DOI: https://doi.org/10.36719/2663-4619/126/141-145

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Structural Elements of Shell-and-Tube Heat Exchangers

Abstract

Shell-and-tube heat exchangers are among the most widely used and versatile types of equipment in industrial heat engineering due to their high reliability, mechanical strength, and adaptability to a broad range of operating conditions. They are extensively applied in petrochemical, energy, metallurgical, chemical, and heavy industries, where processes often involve high pressures, elevated temperatures, corrosive media, and significant heat loads. This study presents the structural principles of shell-and-tube heat exchangers, examines their main components and functional interactions, and discusses the influence of design features on heat transfer efficiency, hydraulic resistance, and mechanical stability. Special attention is given to the classification of shell-and-tube heat exchangers according to TEMA standards, including fixed tube sheet, floating head, U-tube, and kettle-type reboiler designs. The advantages, limitations, and fields of application of each structural type are analysed. The paper emphasizes that the optimal selection of exchanger configuration, materials, and internal elements such as baffles is a critical engineering decision that directly affects operational safety, service life, and energy efficiency.

Keywords: *shell-and-tube heat exchanger, heat transfer, TEMA standards, thermal expansion, baffles, industrial heat engineering, energy efficiency*

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Gövdə-boru istilikdəyişdiricilərinin struktur elementləri

Xülasə

Gövdə-borulu istilikdəyişdiricilər yüksək etibarlılığı, mexaniki möhkəmliyi və geniş əməliyyat şərtlərinə uyğunlaşma qabiliyyəti sayəsində sənaye istilik texnikasında ən geniş yayılmış və universal aparat növlərindən biridir. Bu qurğular yüksək təzyiq, yüksək temperatur, korroziv mühitlər və böyük istilik yükləri ilə xarakterizə olunan proseslərin üstünlük təşkil etdiyi neft-kimya, energetika, metallurgiya, kimya və ağır sənaye sahələrində geniş şəkildə tətbiq olunur. Təqdim olunan tədqiqatda gövdə-borulu istilikdəyişdiricilərin konstruktiv prinsipləri şərh edilir, onların əsas elementləri və funksional qarşılıqlı əlaqələri təhlil olunur, həmçinin konstruktiv xüsusiyyətlərin istilik ötürmə səmərəliliyinə, hidravlik müqavimətə və mexaniki dayanıqlığa təsiri araşdırılır. Məqalədə TEMA standartlarına əsasən gövdə-borulu istilikdəyişdiricilərin təsnifatına, o cümlədən sabit boru lövhəli, üzən başlıqlı, U formalı borulu və kettle tipli reboiler konstruksiyalarına xüsusi diqqət yetirilir. Hər bir konstruktiv tipin üstünlükləri, məhdudiyyətləri və tətbiq sahələri təhlil edilir. Məqalədə istilikdəyişdiricinin konstruksiya tipinin, material seçiminin və arakəsmələr kimi daxili elementlərin optimal müəyyənləşdirilməsinin istismar təhlükəsizliyinə, aparatın xidmət müddətinə və enerji səmərəliliyinə birbaşa təsir göstərən mühüm mühəndis qərarı olduğu vurğulanır.

Açar sözlər: *gövdə-borulu istilikdəyişdirici, istilik ötürülməsi, TEMA standartları, termal uzanma, arakəsmələr, sənaye istilik texnikası, enerji səmərəliliyi*

ELMİ İŞ Beynəlxalq Elmi Jurnal. 2026 / Cild: 20 Sayı: 2 / 141-145 ISSN: 2663-4619
SCIENTIFIC WORK International Scientific Journal. 2026 / Volume: 20 Issue: 2 / 141-145 e-ISSN: 2708-986X

Introduction

Shell-and-tube heat exchangers are considered one of the most widely used and versatile types of equipment in industrial heat engineering (Chukwudi & Ogunedo, 2018). Owing to their ability to operate reliably over long periods under conditions of high pressure, high temperature, corrosive environments, and large heat loads, these units are used as key technological components in the petrochemical, energy, metallurgical, chemical, and heavy industry sectors.

Research

The main advantages of this type of heat exchanger are their adaptability to a wide range of operating conditions, high mechanical strength, and a flexible structural design that facilitates maintenance and servicing (Marzouk et al., 2023).

