Fundamentals Of Heat Exchanger Design

in the petroleum-refining and chemical industries; as steam generators, condensers, boiler feedwater heaters, and oil coolers in power plants; as condensers and evaporators in some air-conditioning and refrigeration applications; in waste heat recovery applications with heat recovery from liquids and condensing fluids; and in environmental control.

Next, major components of shell-and-tube exchangers are briefly described.

Tubes. Round tubes in various shapes are used in shell-and-tube exchangers. Most common are the tube bundles[†] with straight and U-tubes (Fig. 1.5) used in process and power industry exchangers. However, sine-wave bend, J-shape, L-shape or hockey sticks, and inverted hockey sticks are used in advanced nuclear exchangers to accommodate large thermal expansion of the tubes. Some of the enhanced tube geometries used in shell-and-tube exchangers are shown in Fig. 1.7. Serpentine, helical, and bayonet are other tube shapes (shown in Fig. 1.8) that are used in shell-and-tube exchangers. In most applications, tubes have single walls, but when working with radioactive,
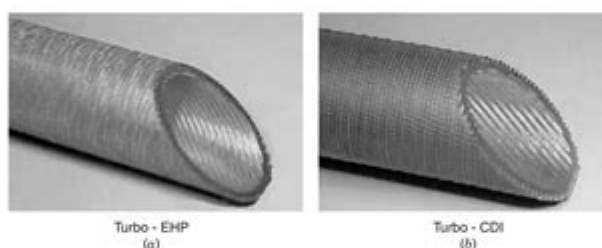

Turbo - EHP   Turbo - CDI
(a)   (b)

FIGURE 1.7   Some enhanced tube geometries used in shell-and-tube exchangers: (*a*) internally and externally enhanced evaporator tube; (*b*) internally and externally enhanced condenser tube. (Courtesy of Wolverine Tube, Inc., Decatur, AL.)

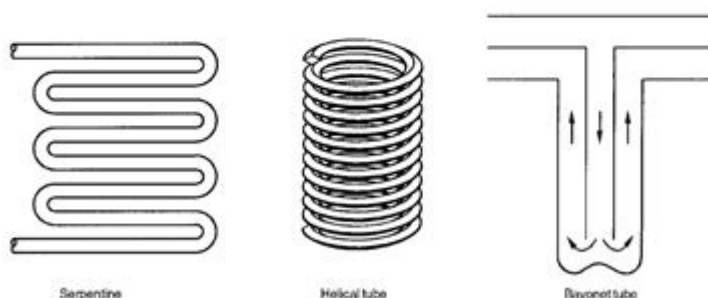Serpentine   Helical tube   Bayonet tube

FIGURE 1.8   Additional tube configurations used in shell-and-tube exchangers.

[†] A *tube bundle* is an assembly of tubes, baffles, tubesheets and tie rods, and support plates and longitudinal baffles, if any.

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Heat exchangers are essential components in many industrial processes, playing a crucial role in thermal management by transferring heat from one fluid to another. The design of heat exchangers involves a comprehensive understanding of thermodynamics, fluid mechanics, and material science to ensure optimal performance, efficiency, and safety. This article outlines the fundamental principles and considerations involved in heat exchanger design.

Types of Heat Exchangers

Heat exchangers can be classified based on various criteria, including their construction, flow arrangement, and application. Understanding these types is vital for selecting the right heat exchanger for a specific application.

1. Based on Construction

- Shell and Tube Heat Exchangers: Composed of a series of tubes, one set carries the hot fluid while the other carries the cold fluid. They are widely used due to their ability to handle high pressures and temperatures.

- Plate Heat Exchangers: Made up of multiple thin plates stacked together, they provide a large surface area for heat transfer in a compact design. They are highly efficient and easy to clean.

- Air Cooled Heat Exchangers: Utilize air as the cooling medium, often used in applications where water is scarce or expensive.

- Double Pipe Heat Exchangers: Consist of one pipe inside another, allowing two fluids to flow in opposite directions. They are simple to construct but have lower heat transfer efficiency compared to other types.

2. Based on Flow Arrangement

- Counterflow: The hot and cold fluids flow in opposite directions. This arrangement maximizes the temperature gradient and enhances heat transfer efficiency.

- Parallel Flow: Both fluids move in the same direction. This design is simpler but less effective in achieving high temperature changes.

- Crossflow: One fluid flows perpendicular to the other. This design is common in air-to-liquid applications and offers a balance between simplicity and effectiveness.

Key Design Considerations

Designing an efficient heat exchanger requires careful consideration of several factors:

1. Heat Transfer Area

The heat transfer area is critical for the effectiveness of a heat exchanger. The larger the area, the more heat can be transferred between the fluids. The area can be calculated using the equation:

$$ Q = U \times A \times \Delta T_{lm} $$

Where:
- Q = Heat transfer rate (W)
- U = Overall heat transfer coefficient (W/m²K)
- A = Heat transfer area (m²)
- ΔT_{lm} = Log mean temperature difference (K)

2. Flow Rate and Velocity

The flow rate of the fluids significantly impacts the heat exchanger's performance. Higher fluid velocities can enhance heat transfer through increased turbulence. However, high velocities may also lead to increased pressure drop and higher pumping costs.

3. Temperature and Pressure Conditions

Designers must consider the operating temperatures and pressures, as these factors determine the materials used and the overall design. It is essential to ensure that the heat exchanger can withstand the maximum expected pressures and temperatures without failure.

