# An extensive overview of heat exchangers in the process industry

The range of heat exchangers used within the process industry is extensive. In this article, BASF's Lead Mechanical Engineer, Aeishwarya Chaudhari, and Mechanical Team Lead, Mahesh Kulkarni, offer a detailed overview of heat exchanger types and their applications.

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## Heat exchanger types based on flow

Fundamentally, heat exchangers can be categorized into the following main types based on the flow direction of the fluids in a heat exchanger:

**Co-current flow type**

These heat exchangers are also known as heat exchangers with parallel flow. In this type of heat exchanger, both the fluids flow in the same direction as depicted in Figure 1

**Counter-current flow type**

These heat exchangers are the ones in which both the fluids flow in the opposite direction as seen in Figure 1

**Cross flow type**

These heat exchangers are the ones in which both the fluids flow in the direction perpendicular to each other as depicted in Figure 1

**Hybrid flow type**

These heat exchangers are the ones in which more than one type of flow types are used for the heat transfer as seen in Figure 1

## Heat exchanger types based on construction

Heat exchangers are also categorized into various types based on their construction. Following are the most commonly found heat exchangers in any process facility.

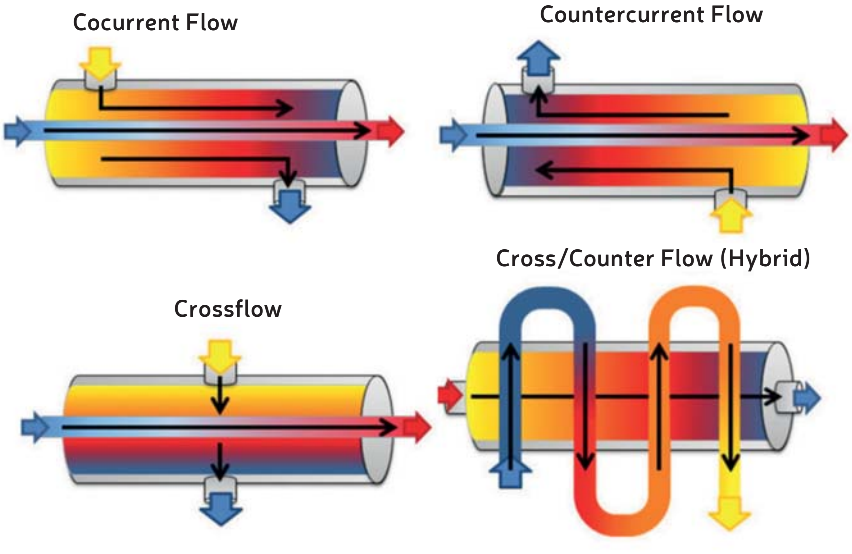



*Figure 1: Types of heat exchanger based on flow.*

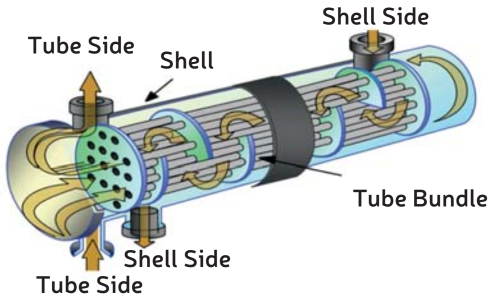



*Figure 2: An example of a shell and tube heat exchanger.*

### Shell and tube heat exchangers - Fixed tubesheet

- Fixed Tube Sheet Exchangers TEMA Types: (TEMA Rear End Head Type-L, M and N)
- In these heat exchangers, tube sheets are welded to the shell at both ends
- This provides excellent protection from leakage of shell side fluids to the outside for lethal service
- The tube bundle cannot be removed for cleaning, maintenance, or inspection, whilst individual tubes can be accessed for cleaning or replacement
- This type is suited for services where the shell side fouling factor is below 0.00035m$^2$-K/W, and where the exchanger type is a single tube pass
- Differential thermal expansion between the shell and tubes limits applicability to a moderate temperature difference. All conditions must be specified in the process data sheet for the mechanical engineer to determine the necessity for a thermal expansion joint
- For services which would require a thermal expansion joint, U-tube exchangers may be more economical

