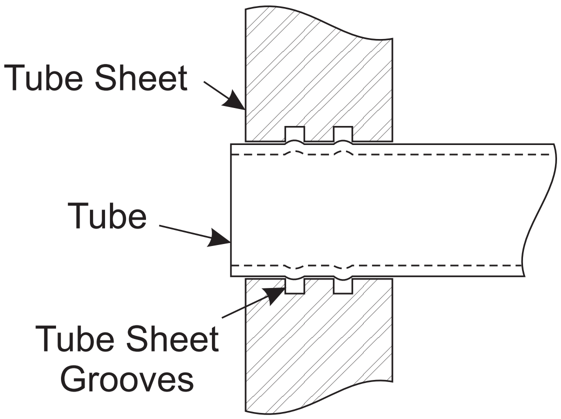
Tubes

Tubing that is generally used in TEMA sizes is made from low carbon steel, copper, Admiralty, Copper-Nickel, stainless steel, Hastalloy, Inconel, titanium and a few others. It is common to use tubing from 5/8” to 1-1/2” in these designs. Tubes are either generally drawn and seamless or welded. High quality ERW (electro-resistance welded) tubes exhibit superior grain structure at the weld. Extruded tube with low fins and interior rifling is specified for certain applications. Surface enhancements are used to increase the available metal surface or aid in fluid turbulence, thereby increasing the effective heat transfer rate. Finned tubing is recommended when the shell side fluid has a substantially lower heat transfer coefficient than the tube side fluid. Finned tubing has an outside diameter in the finned area slightly under the unfinned, or landing area for the tube sheets. This is to allow assembly by sliding the tubes through the baffles and tube supports while minimizing fluid bypass.

U-tube designs are specified when the thermal difference of the fluids and flows would result in excessive thermal expansion of the tubes. U-tube bundles do not have as much tube surface as straight tube bundles, due to the bending radius, and the curved ends cannot be easily cleaned. Additionally, interior tubes are difficult to replace, many times requiring the removal of outer layers, or simply plugging the tube. Because of the ease in manufacturing and service, it is common to use a removable tube bundle design when specifying U-tubes.

Tubesheets

Tubesheets are usually made from a round flat piece of metal with holes drilled for the tube ends in a precise location and pattern relative to one another. Tube sheet materials range as tube materials. Tubes are attached to the tube sheet by pneumatic or hydraulic pressure or by roller expansion. Tube holes can be drilled and reamed and can be machined with one or more grooves. This greatly increases the strength of the tube joint.



The tubesheet is in contact with both fluids and so must have corrosion resistance allowances and have metalurgical and electrochemical properties appropriate for the fluids and velocities. Low carbon steel tube sheets can include a layer of a higher alloy metal bonded to the surface to provide more effective corrosion resistance without the expense of using the solid alloy.

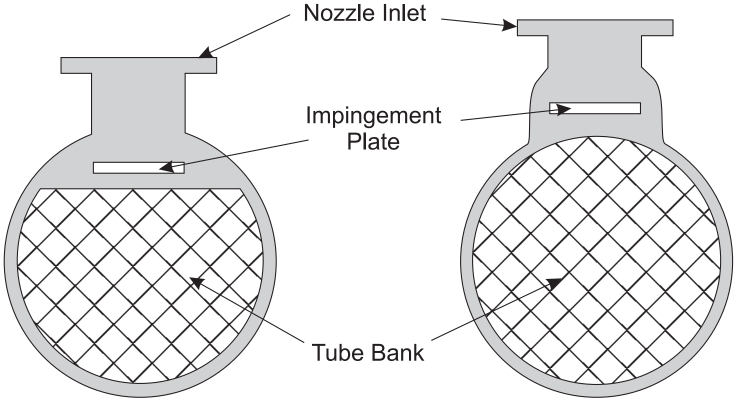
The tube hole pattern or “pitch” varies the distance from one tube to the other and angle of the tubes relative to each other and to the direction of flow. This allows the manipulation of fluid velocities and pressure drop, and provides the maximum amount of turbulance and tube surface contact for effective heat transfer.

