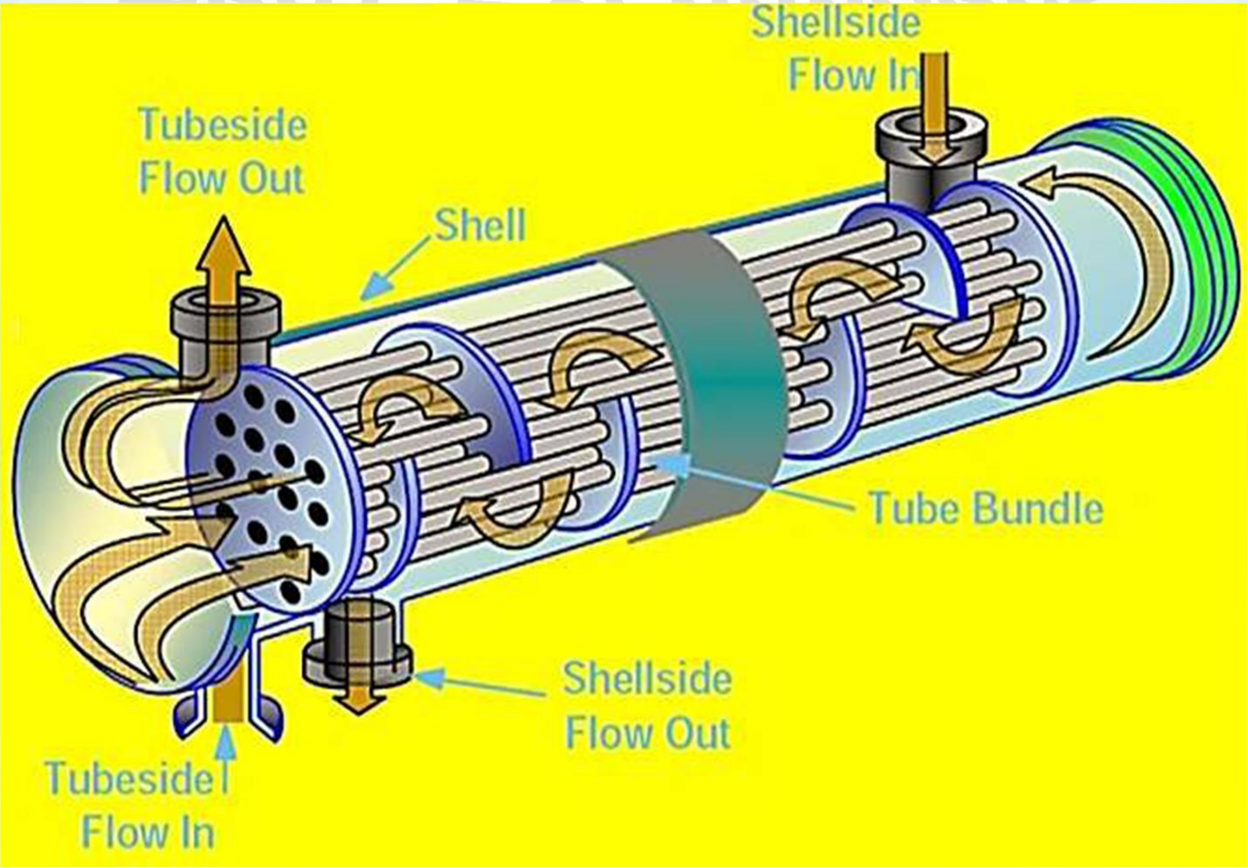
# Shell and Tube Heat Exchangers



Abhishek Kumar Chandra

- The most commonly used heat exchanger is the shell and tube type. It is the "workhorse" of industrial process heat transfer.
- Shell and tube heat exchangers can be constructed with a very large heat transfer area in a relatively small volume, fabricated from alloy steels to resist corrosion.
- They are used for heating, cooling, and for condensing a very wide range of fluids.
- It has many applications in the power generation, petroleum refinery, chemical industries, and process industries.

## Construction Details for Shell And Tube Exchangers

- ✓ The major components of a shell and tube exchanger are tubes, baffles, shell, front head, rear head, and nozzles.
- ✓ Other components include tie-rods and spacers, impingement plates, sealing strips, supports, and lugs.

- ✓ Expansion joint is an important component in the case of fixed tubesheet exchanger for certain design conditions.

The selection criteria for a proper combination of these components are dependent upon the operating pressures, temperatures, thermal stresses, corrosion characteristics of fluids, fouling, cleanability, and cost.

## Design Standards

- **TEMA Standard**

TEMA standards are followed in most countries of the world for the design of shell and tube heat exchangers.

The TEMA standards are applicable to unfired shell and tube heat exchangers with inside diameters not exceeding 60 in. (1524 mm). Each section is identified by an uppercase letter symbol, which precedes the paragraph numbers of the section and identifies the subject matter.

TEMA classes R, C, and B have been combined into one section titled class RCB.

Details of R, C, and B classification are as follows:

1. TEMA B—generally for chemical process services, more stringent than TEMA C, but not

as stringent as R

2. TEMA C—for generally moderate commercial and process application requirements, the

most commonly used in industries

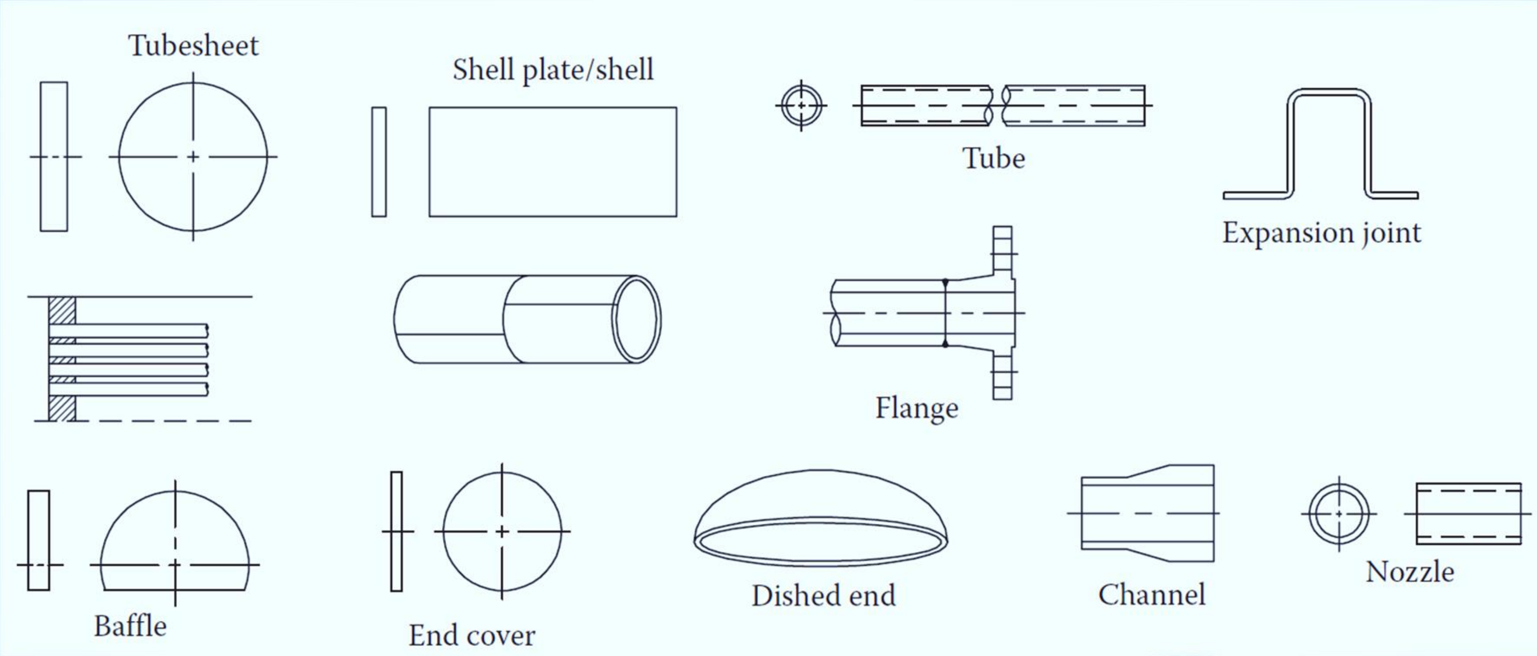
3. TEMA R—the highest integrity design

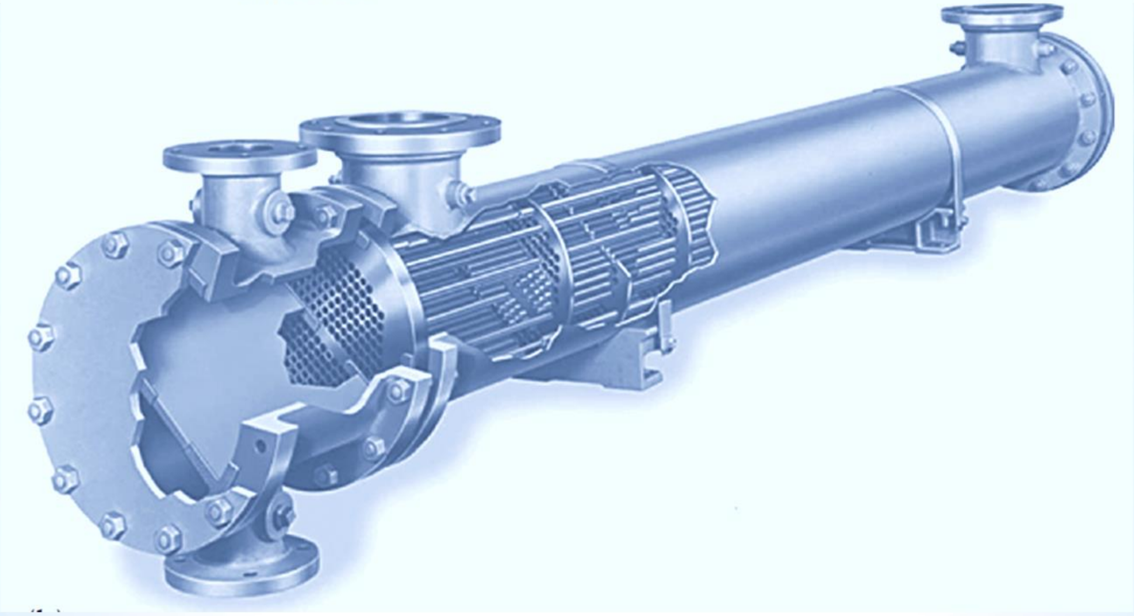
- **ANSI/API Standard 660**

ANSI/API Standard 660 is the national adoption of ISO 16812:2002—Petroleum and natural gas industries—Shell and tube heat exchangers.