### Shell and tube heat exchangers - U-tube

- U-tube exchangers TEMA Types: (TEMA Rear End Head Type-U)
- Both ends of the U-tube are fixed to a single tube sheet
- Advantages are that it eliminates the problems of differential thermal expansion, and the U-tube bundle can be easily removed for cleaning and maintenance
- Construction only requires one tube sheet joint, and they are well suited for high pressure and high temperature applications
- Disadvantages are that repairing of individual tubes, except those on the outside of the bundle, are limited

### Shell and tube heat exchangers - Floating head

- The floating tube sheet shell and tube exchanger is equipped with straight tubes attached at both ends to a tube sheet
- One tube sheet is free to move as the exchanger heats up or cools down
- Mechanical cleaning is possible for both the shell and the tube side
- There are many designs of rear end enclosure to provide access to the tube-sheet for servicing, maintenance, and inspection

Figure 3: Plate and frame heat exchanger.

### Plate and frame type heat exchangers

This type of exchanger has a compact design as compared to the shell and tube or air-cooled heat exchanger. They are also easy to install and maintain. Opening and closing a standard unit does not require dismantling of associated piping. Capacity can be augmented by simply adding plates in case of gasketed plate heat exchanger. True counter current flow can be achieved (delta T as low as 1°C). However, the use of these heat exchangers is generally limited by very high design pressures (plates), very high design temperatures (gasket materials) and viscous fluids.

### Air cooled heat exchanger

These exchangers are used when reliable source of cooling water is unavailable. They come in 2 types: Induced draft and forced draft. They are generally used when required by project economics. Installation of these exchangers is also dependent on the available plot size. Aluminum finned tubes are generally used to enhance heat transfer rate and efficiency due to low heat transfer coefficient of air. The temperature of process fluid is governed by ambient air temperature.
These exchangers require various controls such as variable pitch fan blades, variable speed fans, motors, instrument connections, louvers etc.

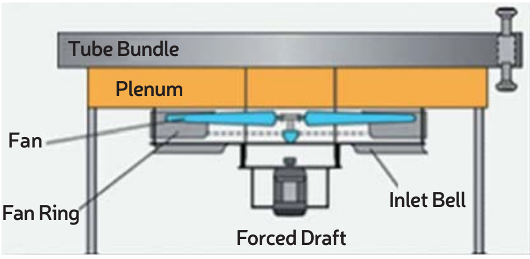



Figure 5: Example of forced draft air cooled heat exchanger.

### Spiral type heat exchanger

This type of heat exchanger is a proprietary design and also uses plates for the heat transfer. These exchangers use spiral coiled plates which are arranged in a concentric way. This is a very compact design and thereby consumes very little space. These exchangers are designed to handle heat transfers of highly viscous fluids.

Figure 6: Spiral heat exchanger.

### Hairpin type heat exchanger

Hairpin type heat exchangers are also known as double pipe heat exchangers. The construction of these exchangers is quite simple as compared to conventional shell and tube heat exchangers. These exchangers are quite economical. Typical components such as girth flanges and tube sheets are also not seen in this type of heat exchanger. As the name suggests, there is an outer pipe and an inner pipe where the heat transfer happens. These are single pass heat exchangers. The appearance of these exchangers is like a hairpin.

Figure 4: Hairpin heat exchanger.

## Thermal and hydraulic design

Process design for heat exchangers must be based on a clear understanding of the criteria by which the heat exchanger will be judged. These criteria are simple to state, but a designer attempts to apply them to a specific case.

The criteria are in an approximate order of importance:

1. A heat exchanger should satisfy the fulfilment of the process requirements to accomplish the thermal change on the streams within the allowable pressure drops, and to retain the capability to do this in the presence of fouling until the next scheduled maintenance period. However, it must be recognized that the design process is fraught with uncertainties. The precise physical properties are known, the design methods incorporate basic correlations of various degrees based on experiments and experience. The exchangers are constructed only within certain dimensional limits, the actual operating conditions and process stream characteristics.
2. The heat exchanger must withstand the service conditions of the plant environment. The immediate consideration here is the mechanical stresses, not only in normal operation but in shipping, installation, start-up, shutdown, and off-specification operation caused by plant upsets and conceivable accidents. There are external mechanical stresses imposed by the piping on the exchanger by both steady state and transient flow and temperature variations of the streams. The exchanger must resist corrosion by the service and process streams and by the environment.
3. The exchanger must be maintainable, which usually means choosing a configuration that permits cleaning as required and replacement of tubes, gaskets, and any other components that are especially vulnerable to corrosion, erosion, vibration, or aging. This requirement may also place limitations on positioning the exchanger and providing clear space around it.
4. Consider the advantages of a multi-shell arrangement with flexible piping and valving provided to allow one unit to be taken out of service for maintenance without severely upsetting the rest of the plant.
5. The exchanger should be as cost efficient as possible, consistent with the above criteria being satisfied. Balanced against possible savings in CAPEX and OPEX.

There may be limitations on exchanger diameter, length, weight, and/or tube specifications due to site requirements, lifting and servicing capabilities, and maintaining an inventory of replacement tubes and gaskets.

## Heat transfer calculation

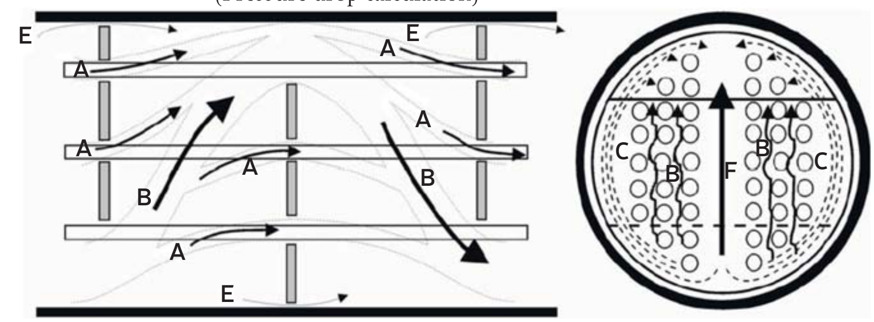
The local rate of heat transfer is related to the local temperature difference between the two streams by dQ = U*(Th - Tc) dA* where Th and T, are the local temperatures of the hot and cold streams, respectively. The asterisks are retained on U and A to indicate that these values must be on a consistent area basis and that this may be any convenient one. The differential form is used here to emphasize that a given set of values of U*, Th, and Tc will ordinarily be valid only at one point in the heat exchanger, and at this point an amount of heat dQ is transferred through an element of area dA*

$$A^* = \int_o^{Q_T} \frac{dQ}{U^*(T_h - T_c)}$$

This equation can be integrated analytically if a number of assumptions are made. The result, given below, is the mean temperature difference (MTD) concept. The following key assumptions that need to be made:

1. Every drop of fluid that enters the heat exchanger in a given stream has an equal opportunity to encounter heat transfer surface. That is, if any part of a stream is able to bypass heat transfer surface in passing through the exchanger, the MTD concept is inapplicable, at least in its unmodified form.

(Pressure drop calculation)




A = Tube Baffle Leakage  B = Crossflow  C = Crossflow Bypass
E = Shell Baffle Leakage  F = Tube Pass Partition Bypass