Where the tube and tube sheet materials are joinable, weldable metals, the tube joint can be further strengthened by applying a seal weld or strength weld to the joint. A strength weld has a tube slightly reccessed inside the tube hole or slightly extended beyond the tube sheet. The weld adds metal to the resulting lip. A seal weld is specified to help prevent the shell and tube liquids from intermixing. In this treatment, the tube is flush with the tube sheet surface. The weld does not add metal, but rather fuses the two materials. In cases where it is critical to avoid fluid intermixing, a double tube sheet can be provided. In this design, the outer tube sheet is outside the shell circuit, virtually eliminating the chance of fluid intermixing. The inner tube sheet is vented to atmosphere so any fluid leak is easily detected.

Shell Assembly

The shell is constructed either from pipe up to 24” or rolled and welded plate metal. For reasons of economy, low carbon steel is in common use, but other materials suitable for extreme temperature or corrosion resistance are often specified. Using commonly available shell pipe to 24” in diameter results in reduced cost and ease of manufacturing, partly because they are generally more perfectly round than rolled and welded shells. Roundness and consistent shell ID is neccessary to minimize the space between the baffle outside edge and the shell as excessive space allows fluid bypass and reduced performance. Roundness can be increased by expanding the shell around a mandrell or double rolling after welding the longitudnal seam. In extreme cases the shell can be cast and then bored to the correct ID.

In applications where the fluid velocitiy for the nozzle diameter is high, an impingement plate is specified to distribute the fluid evenly to the tubes and prevent fluid enduced erosion, cavitation and vibration. An impingement plate can be installed inside the shell, which prevents installing a full tube bundle, resulting in less available surface. It can alternately be installed in a domed area above the shell. The domed area can either be reducing coupling or a fabricated dome. This style allows a full tube count and therefore maximizes the utilization of shell space.

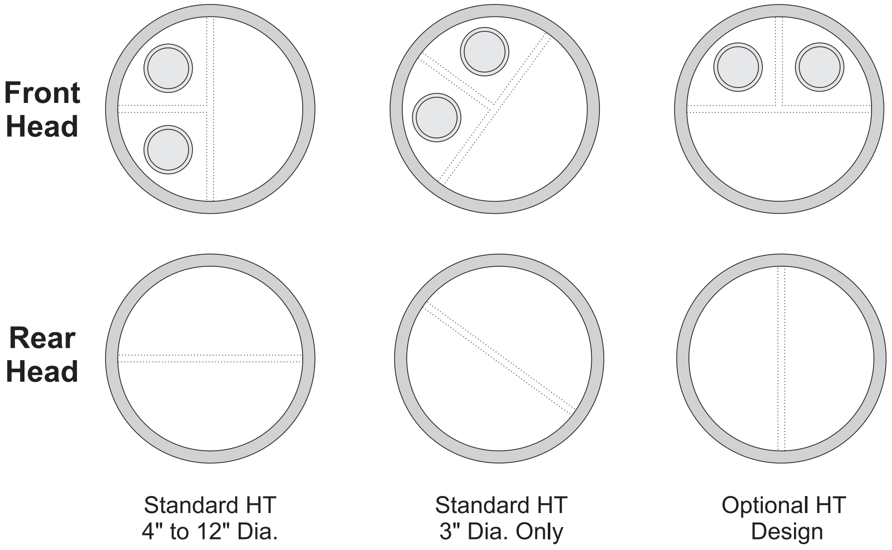


End Channels and Bonnets

End channels or bonnets are typically fabricated or cast and control the flow of the tubeside fluid in the tube circuit. They are attached to the tube sheets by bolting with a gasket between the two metal surfaces. In some cases, effective sealing can be obtained by installing an O-ring in a machined groove in the tube sheet.

The head may have pass ribs that dictate if the tube fluid makes one or more passes through the tube bundle sections. Front and rear head pass ribs and gaskets are matched to provide effective fluid velocities by forcing the flow through various numbers of tubes at a time. Generally, passes are designed to provide roughly equal tube-number access and to assure even fluid velocity and pressure drop throughout the bundle. Even fluid velocities also affect the film coefficients and heat transfer rate so that accurate prediction of performance can be readily made. Designs for up to six tube passes are common. Pass ribs for cast heads are intregrally cast and then machined flat. Pass ribs for fabricated heads are welded into place. The tube sheets and tube layout in multi-pass heat exchangers must have provision for the pass ribs. This requires either removing tubes to allow a low cost straight pass rib, or machining the pass rib with curves around the tubes, which is more costly to manufacture. Where a full bundle tube count is required to satisfy the thermal requirements, this machined pass rib approach may prevent having to consider the next larger shell diameter.