This International Standard specifies requirements and gives recommendations for the

mechanical design,
fabrication,
testing,
material selection,
inspection,
preparation for the shipment of shell and tube heat exchangers for the petroleum and natural gas industries.


Tubesheet
Shell plate/shell
Tube
Expansion joint
Flange
Baffle
End cover
Dished end
Channel
Nozzle



## Tubes

Tubes of circular cross section are exclusively used in exchangers.

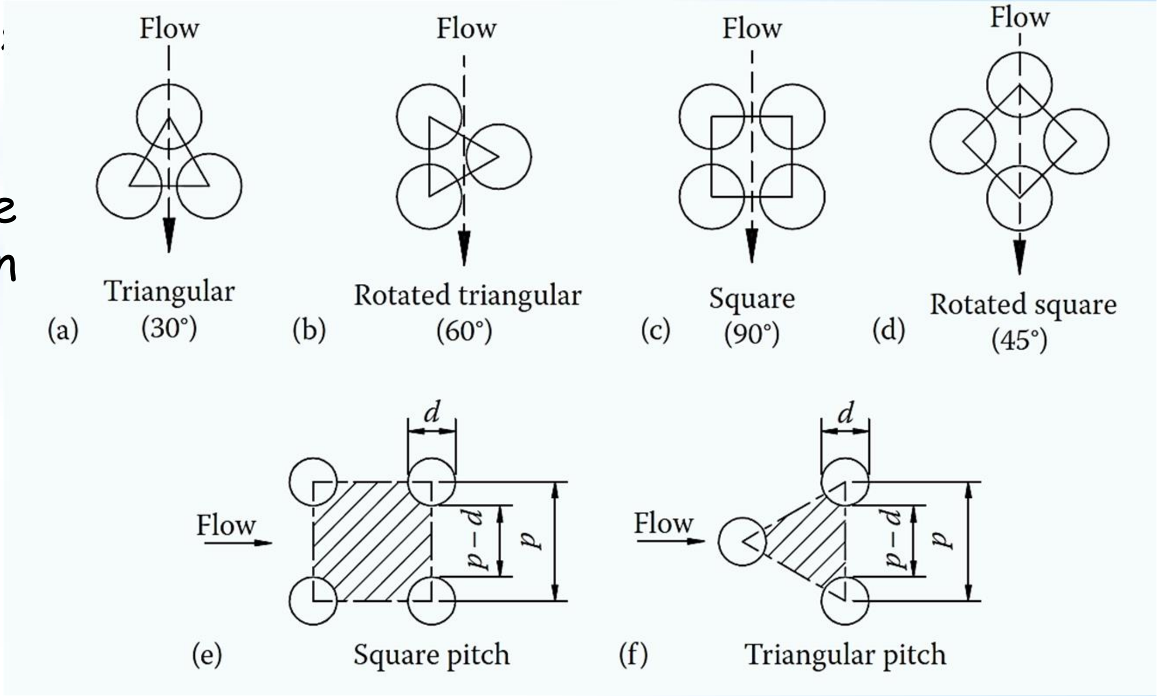
There are two types of tubes: straight tubes and U-tubes. The tubes are further classified as

1. Plain tubes
2. Finned tubes
3. Duplex or bimetallic tubes
4. Enhanced surface tube

## Tube Layout

The selection of the tube layout pattern depends on the following parameters:

1. Compactness
2. Heat transfer
3. Pressure drop
4. Accessibility for mechanical cleaning
5. Phase change in shell side



(a) Triangular (30°)
(b) Rotated triangular (60°)
(c) Square (90°)
(d) Rotated square (45°)
(e) Square pitch
(f) Triangular pitch

**Triangular and rotated triangular layouts** (30° and 60°) provide a compact arrangement, better shell side heat transfer coefficients, and stronger tube sheets for a specified shell side flow area.

For a given tube pitch/outside diameter ratio, about 15% more tubes can be accommodated within a given shell diameter using these layouts.

These layout patterns are satisfactory for clean services, but mechanical cleaning is not possible. Only chemical cleaning or water jet cleaning is possible.

**Square and Rotated Square layouts**

The square pitch is generally not used in the fixed design because of no need of mechanical cleaning on the shellside.

These layout patterns offer lower pressure drops and lower heat transfer coefficients than triangular pitch.

Shah [4] suggests a square layout for the following applications:

1. If the pressure drop is a constraint on the shellside, the 90° layout is used for turbulent flow, since in turbulent flow, the 90° has superior heat transfer rate and less pressure drop.

2. For reboilers, a square layout will be preferred for stability reasons. The 90° layout provides vapor escape lanes.

## Tube Diameter

Tube size is specified by outside diameter and wall thickness.

From the heat transfer point of view, smaller diameter tubes yield higher heat transfer coefficients and result in a compact exchanger.

However, larger diameter tubes are easier to clean, more rugged, and they are necessary when the allowable tubeside pressure drop is small.

Almost all heat exchanger tubes fall within the range of 1 in. (6.35 mm) to 2 in. (5.8 mm) outside diameter.

TEMA tube sizes in terms of outside diameter are ¼, 3/8, ½, 5/8, ¾, 7/9, 1, 1.25, 1.5, and 2 in.

## Tube Wall Thickness

The tube wall thickness is generally identified by the Birmingham wire gauge.

Standard tube sizes and tube wall thickness in inches are presented in TEMA Table.

Tube wall thickness must be checked against the internal and external pressures separately, or maximum pressure differential across the wall.

However, in many cases, the pressure is not the governing factor in determining the wall thickness. Except when pressure governs, the wall thickness is selected on these bases:

(1) Providing an adequate margin against corrosion,

(2) Fretting and wear due to flow-induced vibration,

(3) Axial strength, particularly in fixed exchangers,

(4) Standardized dimensions,

(5) Cost.

## U -Tube

### U-Tube U-Bend Requirements as per TEMA

When U-bends are formed, it is normal for the tube wall at the outer radius to thin. As per TEMA section RCB-2.33, the minimum tube wall thickness in the bent portion before bending shall be [2]

$$t_o = t_1\left(1 + \frac{d}{4R_b}\right)$$

where

$t_o$ is the original tube wall thickness

$t_1$ the minimum tube wall thickness calculated by code rules for a straight tube subjected to the same pressure and metal temperature

$d$ the tube outer diameter

$R_b$ the mean radius of bend

## Baffles

Baffles must generally be employed on the shell side

to support the tubes, to maintain the tube spacing,

to direct the shell side fluid across or along the tube bundle in a specified manner.

There are a number of different types of baffles, and these may be installed in different ways to provide the flow pattern required for a given application.

## Classification of Baffles

Baffles are either normal or parallel to the tubes. Accordingly, baffles may be classified as transverse or longitudinal.

The transverse baffles increase the turbulence of the shell fluid.

- Transverse Baffles

Transverse baffles are of two types:

(1) plate baffles and (2) rod baffles.

Three types of plate baffles are

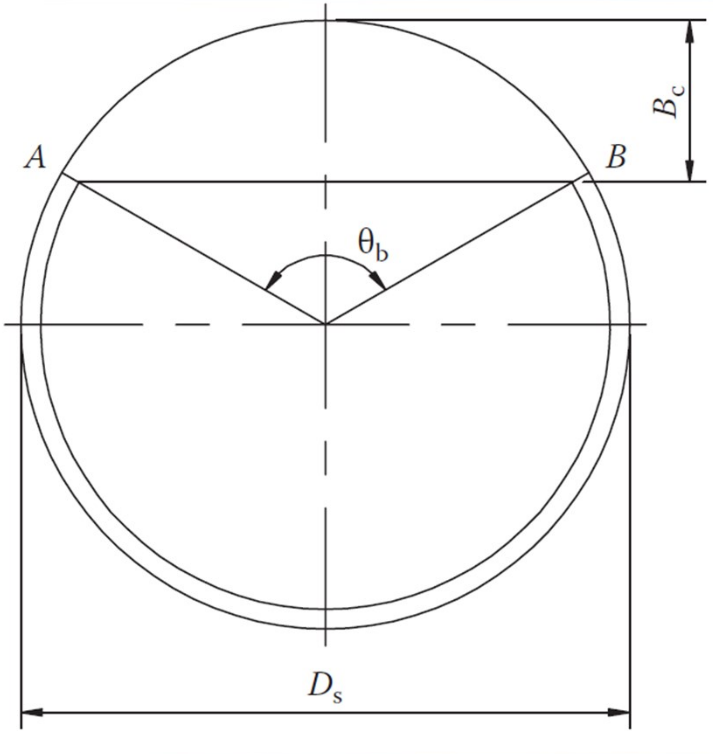
(1) segmental, (2) disk and doughnut, (3) orifice baffles.

**Segmental Baffles**

The baffle cuts vary from 20% to 49% with the most common being 20%–25%, and the optimum baffle cut is generally 20%, as it affords the highest heat transfer for a given pressure drop.

Baffle cuts smaller than 20% can result in high pressure (HP) drop.