*Figure 7: Flowstreams.*

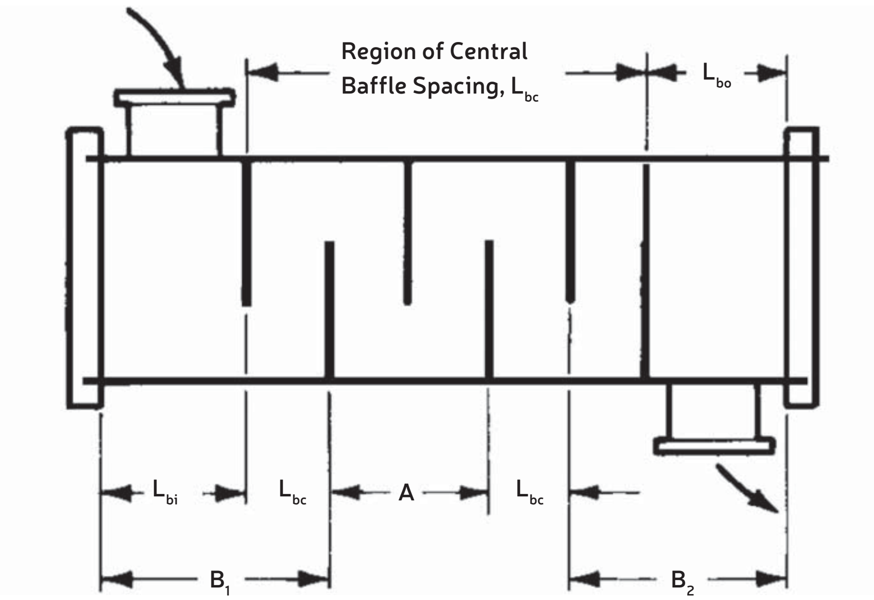



*Figure 8: Cross sectional view : Internal baffle spacing.*

2. The heat exchanger is at steady state.
3. The specific heats of each stream are constant. An isothermal phase transition (e.g., condensation of a pure vapor with negligible pressure drop) corresponds to an infinite specific heat, which satisfies the assumption and in fact simplifies the result.
4. The overall heat transfer coefficient is constant.
5. Heat losses or gains to/from the surroundings are negligible.
6. Longitudinal heat flow is negligible.
7. The flow arrangement is either purely counter current or purely concurrent.

Correlations for thermal and hydraulic design uses the dimensionless numbers in fluid mechanics and heat transfer.

## Overall heat transfer coefficient

Heat transfer coefficient (HTC) for fluid flowing through pipe or tube is defined using the Dittus-Bolter equation:

$$Nu = 0.023Re^{0.8}\, Pr^{0.4}$$

and heat transfer coefficient is given by:

$$h = Nu\, k$$

Inside heat transfer coefficient (*hi*) is found by using inside diameter and all inside fluid-properties while outside heat transfer coefficient (*ho*) is found by using hydraulic diameter and all outside-fluid properties.

The overall heat transfer coefficient (*U*) is given by:

$$\frac{1}{U} = \frac{1}{h_o} + \frac{1}{h_i}\left(\frac{A_o}{A_1}\right) + R_{fo} + R_{f1}\left(\frac{A_o}{A_1}\right) + R_w$$

Wall resistance *Rw* is given by:

$$R_w = \frac{t_{wt} \times 10^{-3}}{k_{tw}} = \frac{\text{Wall thickness}}{\text{Wall thermal conductivity}}$$

(Pressure drop calculation)

Pressure drop for fluids flowing through pipe can be found out by Darcy-Wisbac equation.

$$\Delta p = \frac{fLv^2}{2gd}$$

Where '*f*' is the friction factor for the particular fluid, *L* be the tube length, *v* is the fluid flow velocity and *d* is the diameter of tube. Velocity and diameter are taken in the same way as that for heat transfer coefficient.

## Thermal design for shell and tube heat exchangers

Shell and tube heat exchangers (STHE) have complex structures and design procedures are also complex. D.Q.Kern developed a procedure to design heat exchangers. Tinker identified various streams in shell side fluid flow, which is important for heat transfer calculation. Bell Delaware, combining the Kern and Tinker analysis and using obtained results, give the step-by-step design of STHE.

**For STHE design, the following steps are followed:**

1. Assume Overall HTC "U" based on process fluids.
2. Calculate LMTD
3. Take average temperature of shell side and tube side fluid and find out fluid properties at this temperature

4. Calculate area required for heat transfer
5. For the required area of heat transfer, find out number of tubes, shell size, baffle distance
6. Optimize the sizing of heat exchanger by changing number of passes, baffle spacing etc and find out HTC based on geometry with maximum fluid flow in "B" stream shown in above figure. During doing so, please also take care of the allowable pressure drop as decrease in baffle spacing, increase pressure drop.
7. Recheck the design using HTC calculated.

Detailed formulation is available in the Heat Exchanger Design Handbook. Commercial applications of heat exchangers like "HTRI", "Aspen" etc use similar updated correlation.

**Cross flow heat exchangers:**
In this type of heat exchanger, tubes are bare tubes or with fins. Fins are used to increase heat transfer rate - Kays and London gave a detailed step by step method to calculate HTC and pressure drop. In air-cooled heat exchangers, a similar formulation is used.