Cast head materials are typically used in smaller diameters to around 14” and are made from iron, ductile iron, steel, bronze or stainless steel. They typically have pipe-thread connections. Cast heads and tube side piping must be removed to service tubes.



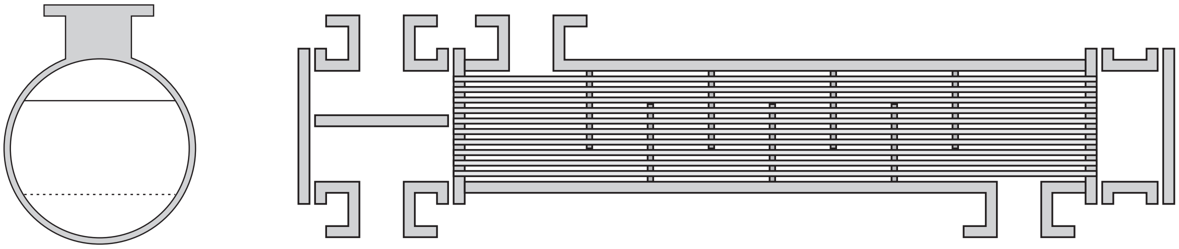
4-PASS Tubeside Designs

Fabricated heads can be made in a wide variety of configurations. They can have metal cover designs that allow servicing the tubes without disturbing the shell or tube piping. Heads can have axially or tangentially oriented nozzles, which are typically ANSI flanges.

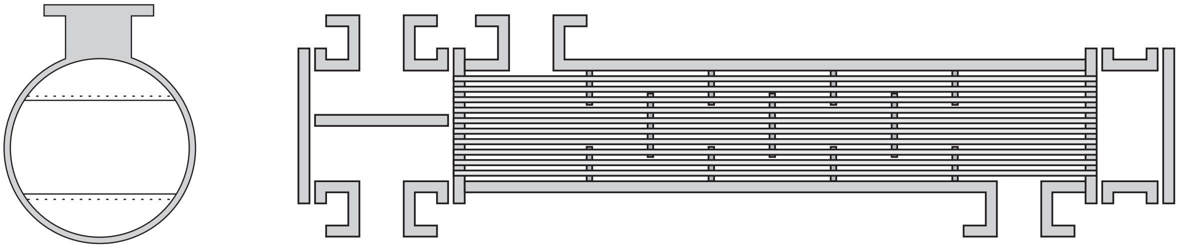
Baffles

Baffles serve two important functions. They support the tubes during assembly and operation and help prevent vibration from flow induced eddies and direct the shell side fluid back and forth across the tube bundle to provide effective velocity and heat transfer rates. The diameter of the baffle must be slightly less than the shell inside diameter to allow assembly, but must be close enough to avoid the substantial performance penalty caused by fluid bypass around the baffles. Shell roundness is important to acheive effective sealing against excessive bypass. Baffles can be made from a variety of materials compatible with the shell side fluid. They can be punched or machined. Some baffles are made by a punch which provides a lip around the tube hole to provide more surface against the tube and eliminate tube wall cutting from the baffle edge. The tube holes must be precise enough to allow easy assembly and field tube replacement, yet minimize the chance of fluid flowing between the tube wall and baffle hole, resulting in reduced thermal performance and increased potential for tube wall cutting from vibration.

Baffles do not extend edge to edge, but have a cut that allows shell side fluid to flow to the next baffled chamber. For most liquid applications, the cuts areas represent 20-25% of the shell diameter. For gases, where a lower pressure drop is desirable, baffle cuts of 40-45% is common. Baffles must overlap at least one tube row in order to provide adequate tube support. They are spaced throughout the tube bundle somewhat evenly to provide even fluid velocity and pressure drop at each baffled tube section.



Single Segmental Baffle arrangement
Note: Overlap of at least one tube is required
to provide adequate tube support.



Double Segmental Baffle arrangement
Note: Overlap of at least one tube is required
to provide adequate tube support.

Single-segmental baffles force the fluid or gas across the entire tube count, where is changes direction as dictated by the baffle cut and spacing. This can result in excessive pressure loss in high velocity gases. In order to effect heat transfer, yet reduce the pressure drop, double-segmental baffles can be used. This approach retains the structural effectiveness of the tube bundle, yet allows the gas to flow between alternating sections of tube in a straighter overall direction, thereby reducing the effect of numerous changes of direction. This approach takes full advantage of the available tube surface but a reduction in performance can be expected due to a reduced heat transfer rate. Because pressure drop varies with velocity, cutting the velocity in half by using double-segmental baffles results in roughly 1/4 of the pressure drop as seen in a single-segmental baffle space over the same tube surface.