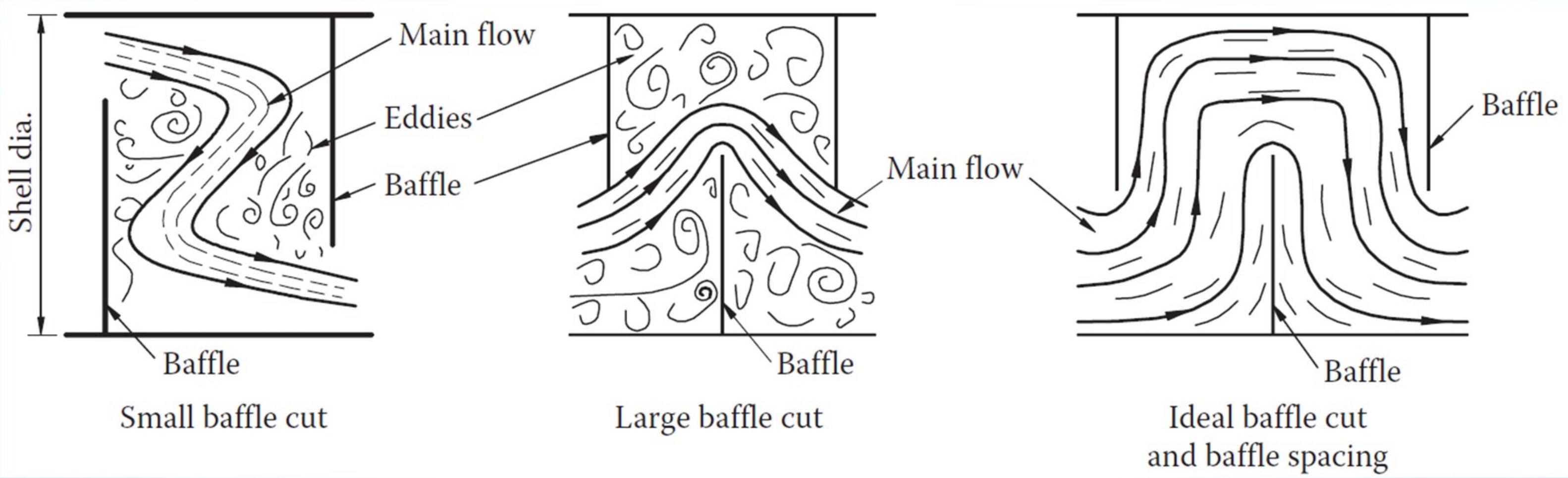
As the baffle cut increases beyond 20%, the flow pattern deviates more and more from crossflow and can result in stagnant regions or areas with lower flow velocities

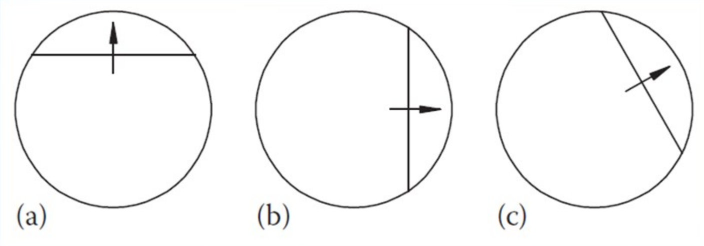


*Baffle spacing*: The practical range of single segmental baffle spacing is 1/5 to 1 shell diameter, though optimum could be 40%–50% [1].

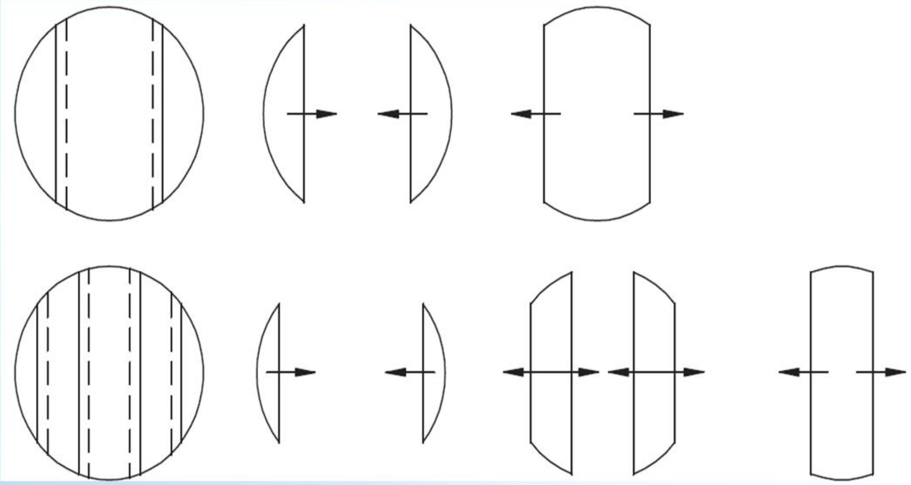
The inlet and outlet baffle spacings are in general larger than the "central" baffle spacing to accommodate the nozzles.

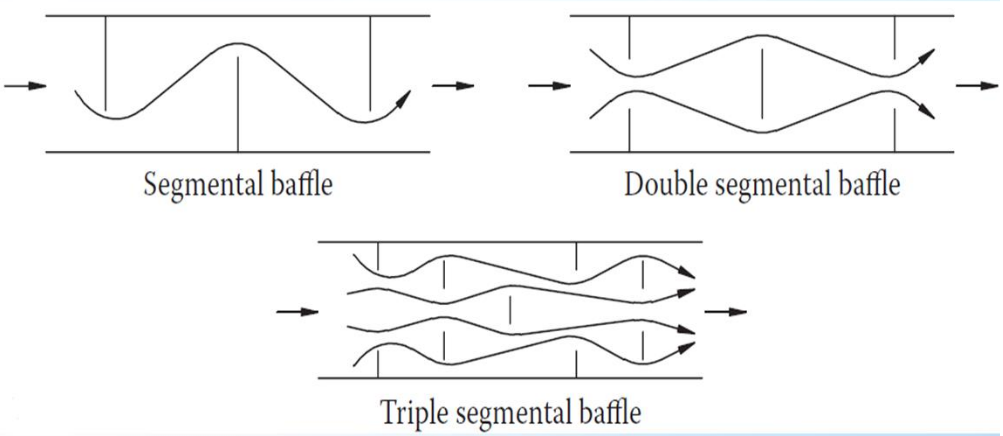
*Baffle thickness*: TEMA provide the minimum thickness of transverse baffles applying to all materials for various shell diameters and plate spacings.





Baffle cut orientation: (a) horizontal; (b) vertical; and (c) rotated.

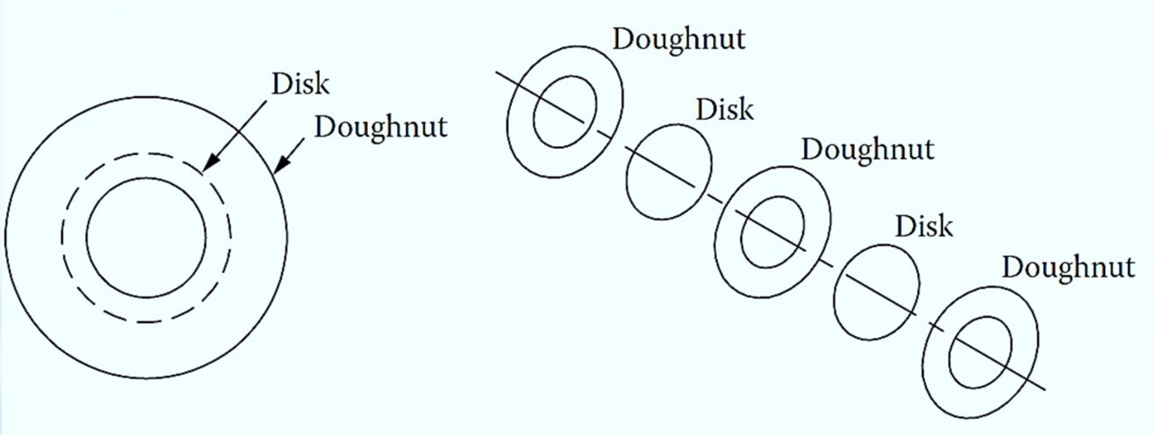




Segmental baffles layout. (a) Double and triple segmental baffles with end view flow pattern, stream flow distribution with segmental baffles.

## Disk and Doughnut Baffle

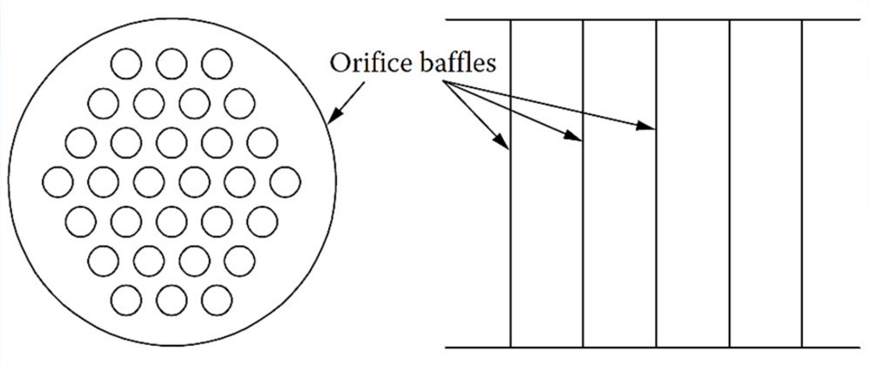
The disk and doughnut baffle is made up of alternate "disks" and "doughnut" baffles as shown in Figure. Disk and doughnut baffle heat exchangers are primarily used in nuclear heat exchangers



## Orifice Baffle

In an orifice baffle, the tube-to-baffle hole clearance is large so that it acts as an orifice for the shellside flow.

These baffles do not provide support to tubes, and, due to fouling, the annular orifices plug easily and cannot be cleaned. This baffle design is rarely used.

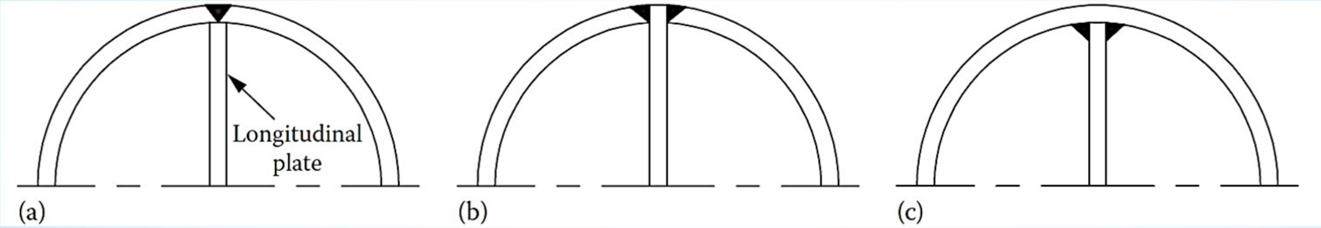


## Longitudinal Baffles

Longitudinal baffles divide the shell into two or more sections, providing multipass on the shellside. But this type should not be used unless the baffle is welded to the shell and tubesheet.