## Mechanical design of shell and tube heat exchangers

The major mechanical components in a typical shell and tube heat exchanger are dish ends, flanges, tubesheet, expansion joints and shell. There are other internal components seen in this type of heat exchanger such as tubes, baffles, tie rods, sealing strips and impingement plates. Since the components such as flanges, tubesheet and expansion joints are the most critical in terms of mechanical design, our major focus would be to address the mechanical design aspects of these components.

- **Flanges:** To design the flanges of the heat exchanger which are designed in accordance with ASME Section VIII Div. 1, mandatory appendix 2 is to be used. This mandatory appendix defines clear steps to arrive at the thickness and bolt area requirement of the flanges for the required design pressure and temperature conditions. This appendix also defines the gasket factors which are used to design the thickness of the flanges. Whether to consider the corrosion allowance on the ID of the flanges or on the face of the flanges shall be in accordance with the project specifications. Also, whether to design the flanges for the full bolt load shall also be in accordance with the project specifications. The flange rigidity shall also be checked as per Appendix 2. TEMA needs to be referred to arrive at the BCD and other dimensions of the flanges. Thickness and bolt requirement shall be in accordance with Mandatory Appendix 2 of ASME Section VIII Div.1.
- **Tubesheet:** UHX section of ASME Section VIII Div.1 has defined clear steps to design and determine the thickness of the tubesheet for the necessary design and operating conditions. There are various types of configurations of tube sheets given in ASME. One of those shall be strictly adhered to. Design of tubesheet is based on design, test and other operating conditions but not limited to operating conditions such as normal operating, start up, shutdown, cleaning and upset conditions (such as shell side flow failure, tube side flow failure etc.). Differential pressure methodology is generally not applied to while designing tube sheets. However, if this is explicitly mentioned in the project specification, then the tubesheet can be designed for differential pressure as per UHX.
- **Expansion Joints:** In a fixed tubesheet shell and tube heat exchanger, when the heat exchanger design and configuration do not allow the differential thermal expansion, its obligatory to design and provide an expansion joint to cater to this differential thermal expansion. This can result due to very high difference in shell and channel side design / operating temperatures. This can also result due to different metallurgy used on shell and channel side. At the same time, it should also be adequate to contain the pressure. ASME allows a designer to use either a thin expansion joint which is commonly referred to as "expansion bellow" or a thick expansion joint. Expansion joint with thickness less than 5 mm is termed as thin expansion joint or a bellow and an expansion joint with thickness more than 5 mm is called as "thick expansion joint". Appendix 26 of ASME Section VIII Div. 1 gives guidelines to design and fabricate an expansion bellow with different acceptable configurations. Appendix 5 of ASME Section VIII Div. 1 gives guidelines to fabricate a thick expansion joint with different acceptable configurations. For design qualification of thick expansion joint, design adequacy check by means of FEA (Finite Element Analysis) is mandatory as per TEMA.

## Summary

| SHELL AND TUBE HEAT EXCHANGER (STHEs) | PLATE AND FRAME TYPE HEAT EXCHANGER (PHEs) |
|---|---|
| Simple and effective construction | Compact design |
| Conventional design & low cost | Proprietary design; higher initial cost for PHEs with Ti plates and cost effective with SS plates |
| Used when regular maintenance and cleaning is required | Frequent cleaning and maintenance is not envisaged |
| Consumes a bit more space for the same duty as compared to PHE | Consumes lesser space as compared to STHEs |
| A better and economic solution for sea water coolant, or other fluids at risk of clogging in narrow spaces | Cannot handle viscous fluids |
| Types: fixed tube sheet / u – tube / floating head | Types: gasketed / semi-welded / welded |
| Lower heat transfer efficiency | Higher heat transfer efficiency |
| No future expandability | Provision to have future expansion by adding plate |
| Temperature approach= 5°C or more | Temperature approach= 1°C |

**About the authors**

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Mr. Mahesh Kulkarni works as a Manager in Technical Expertise and Discipline Engineering of BASF, Mumbai. He has more than 22 years of experience and specialises in FEA analysis in the process industries.