4. Material Selection

The choice of materials is vital for heat exchanger design. Factors to consider include:

- Corrosion Resistance: Depending on the fluids involved, materials should resist corrosion to ensure longevity.
- Thermal Conductivity: Materials with high thermal conductivity, such as copper or aluminum, are preferred for efficient heat transfer.
- Strength: The materials must withstand the mechanical stresses due to pressure and temperature.

Common materials used in heat exchanger construction include stainless steel, carbon steel, titanium, and various alloys.

Thermal Design Calculations

The thermal design of a heat exchanger involves calculating the required heat transfer area, selecting the appropriate flow arrangement, and determining the overall heat transfer coefficient. Key steps in thermal design calculations include:

1. Determine the Heat Duty (Q)

The heat duty is the amount of heat to be transferred, calculated using:

$$ Q = \dot{m} \times C_p \times (T_{hot,in} - T_{hot,out}) $$

Where:
- $ \dot{m} $ = Mass flow rate (kg/s)
- $ C_p $ = Specific heat capacity (J/kgK)
- $ T_{hot,in} $ and $ T_{hot,out} $ = Inlet and outlet temperatures of the hot fluid (°C)

2. Calculate the Log Mean Temperature Difference (LMTD)

The log mean temperature difference is calculated using:

$$ \Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} $$

Where:
- $ \Delta T_1 $ = Temperature difference at one end of the heat exchanger
- $ \Delta T_2 $ = Temperature difference at the other end

3. Determine the Overall Heat Transfer Coefficient (U)

The overall heat transfer coefficient can be calculated using:

$$ \frac{1}{U} = \frac{1}{h_{hot}} + \frac{R_{f}}{A} + \frac{1}{h_{cold}} $$

Where:
- $ h_{hot} $ and $ h_{cold} $ = Heat transfer coefficients for hot and cold fluids
- $ R_{f} $ = Fouling resistance

4. Calculate the Required Heat Transfer Area (A)

Once Q, U, and ΔT_{lm} are known, the required heat transfer area can be calculated using:

$$A = \frac{Q}{U \times \Delta T_{lm}}$$

Mechanical Design Considerations

In addition to thermal design, mechanical aspects must also be considered to ensure the heat exchanger's integrity and reliability under operating conditions.

1. Pressure Drop

Understanding the pressure drop across the heat exchanger is crucial for selecting pumps and ensuring efficient operation. The pressure drop can be calculated using the Darcy-Weisbach equation or empirical correlations based on the flow arrangement.

2. Structural Integrity

Calculating the stresses and ensuring the heat exchanger can withstand mechanical loads is essential. This includes thermal expansion considerations, especially in high-temperature applications.

3. Maintenance and Cleaning

Designing for easy maintenance and cleaning can significantly enhance the operational life of a heat exchanger. Features such as removable covers or cleanable plates can facilitate regular maintenance.

Conclusion

The fundamentals of heat exchanger design encompass a wide array of principles and considerations, from understanding the different types of heat exchangers to conducting thermal and mechanical design calculations. By carefully evaluating the specific requirements of a given application, engineers can design efficient and reliable heat exchangers that meet operational demands. The interplay of thermal performance, material

selection, and maintenance considerations is critical in ensuring the longevity and effectiveness of heat exchangers in various industrial applications. Understanding these fundamentals not only aids in designing effective systems but also plays a vital role in optimizing energy usage and reducing operational costs.

Frequently Asked Questions

What are the primary types of heat exchangers used in industrial applications?

The primary types of heat exchangers used in industrial applications include shell and tube heat exchangers, plate heat exchangers, air-cooled heat exchangers, and finned tube heat exchangers.

What is the significance of the overall heat transfer coefficient in heat exchanger design?

The overall heat transfer coefficient is crucial as it quantifies the heat transfer efficiency of the heat exchanger. It combines the effects of conduction, convection, and fouling, allowing designers to predict the thermal performance of the exchanger.

How do you determine the required heat transfer area for a heat exchanger?

The required heat transfer area can be determined using the equation $Q = U \times A \times \Delta T_{lm}$, where Q is the heat transfer rate, U is the overall heat transfer coefficient, A is the heat transfer area, and ΔT_{lm} is the log mean temperature difference.

What is the role of flow arrangement in heat exchanger performance?

The flow arrangement, such as counterflow, parallel flow, or crossflow, influences the thermal performance and efficiency of the heat exchanger. Counterflow arrangements typically provide higher heat transfer efficiency compared to parallel flow.

What materials are commonly used in heat exchanger construction, and why?

Common materials include stainless steel, carbon steel, and copper alloys due to their good thermal conductivity, corrosion resistance, and mechanical strength, which are essential for maintaining efficiency and durability under varying operating conditions.

How does fouling affect heat exchanger performance?

Fouling leads to a decrease in heat transfer efficiency by creating an insulating layer on heat transfer surfaces, increasing the thermal resistance and requiring higher energy input to maintain the desired temperature levels.

What are the key design considerations for a heat exchanger?

Key design considerations include the selection of heat exchanger type, material choice, thermal and hydraulic performance, fouling potential, operational temperature and pressure, and maintenance accessibility.

What is the purpose of using baffles in shell and tube heat exchangers?

Baffles are used in shell and tube heat exchangers to direct fluid flow, increase turbulence, improve heat transfer rates, and support the tubes, thereby enhancing the overall thermal and hydraulic performance.

How do temperature and pressure affect heat exchanger design?

Temperature and pressure directly influence the selection of materials, the design of heat transfer surfaces, and the choice of heat exchanger type. Higher temperatures and pressures require materials that can withstand extreme conditions and may necessitate thicker walls or special coatings.

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