Lists of some sealing devices that are used to seal the baffle and shell. They are the following:

- Sealing strips or multiplex arrangement
- Packing arrangement
- Slide-in or tongue-and-groove arrangement



Longitudinal baffle weld joint with shell. (a) Shell gouged and welded, (b) baffle passes through shell and welded, and (c) baffle welded to inside of the shell.

## Rod Baffles

Phillips RODbaffle design uses alternate sets of rod grids instead of plate baffles, enabling the tubes to be supported at shorter intervals without resulting in a large pressure drop.

Flow-induced vibration is virtually eliminated by this design.

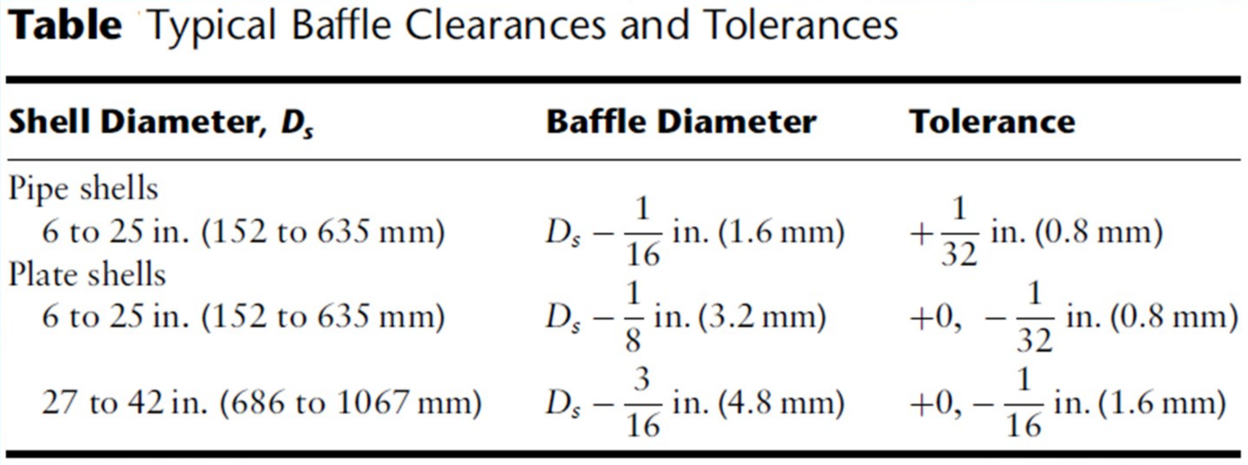


**Table** Typical Baffle Clearances and Tolerances

| **Shell Diameter, $D_s$** | **Baffle Diameter** | **Tolerance** |
|---|---|---|
| Pipe shells | | |
| 6 to 25 in. (152 to 635 mm) | $D_s - \frac{1}{16}$ in. (1.6 mm) | $+\frac{1}{32}$ in. (0.8 mm) |
| Plate shells | | |
| 6 to 25 in. (152 to 635 mm) | $D_s - \frac{1}{8}$ in. (3.2 mm) | $+0, \; -\frac{1}{32}$ in. (0.8 mm) |
| 27 to 42 in. (686 to 1067 mm) | $D_s - \frac{3}{16}$ in. (4.8 mm) | $+0, -\frac{1}{16}$ in. (1.6 mm) |

## Tubesheet and its Connection with Shell and Channel

A tubesheet is an important component of a heat exchanger. It is the principal barrier between the shell side and tubeside fluids.

Proper design of a tubesheet is important for safety and reliability of the heat exchanger.

Tubesheets are mostly circular with uniform pattern of drilled holes as shown in Figure.

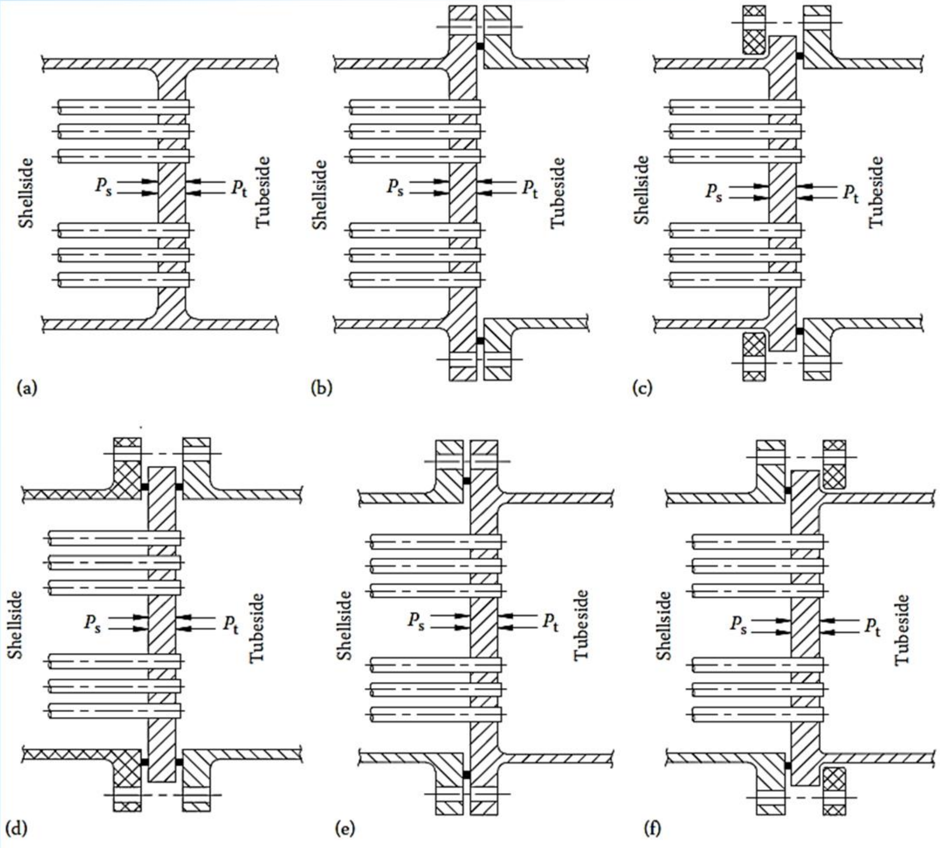
Tubesheets are connected to the shell and the channels either by welds (integral) or with bolts (gasketed joints) or with a combination thereof in six possible types:

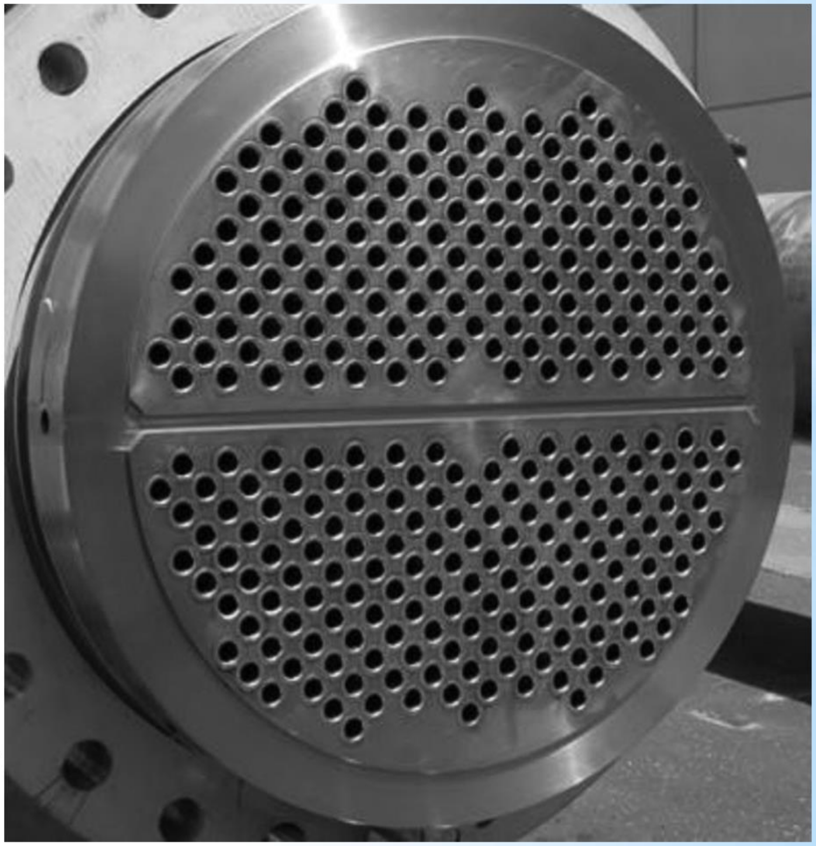
1. Both shellside and tubeside are integral with tubesheet
2. Shellside integral and gasketed on tubeside, tubesheet extended as a flange
3. Shellside integral and tubeside gasketed construction

4. Both shellside and tubeside gasketed construction

5. Tubesheet gasketed on shellside and integral with channel, extended as a flange

6. Shellside gasketed and tubeside integral construction





## Tube-to-Tubesheet Attachment

Tubes are attached to the tubesheet by

(1) rolling, (2) welding, (3) rolling and welding, (4) explosive welding, (5) brazing.