TEMA Designations

Because of the number of variations in mechanical designs for front and rear heads and shells, and for commercial reasons, TEMA has designated a system of notations that correspond to each major type of front head, shell tyle and rear head. The first letter identifies the front head, the second letter identifies the shell type and the third letter identifies the rear head type. The TEMA standard notation system is shown on the next page. Selecting the best TEMA type for a given application is beyond the scope of this discussion. Refer to the API Training Manual section entitled Selecting TEMA Heat Exchangers.

Differential Thermal Expansion

Since the duty of heat exchangers includes the handling of fluids of differing temperature, flow rate and thermal properties, differential expansion of the metals will take place. When the terminal temperature difference between the fluids is substantial, over 50-60 degrees, these stresses can become severe, causing shells to become deformed and damage mounting supports, tubes to deform the tube sheet or tubes to become broken or dislodged from the tube sheet. Fixed tube sheet designs are most vulnerable to differential thermal expansion, because there is no inherent provision to absorb the stresses. One approach in common use is installing an expansion joint in the shell pipe of such designs. This is a cost effective approach for pipe-size shells. An expansion joint can also be installed in the tube side of floating head designs, but manufacturing costs are much higher. Alternative approaches involve the design of a U-tube bundle so that each tube can inpendently expand and contract as needed or by using a rear floating internal tube sheet design which allows the entire bundle as a unit to expand and contract. The floating head is typically sealed against the interior of the shell by means of packing or O-ring designs.

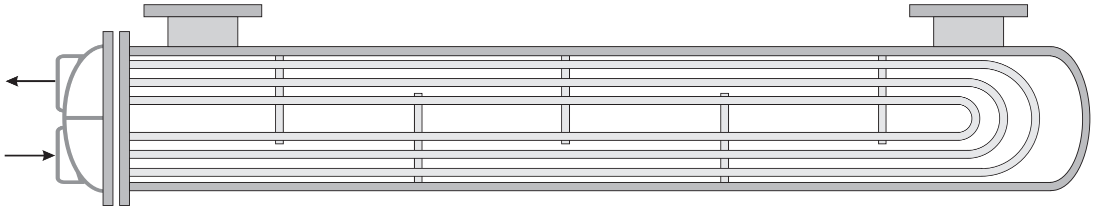


Diagram of U-Tube Heat Exchanger

U-tube designs while offering the best answer for differential thermal expansion, have some drawbacks. Individual tubes can be difficult of expensive to replace, especially for interior tubes. Also, the tube interior cannot be effectively cleaned in the u-bends. Erosion damage is also frequently seen in the u-bends in high tube side velocity applications. In large diameter shells, the long length of unsupported tube in the u-bends of outer tubes can lead to vibration induced damage.

Floating Head Designs

In an effort to reduce thermal stresses and provide a means to remove the tube bundle for cleaning, several floating rear head designs have been established. The simplest is a “pull-through” design which allows the tube bundle to be pulled entirely through the shell for service or replacement. In order to accomodate the rear head bolt circle, tubes must be removed resulting in a less efficient use of shell size. In addition, the missing tubes result in larger annular spaces and can contribute to reduced flow across the effective tube surface, resulting in reduced thermal performance. Some designs include sealing strips installed in the shell to help block the bypass steam.

Another floating head design that partially addresses the above disadvantages is a “split-ring floating head”. Here the floating head bonnet is bolted to a split backing