A shell-and-tube heat exchanger is constructed on the basis of a tube bundle consisting of numerous tubes placed inside a cylindrical shell. In this unit, heat exchange takes place between two main flow zones (Costa & Queiroz, 2008):

1. The first heat carrier flows inside the tubes (tube side), while the second heat carrier flows along the outer surface of the tubes within the shell (shell side).
2. The two media do not mix directly with each other; heat transfer occurs solely through the tube walls. This design principle ensures safe operation and increases the performance of the unit due to the large available heat transfer surface area.

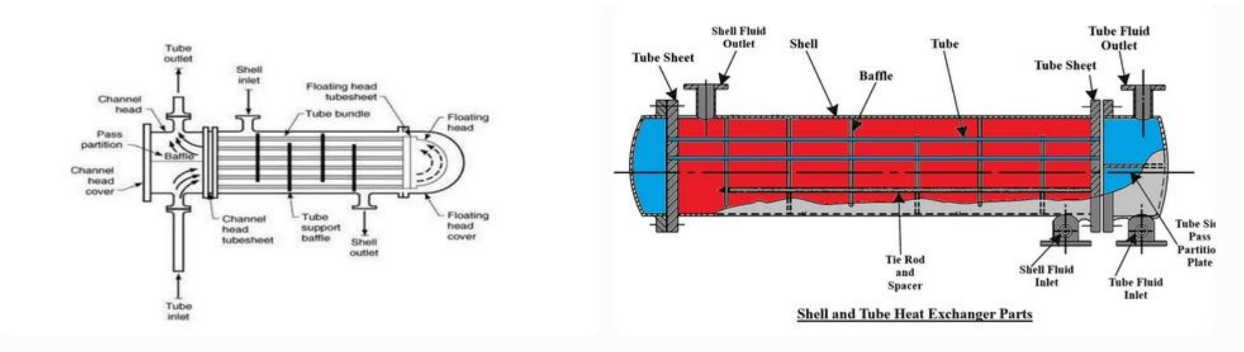

Figure 1. Cross-sectional diagram of a shell-and-tube heat exchanger.

Source: All Info ChE, n.d.).

In the cross-sectional diagram of a typical shell-and-tube heat exchanger (Figure 1), the following main components can be clearly identified:

- **Shell** – the outer cylindrical casing,
- **Tube bundle** – the primary heat transfer elements,
- **Tube sheet** – the structural plate in which the tubes are fixed,
- **Baffles** – elements that change the flow direction on the shell side and intensify heat transfer,
- **Inlet/Outlet nozzles** – inlet and outlet connections for both working fluids,
- **Channel head / bonnet** – the header section where the tube-side flow is distributed.

The functional interaction of these components determines the heat transfer efficiency, hydraulic resistance, and mechanical stability of the unit.

Table 1.2.
Main structural components and their functions.

No.	Component	Function and characteristics	Typical materials
1	**Shell**	The main pressure vessel enclosing the entire tube bundle. The shell-side fluid flows through this section.	Carbon steel, stainless steel, nickel alloys
2	**Tubes**	The primary heat transfer surface. Can be straight, U-shaped, or of other configurations.	Copper, stainless steel, titanium, Inconel
3	**Tube sheets**	Thick metal plates that fix the tubes in place and separate the two pressure zones.	Same as tube material or compatible alloy
4	**Baffles**	Direct the shell-side flow, increase turbulence, and enhance the heat transfer coefficient.	Carbon steel, stainless steel
5	**Tie rods & spacers**	Secure the baffles to each other and to the tube bundle, maintaining proper spacing.	Steel
6	**Stationary head / Channel**	Provides inlet and outlet for the tube-side fluid (Types A, B, C, N).	Steel
7	**Rear head**	Completes the rear side of the tube bundle (fixed, floating, or U-tube types).	Steel
8	**Channel cover, Shell cover**	Close the heads; can be removed for cleaning and maintenance.	Steel
9	**Nozzles**	Pipe connections for fluid inlet and outlet.	Steel
10	**Partition plates**	Direct the fluid inside the head to create multi-pass flow arrangements.	Steel

Source: Silaipillayarputhur & Khurshid, 2019.