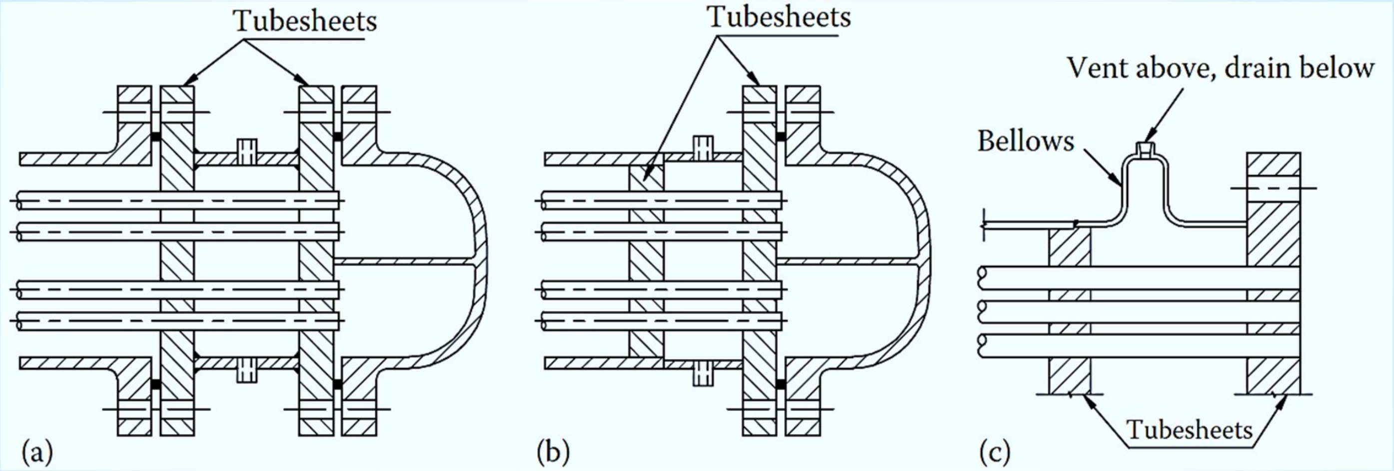
## Double Tubesheets

When the possibility of intermixing of the shellside and tubeside fluids cannot be tolerated, double tubesheet construction will offer positive assurance against one fluid leaking into the other at a tube to tubesheet joint.

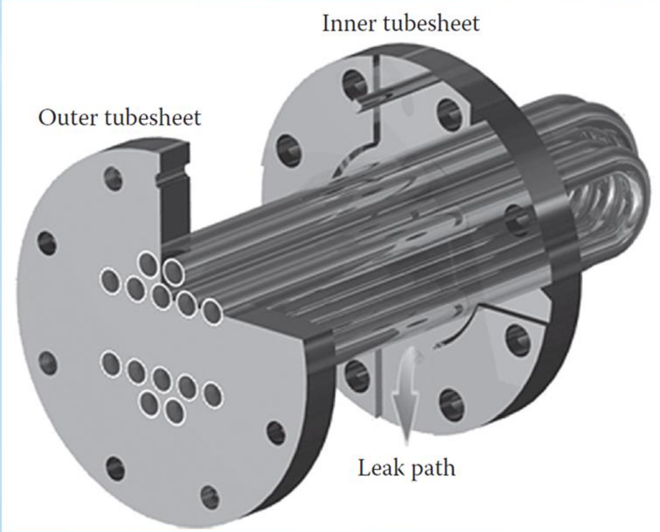
Two designs of double tubesheets are available:

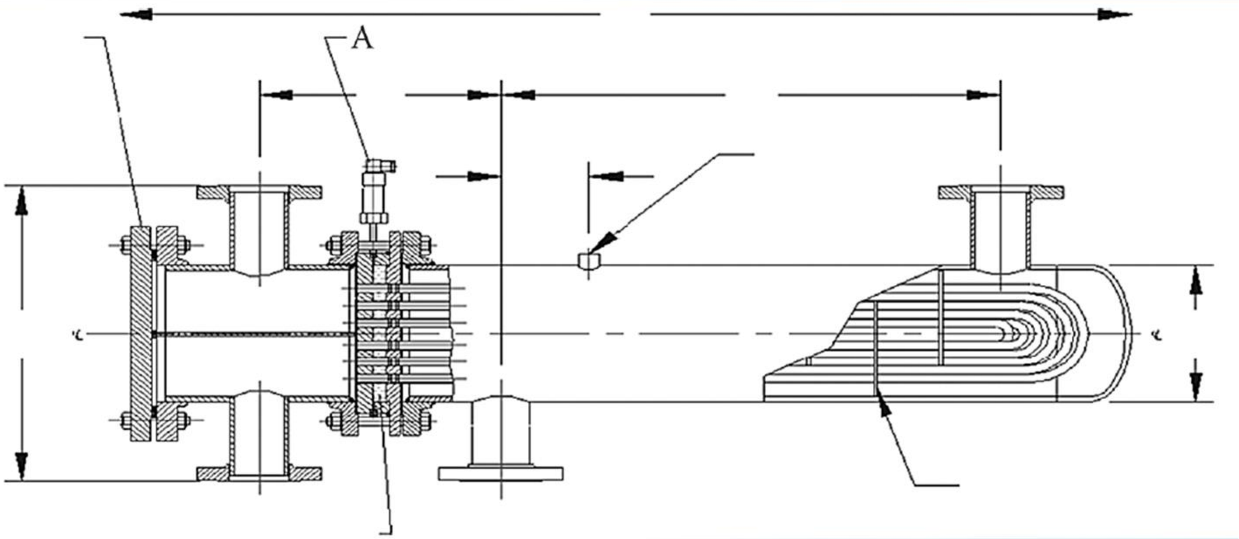
(1) the conventional double tubesheet design, which consists of two individual tubesheets at each end of the tubes

(2) the integral double tubesheet design



Double tubesheet shell and tube heat exchanger—schematic.
(a) Removable tube bundle with light gauge shroud between two tubesheets
(b) Fixed tubesheets with light gauge shroud
(c) Fixed tubesheet with bellows





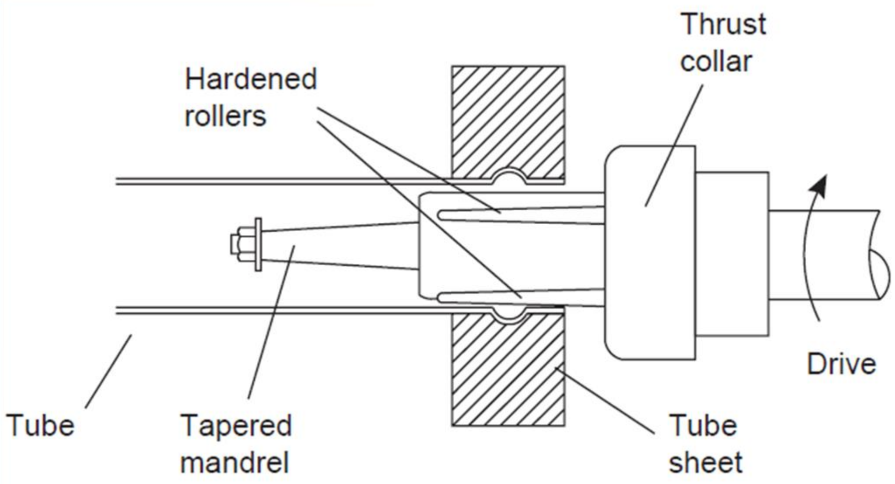
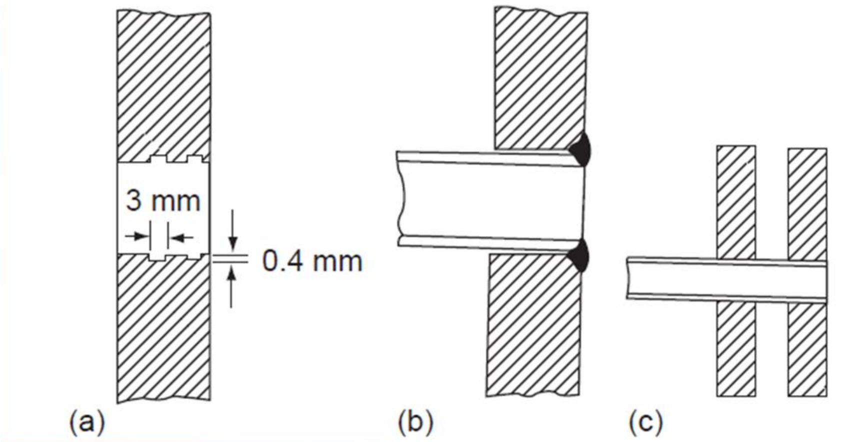


**Figure** Tube rolling.



The joint between the tubes and tube sheet is normally made by expanding the tube by rolling with special tools, as shown in Figure.

Tube rolling is a skilled task; the tube must be expanded sufficiently to ensure a sound leaf-proof joint, but not over thinned, weakening the tube.

The tube holes are normally grooved, as shown in Figure.

The double tubesheet can be installed only in the U-tube, fixed tubesheet, and floating head, outside packed stuffing box exchangers.

It is not feasible to use the double tubesheet in heat exchanger types such as

(1) floating head, pull-through bundle,

(2) floating head with split backing ring,

(3) floating head, outside packed lantern ring exchangers.

## Tube Bundle

A tube bundle is an assembly of tubes, baffles, tubesheets, spacers and tie-rods, and longitudinal baffles, if any.

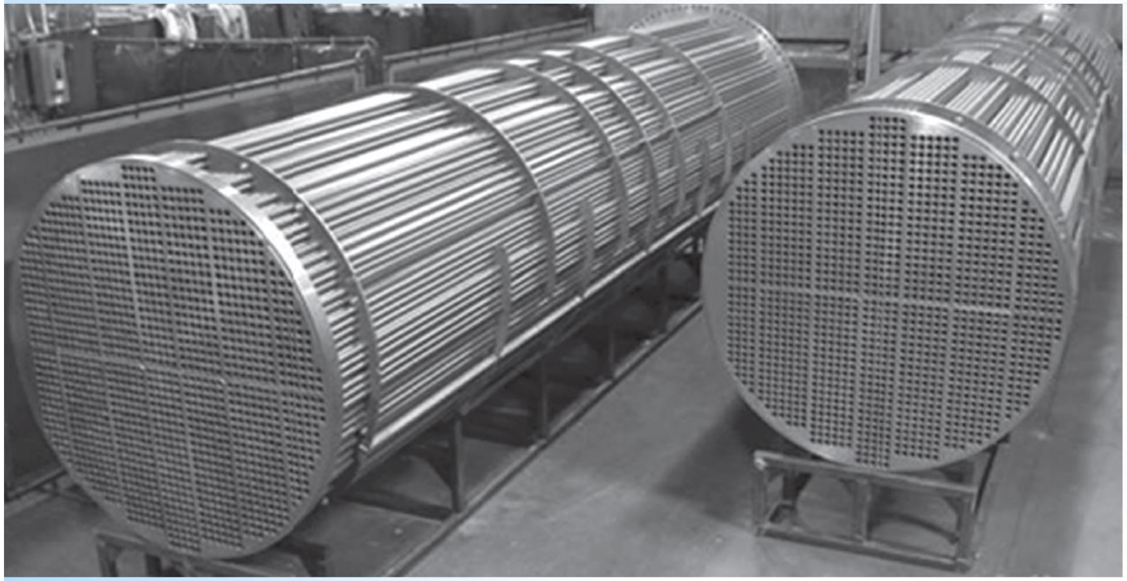
Spacers and tie-rods are required for maintaining the space between baffles.