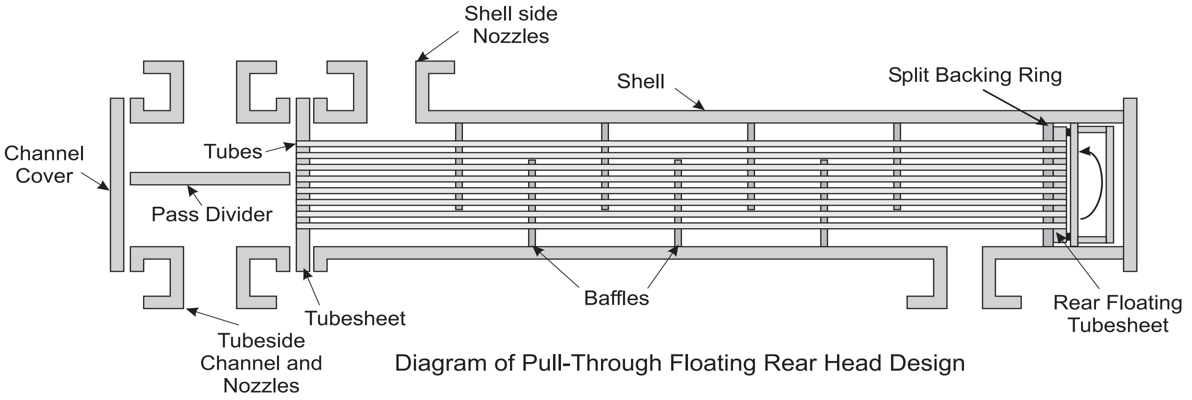


Diagram of Pull-Through Floating Rear Head Design

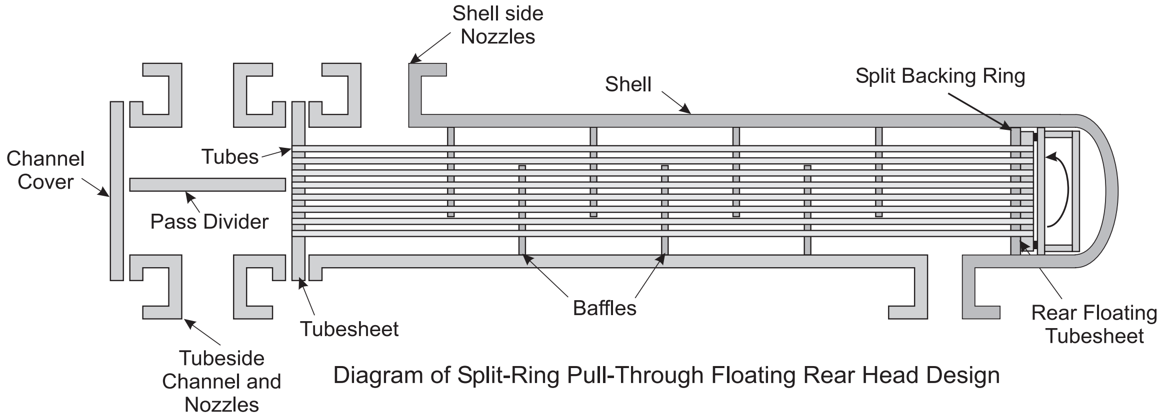


Diagram of Split-Ring Pull-Through Floating Rear Head Design ring instead of the tube sheet. This eliminates the bolt circle diameter and allows a full complement of tubes to fill the shell. This construction is more expensive than a common pull through design, but is in wide use in petrochemical applications. For applications with high pressures or temperatures, or where more positive sealing between the fluids is desired, the pull-through design should be specified.

Two other types, the “outside packed lantern ring” and the “outside packed stuffing box” designs offer less positive sealing against leakage to the atmosphere than the pull though or split ring designs, but can be configured for single tube pass duty.

Shell Constructions

The most common TEMA shell type is the “E” shell as it is most suitable for most industrial process cooling applications. However, for certain applications, other shells offer distinct advantages. For example, the TEMA-F shell design provides for a longitudinal flow plate to be installed inside the tube bundle assembly. This plate causes the shell fluid to travel down one half of the tube bundle, then down the other half, in effect producing a counter-current flow pattern which is best for heat transfer. This type of construction can be specified where a close approach temperature is required and when the flow rate permits the use of one half of the shell at a time.
In heat recovery applications, or where the application calls for increased thermal length to acheive effective overall heat transfer, shells can be installed with the flows in series. Up to six shorter shells in series is common and results in counter-current flow close to performance as if one long shell in a single pass design were used.