The structural configuration of shell-and-tube heat exchangers is determined by the method of attaching the tube bundle to the shell and the mechanism used to compensate for thermal expansion (Arani & Moradi, 2019). These features define the level of thermal stresses acting on the unit, maintenance possibilities, and operational safety. For this reason, within the framework of TEMA (Tubular Exchanger Manufacturers Association) standards, shell-and-tube heat exchangers are classified into several main design types (Ravagnani & Caballero, 2007).

1. **Fixed Tube Sheet**

In this type, the tube sheets are welded directly to the shell, and the design is considered the simplest and most economical from a mechanical standpoint. However, due to differences in the coefficients of thermal expansion between the tubes and the shell, significant thermal stresses may develop under large temperature differences (Abdelhamid et al., 2022). Therefore, fixed tube sheet heat exchangers are generally recommended for processes with relatively small temperature differences (typically < 50–70 °C).

2. **Floating Head**

In this design, the rear tube sheet is free to move, allowing safe compensation of thermal expansion between the tube bundle and the shell. Floating head heat exchangers are regarded as one of the most reliable solutions for high-pressure and large temperature-difference applications (Ahmad et al., 2017). In addition, the ability to easily remove the tube bundle significantly simplifies maintenance and mechanical cleaning operations.

3. U-Tube

In this type, the tubes are bent into a U-shape and attached to only one tube sheet. As a result, thermal expansion of the tube bundle is inherently accommodated without the need for additional mechanisms. Although U-tube heat exchangers are structurally simple and economical, mechanical cleaning is relatively difficult due to the curved shape of the tubes (Patel & Parekh, 2015).

4. Kettle-Type Reboiler (Kettle Reboiler)

Kettle-type heat exchangers are primarily designed for shell-side boiling processes. This configuration provides a large vapor space and ensures stable boiling conditions for the liquid. Kettle reboilers are among the most commonly used reboiler types in petrochemical and distillation processes (Hanifzadeh, 2025).

TEMA standards systematically regulate the design, material selection, mechanical strength, and safety requirements of heat exchangers. In industrial practice, the most commonly applied TEMA classes are as follows (Tulukkanam, 2024):

- **TEMA R** – for petroleum and heavy industry applications,
- **TEMA C** – for general industrial applications,
- **TEMA B** – for the chemical industry.

Typical design dimensions include tube diameters of 19–25 mm, while tube lengths are usually selected within the range of 1.8–6 m (up to 12 m in special designs). Baffle configurations include single-segmental, double-segmental, disc-and-doughnut, rod baffles, and other modern design variants.

The high reliability, large heat transfer surface area, and maintenance-friendly design of shell-and-tube heat exchangers make them indispensable technological units for heavy industry (Kumar et al., 2025). The selection of the optimal design type is based on considerations such as process temperature level, pressure, fouling tendency, corrosion risk, and maintenance requirements. This engineering decision is one of the key factors that directly determines the service life and energy efficiency of the equipment.

Conclusion

Shell-and-tube heat exchangers represent one of the most reliable and versatile solutions in industrial heat engineering. Their widespread use across petrochemical, energy, metallurgical, chemical, and heavy industry sectors is primarily due to their ability to operate safely and efficiently under high pressures, high temperatures, corrosive environments, and large thermal loads. The fundamental design, based on the separation of shell-side and tube-side flows by solid tube walls, ensures operational safety while providing a large effective heat transfer surface.

The structural configuration of shell-and-tube heat exchangers—particularly the method of tube bundle attachment and thermal expansion compensation—plays a decisive role in determining thermal stresses, maintenance accessibility, and overall operational reliability. In this context, TEMA standards provide a systematic framework for classifying designs, selecting materials, and ensuring mechanical strength and safety. Fixed tube sheet, floating head, U-tube, and kettle-type reboiler designs each offer distinct advantages and limitations, making them suitable for different process conditions.

Ultimately, the optimal selection of a shell-and-tube heat exchanger design must consider process temperature and pressure, fouling and corrosion tendencies, and maintenance requirements. A well-founded engineering choice directly influences the equipment's service life, energy efficiency, and long-term operational performance, reinforcing the importance of rigorous design standards and careful application-specific analysis.

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Received: 21.10.2025
Accepted: 02.02.2026