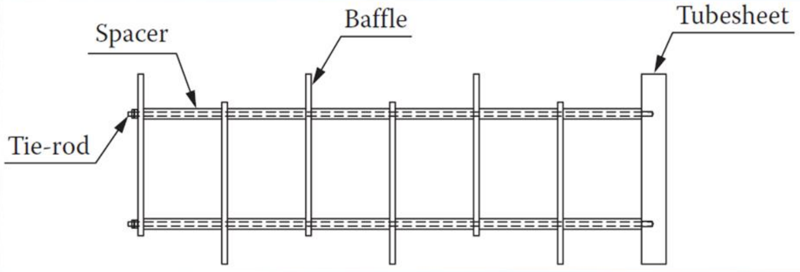
## Spacers, Tie-Rods, and Sealing Devices

The tube bundle is held together and the baffles are located in their correct positions by a number of tie-rods and spacers.

The tie-rods are screwed into the stationary tubesheet and extend the length of the bundle up to the last baffle, where they are secured by locknuts.

Tie-rods and spacers may also be used as a sealing device to block bypass paths due to pass partition lanes or the clearance between the shell and the tube bundle.





## Tube-Sheet Layout (Tube Count)

The bundle diameter will depend not only on the number of tubes but also on the number of tube passes.

Spaces must be left in the pattern of tubes on the tube sheet to accommodate the pass-partition plates.

An estimate of the bundle diameter $D_b$ can be obtained from equation, which is an empirical equation based on standard tube layouts.

$$N_t = K_1 \left(\frac{D_b}{d_o}\right)^{n_1},$$

$$D_b = d_o \left(\frac{N_t}{K_1}\right)^{1/n_1},$$

The constants for use in this equation, for triangular and square patterns, are given in Table.

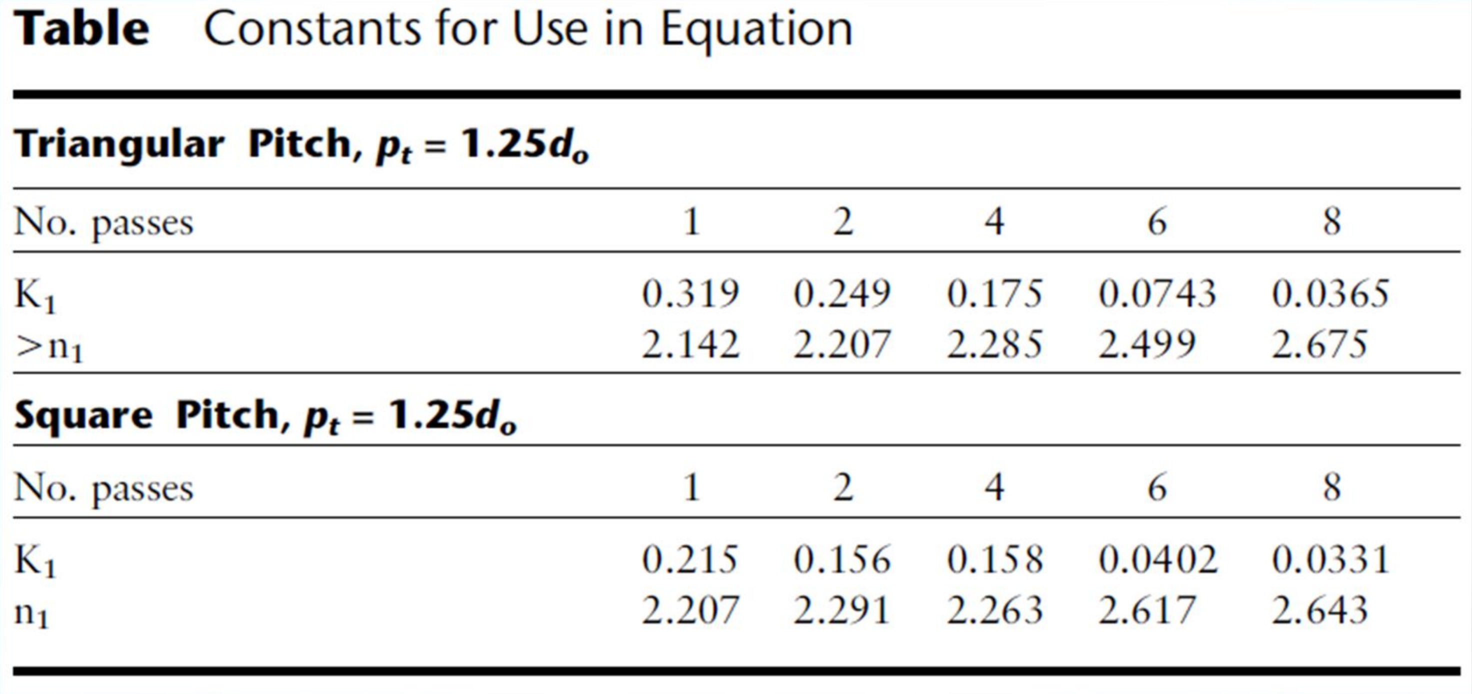


**Table** Constants for Use in Equation

**Triangular Pitch, $p_t = 1.25d_o$**

| No. passes | 1 | 2 | 4 | 6 | 8 |
|---|---|---|---|---|---|
| $K_1$ | 0.319 | 0.249 | 0.175 | 0.0743 | 0.0365 |
| $>n_1$ | 2.142 | 2.207 | 2.285 | 2.499 | 2.675 |

**Square Pitch, $p_t = 1.25d_o$**

| No. passes | 1 | 2 | 4 | 6 | 8 |
|---|---|---|---|---|---|
| $K_1$ | 0.215 | 0.156 | 0.158 | 0.0402 | 0.0331 |
| $n_1$ | 2.207 | 2.291 | 2.263 | 2.617 | 2.643 |

An estimate of the number of tubes in a U-tube exchanger (twice the actual number of U-tubes) can be made by reducing the number given by equation by one center row of tubes.

The number of tubes in the center row, the row at the shell equator, is given by

$$\text{Tubes in center row} = \frac{D_b}{P_t}$$

## Shells

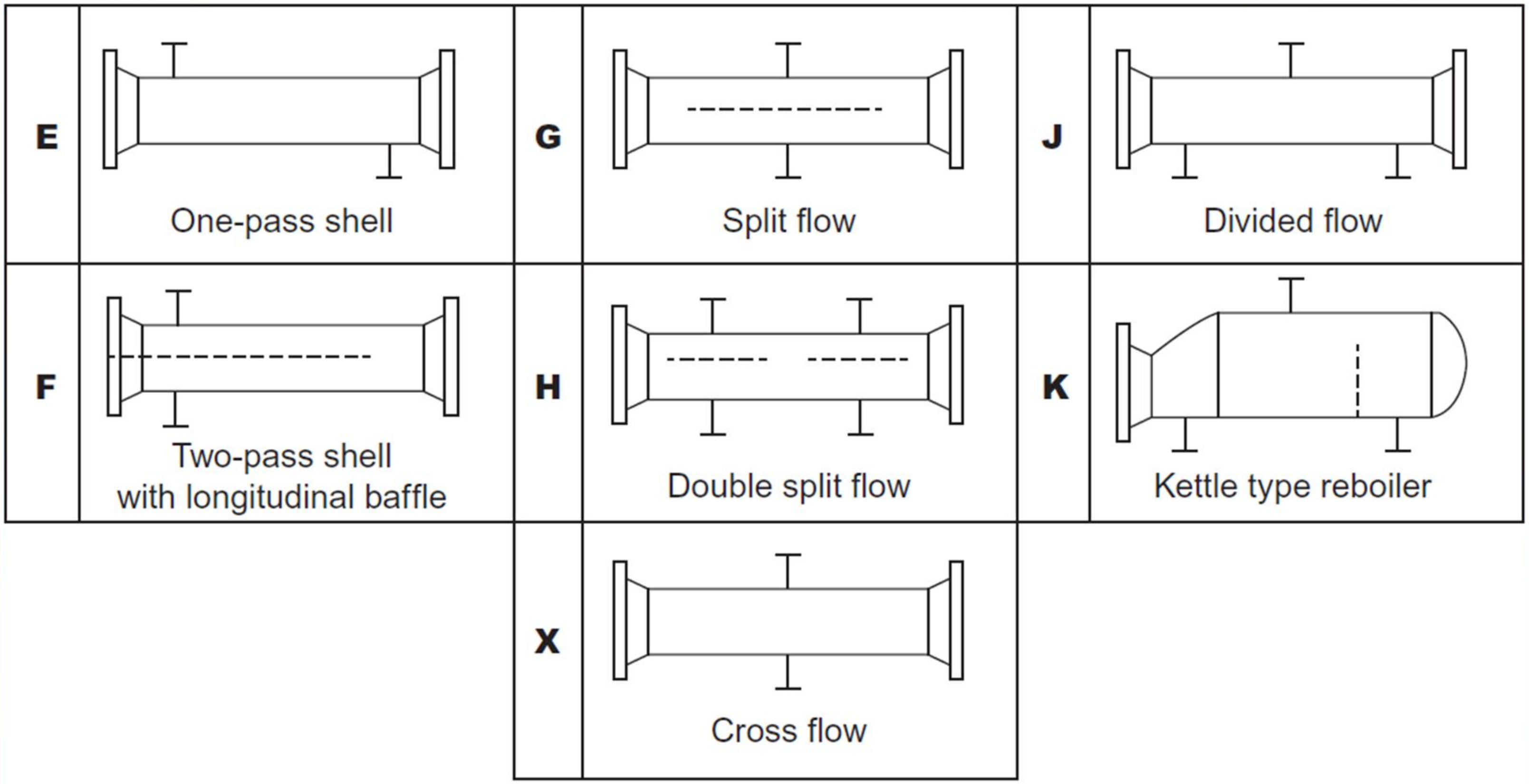
Shells are manufactured in a large range of standard sizes, materials, and thickness.