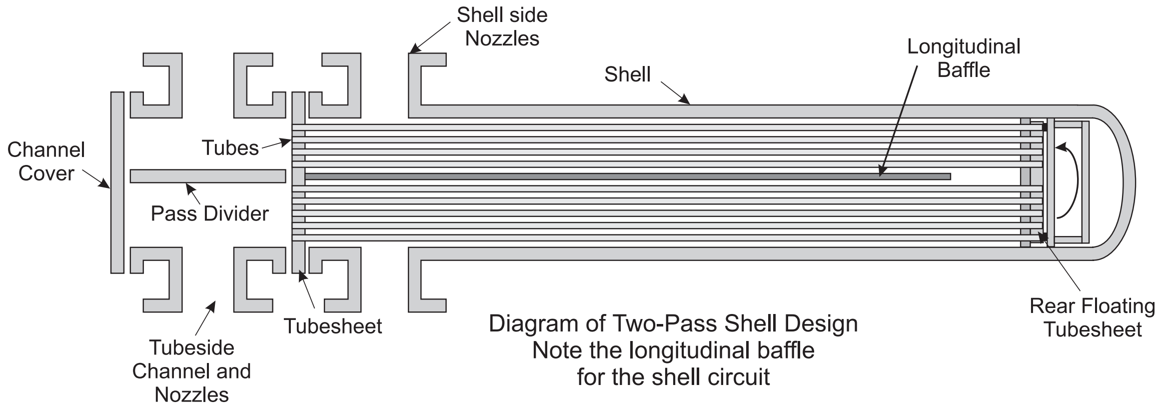
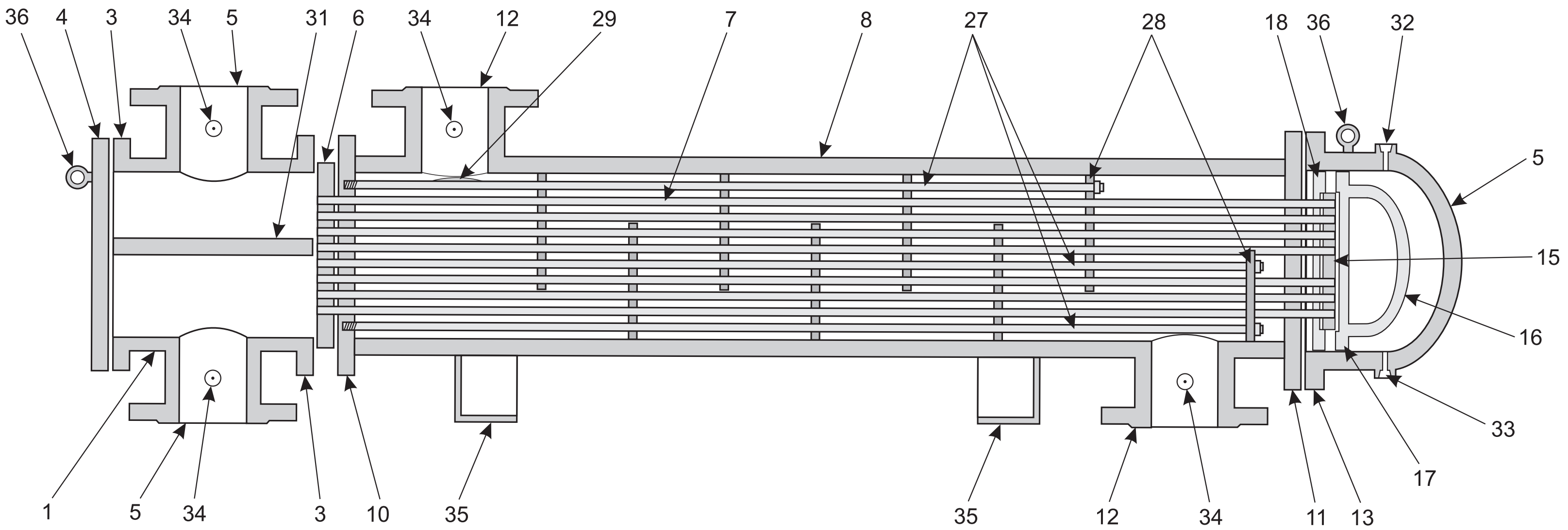