Smaller sizes are usually fabricated from standard size pipes.

Larger sizes are fabricated from plate by rolling.

The cost of the shell is much more than the cost of the tubes; hence, a designer tries to accommodate the required heat transfer surface in one shell.

It is found that a more economical heat exchanger can usually be designed by using a small diameter shell and the maximum shell length permitted by such practical factors as plant layout, installation, servicing, etc..



TEMA shell types

## Pass Arrangement

### Tubeside Passes

The simplest flow pattern through the tubes is for the fluid to enter at one end and exit at the other. This is a single-pass tube arrangement.

To improve the heat transfer rate, higher velocities are preferred. This is achieved by increasing the number of tubeside passes.

The improvements achievable with multipass heat exchangers are sufficiently large, and hence they have become common in industry than the counterflow designs.

Tubeside multiple passes are normally designed to provide roughly equal number of tubes in each pass to ensure an even fluid velocity and pressure drop throughout the bundle.

In a two-tube-pass arrangement, the fluid flows through only half of the total tubes, so that the Reynolds number is high.

Increasing the Reynolds number results in increased turbulence and Nusselt number and finally increase in overall heat transfer coefficient.

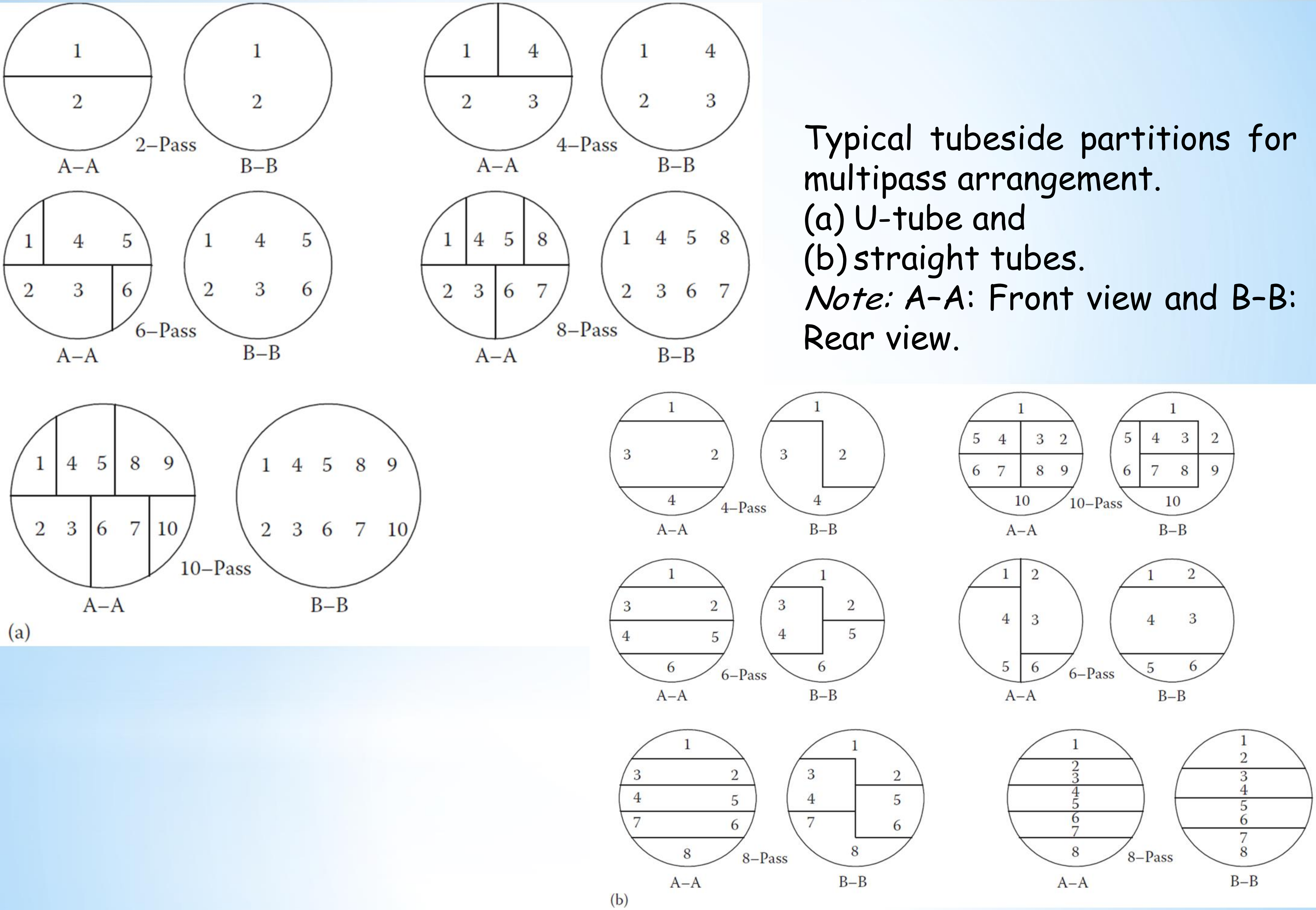
**Number of Tube Passes**

The number of tubeside passes generally ranges from one to eight.

The standard design has one, two, or four tube passes. The practical upper limit is 16.

Larowski et al. [9] suggest the following guidelines for tubeside passes:

- Two-phase flow on the tubeside, whether condensing or boiling, is best kept in a single straight tube run or in a U-tube.
- If the shellside heat transfer coefficient is significantly lower than that on the tubeside, don't increase the film coefficient on the tubeside at the cost of higher tubeside pressure drop, since this situation will lead to a marginal improvement in overall heat transfer coefficient.

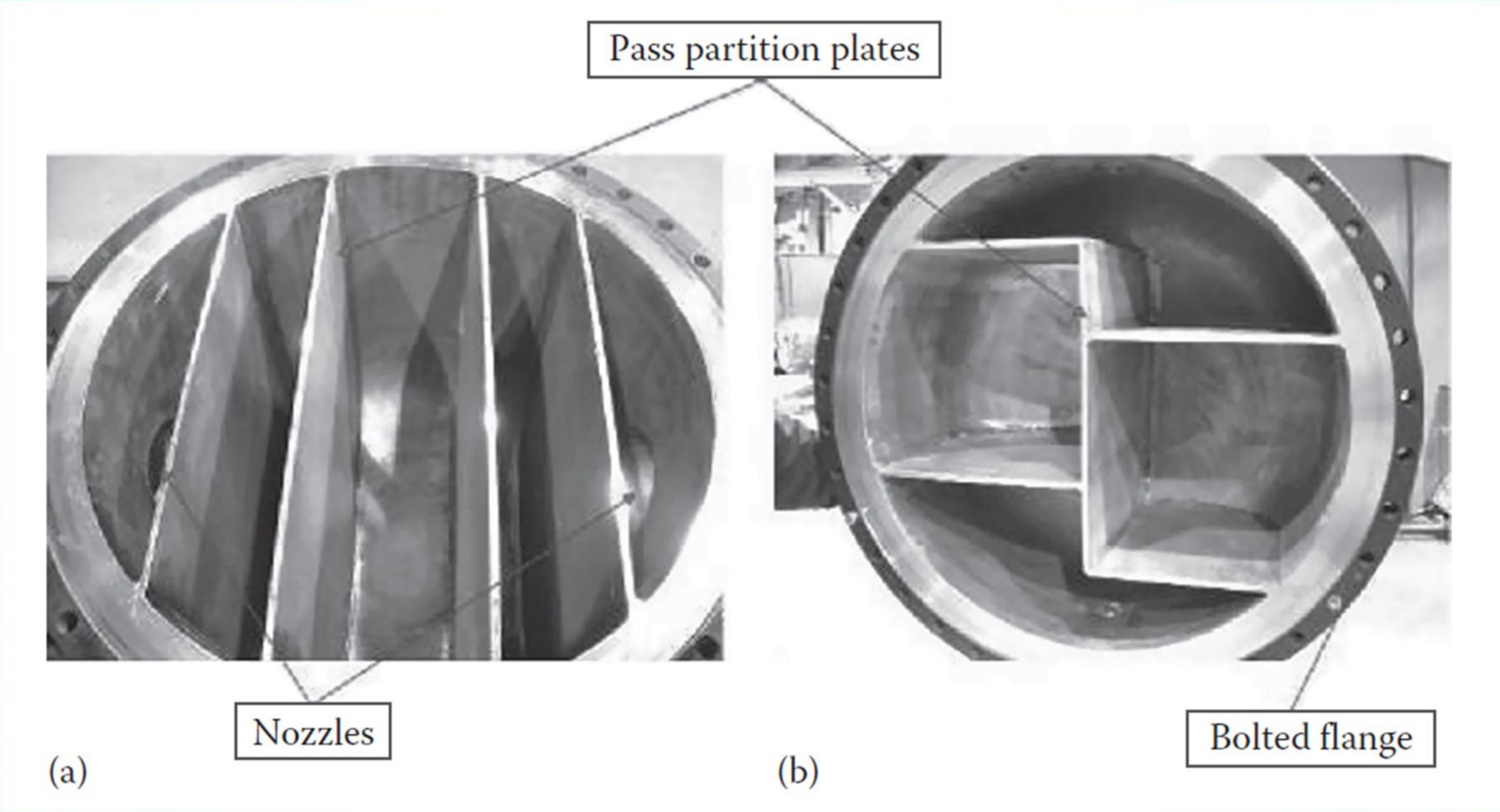


Typical tubeside partitions for multipass arrangement.

(a) U-tube and

(b) straight tubes.

*Note:* A–A: Front view and B–B: Rear view.