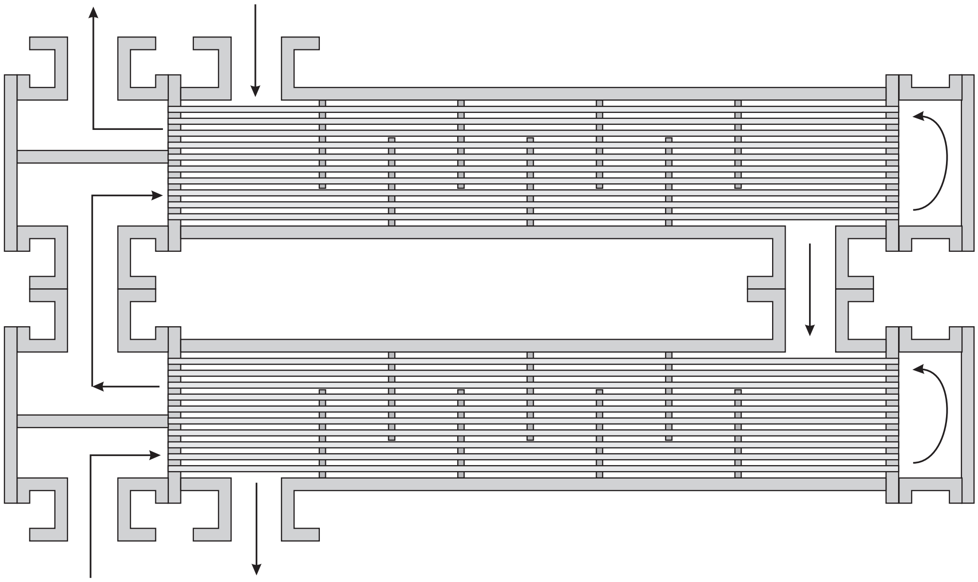
Diagram of Two-Pass Shell Design
Note the longitudinal baffle
for the shell circuit

TEMA G and H shell designs are most suitable for phase change applications where the bypass around the longitudinal plate and counter-current flow is less important than even flow distribution. In this type of shell, the longitufinal plate offers better flow distribution in vapor streams and helps to flush out non-condensables. They are frequently specified for use in horizontal thermosiphon reboilers and total condensers.



TEMA TYPE AES

1. Stationary Head-Channel
2. Stationary Head-Bonnet
3. Stationary Head Flange - Channel or Bonnet
4. Channel Cover
5. Stationary Head Nozzle
6. Stationary Tubesheet
7. Tubes
8. Shell
9. Shell Cover
10. Shell Flange - Stationary Head End
11. Shell Flange - Rear Head End
12. Shell Nozzle
13. Shell Cover Flange
14. Expansion Joint
15. Floating Tubesheet
16. Floating Head Cover
17. Floating Head Cover Flange
18. Floating Head Backing Device
19. Split Shear Ring
20. Slip-On Backing Ring
21. Floating Head Cover - External
22. Floating Tubesheet Skirt
23. Packing Box
24. Packing
25. Packing Gland
26. Lantern Ring
27. Tierods and Spacers
28. Transverse Baffles or Support Plates
29. Impingement Plate
30. Longitudnal Baffle
31. Pass Partition
32. Vent Connection
33. Drain Connection
34. Instrument Connection
35. Support Saddle
36. Lifting Lug
37. Support Bracket
38. Weir
39. Liquid Level Connection



Flow arrangement for Two Heat Exchangers in Series

TEMA J Shells are typically specified for phase change duties where significantly reduced shell side pressure drops are required. They are commonly used in stacked sets with the single nozzles used as the inlet and outlet. A special type of J-shell is used for flooded evaporation of shell side fluids. A separate vapor disengagement vessel without tubes is installed above the main J shell with the vapor outlet at the top of this vessel.

The TEMA K shell, also termed a “kettle reboiler”, is specified when the shell side stream will undergo vaporization. The liquid level of a K shell design should just cover the tube bundle, which fills the smaller diameter end of the shell. This liquid level is controlled by the liquid flowing over a wier at the far end of the entrance nozzle. The expanded shell area serves to facilitate vapor disengagement for boiling liquid in the bottom of the shell. To insure against excessive liquid carry-though with the vapor

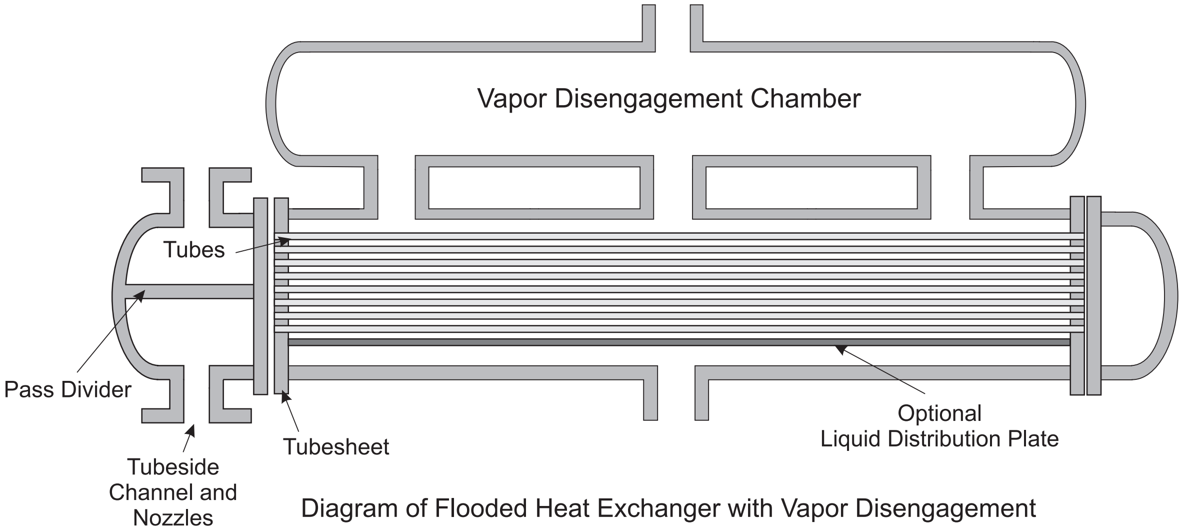


Diagram of Flooded Heat Exchanger with Vapor Disengagement stream, a separate vessel as described above is specified. Liquid carry-through can also be minimized by installing a mesh demister at the vapor exit nozzle. U-bundles are typically used with K shell designs. K shells are expensive for high pressure vaporization due to shell diameter and the required wall thickness.

The TEMA X shell, or crossflow shell is most commonly used in vapor condensing applications, though it can also be used effectively in low pressure gas cooling or heating. It produces a very low shell side pressure drop, and is therefore most suitable for vacuum service condensing. In order to assure adequate distribution of vapors, X-shell designs typically feature an area free of tubes along the top of the exchanger. It is also typical to design X shell condensers with a flow area at the bottom of the tube bundle to allow free condensate flow to the exit nozzle. Careful attention to the effective removal of non-condensables is vital to X-shell constructions.

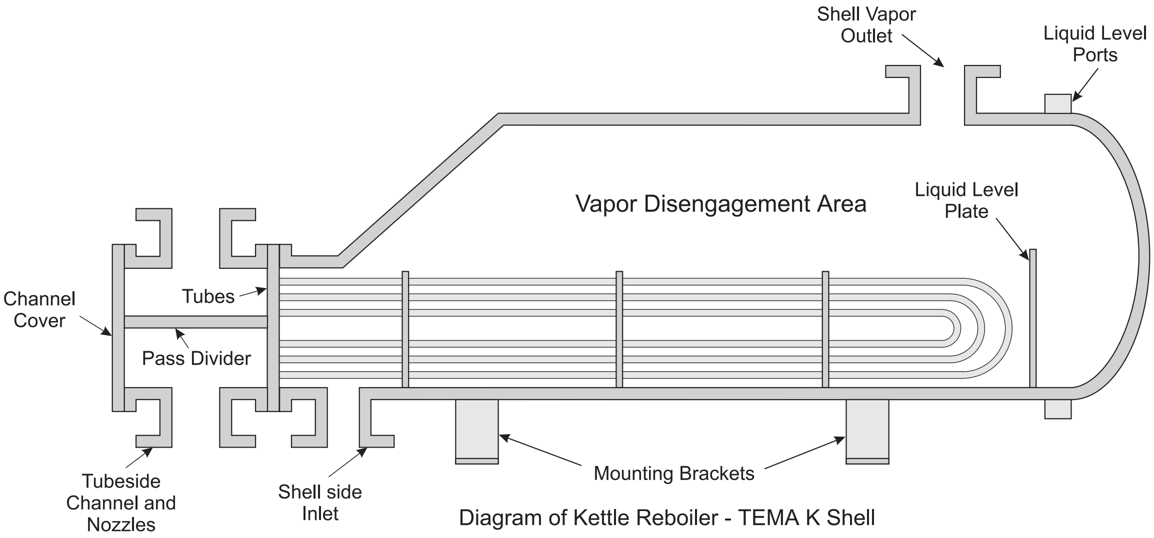


Diagram of Kettle Reboiler - TEMA K Shell