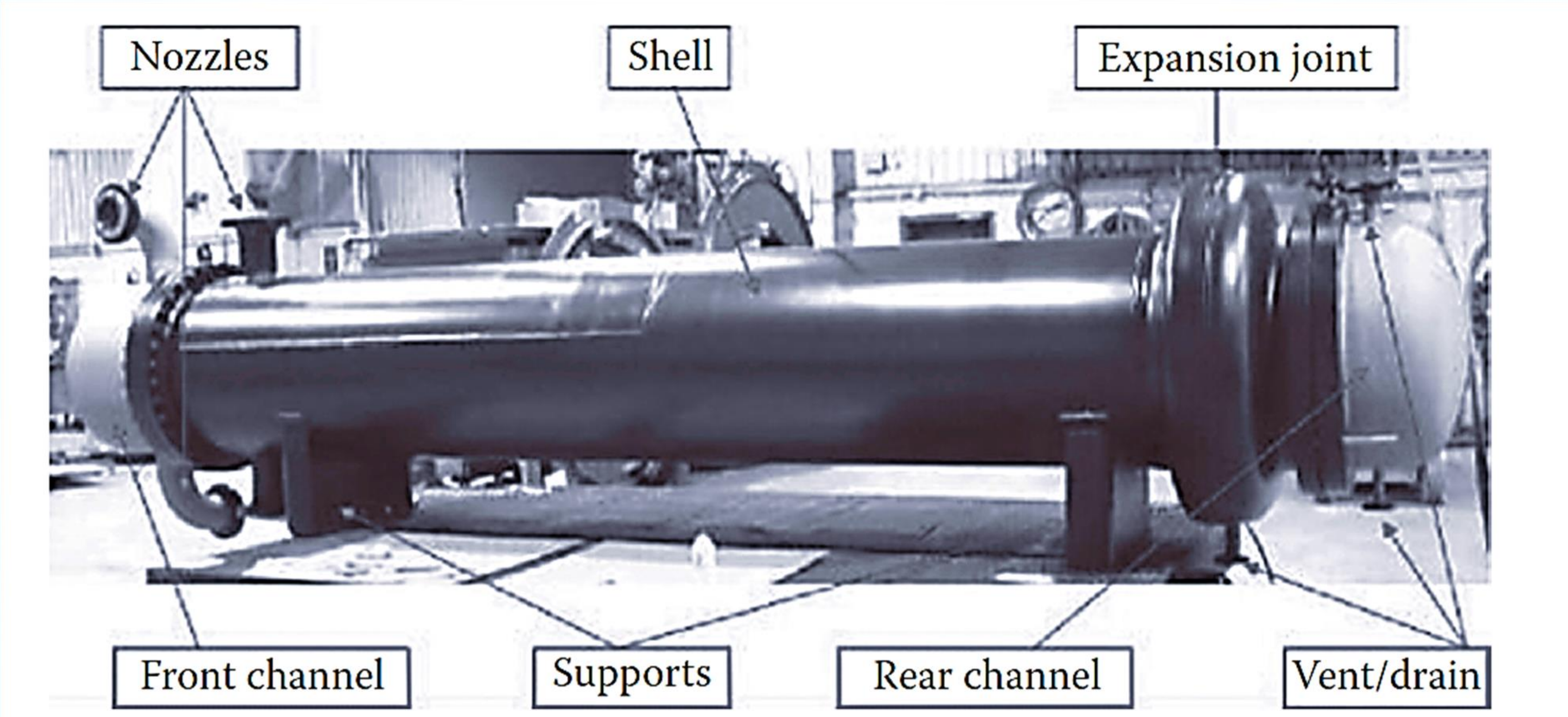
Six-pass partitions in (a) front channel and (b) rear channel. (Courtesy of Festival City Fabricators, div. of CSTI, Stratford, Ontario, Canada.)

## Shellside Passes

For exchangers requiring high effectiveness, multipassing is the only alternative.

Shellside passes could be made by the use of longitudinal baffles. However, multipassing on the shell with longitudinal baffles will reduce the flow area per pass compared to a single pass on the shellside.

This drawback is overcome by shells in series, which is also equivalent to multipassing on the shellside.

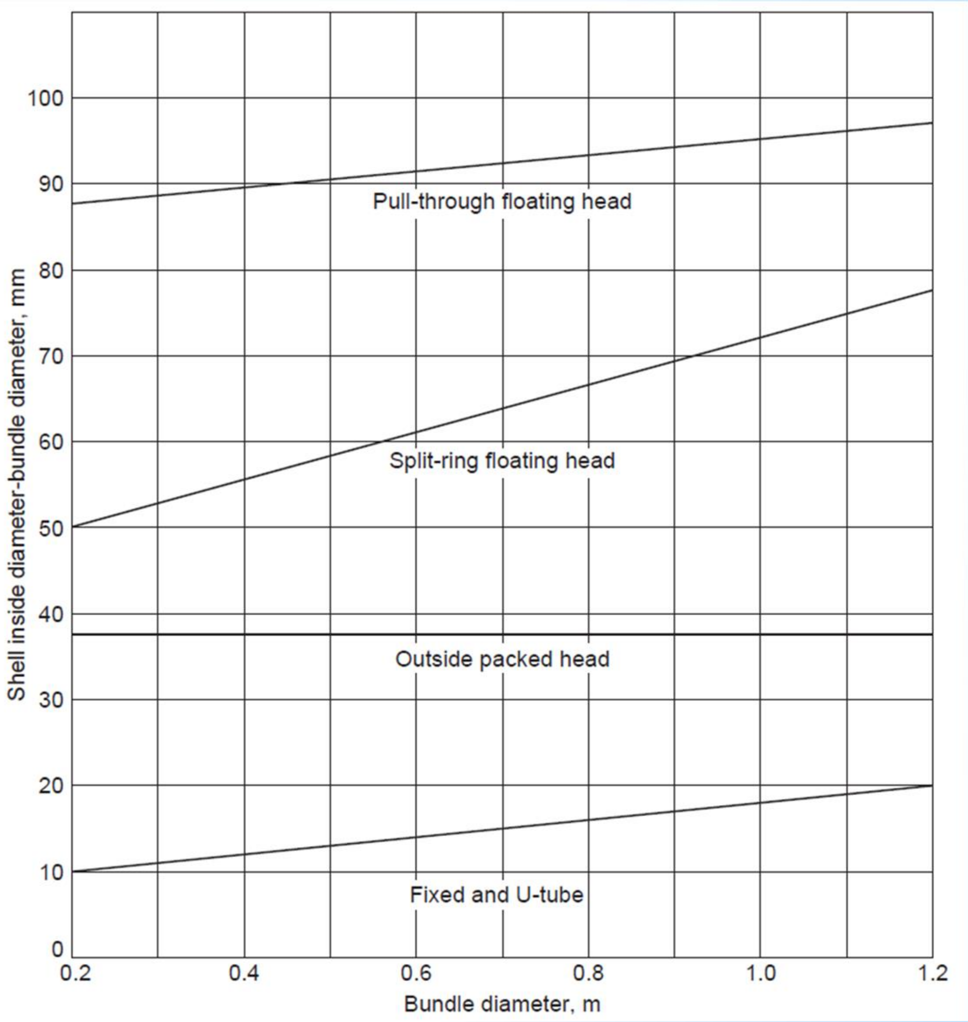


Fixed tubesheet shell and tube heat exchanger with an expansion joint. (Courtesy of Festival City Fabricators, div. of CSTI, Stratford, Ontario, Canada.)

The clearance required between the outermost tubes in the bundle and the shell inside diameter will depend on the type of exchanger and the manufacturing tolerances.

Typical values are given in

Figure



**Shell and Header Nozzles (Branches)**

Standard pipe sizes will be used for the inlet and outlet nozzles.

It is important to avoid flow restrictions at the inlet and outlet nozzles to prevent excessive pressure drop and flow-induced vibration of the tubes.

The baffle spacing is usually increased in the nozzle zone, to increase the flow area.

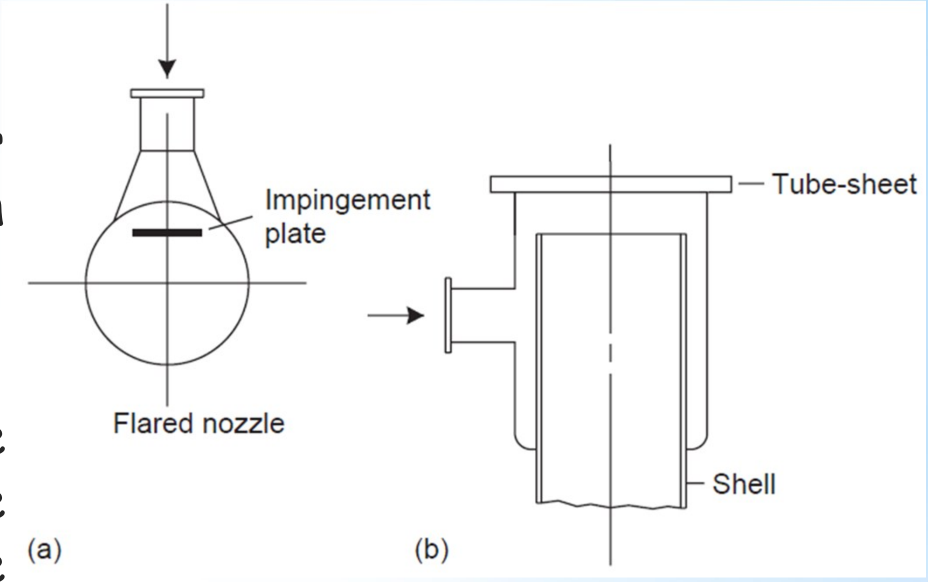
For vapors and gases, where the inlet velocities will be high, the nozzle may be flared, or special designs used, to reduce the inlet velocities; see Figure.

The extended shell design shown in Figure also serves as an impingement plate. Impingement plates are used where the shell-side fluid contains liquid drops or for high-velocity fluids containing abrasive particles.

## Flow-Induced Tube Vibrations

Premature failure of exchanger tubes can occur through vibrations induced by the shell-side fluid flow.

Care must be taken in the mechanical design of large exchangers where the shell-side velocity is high, say greater than 3 m/s, to ensure that tubes are adequately supported.



(a, b) Inlet nozzle designs.

The vibration induced by the fluid flowing over the tube bundle is caused principally by vortex shedding and turbulent buffeting.

Turbulent buffeting of tubes occurs at high flow rates due to the intense turbulence at high Reynolds numbers.