A Review on Thermo-Hydraulic Performance Enhancement of Shell-and-Tube Heat Exchangers Using Conventional and Novel Baffle Designs

Sandeep Kumar

M.tech Scholar , Heat Power and Thermal Engineering

Department Of Mech. Engineering Technocrats Institute Of Technology and Science Bhopal

Dr. Shashi Kumar Jain

Director: Technocrats Institute Of Technology and Science Bhopal

Dr. Ankit Goyal

HOD Department Of Mech. Engineering Technocrats Institute Of Technology and Science Bhopal

Priyavrat Kumar

Assistant Prof. Department Of Mech. Engineering Technocrats Institute Of Technology and Science Bhopal

Abstract- Shell-and-tube heat exchangers (STHEs) are extensively used in power generation, chemical processing, HVAC, petroleum refining, and food industries due to their mechanical robustness, adaptability to high pressure and temperature, and ease of customization. However, conventional STHEs often suffer from inherent limitations such as shell-side flow maldistribution, bypass streams, dead zones, excessive pressure drop, and flow-induced vibration, which collectively reduce thermal effectiveness and increase operational costs. To overcome these challenges, shell-side baffle modification has emerged as one of the most effective and economically feasible performance enhancement techniques. This review presents a comprehensive and systematic assessment of thermo-hydraulic performance enhancement in STHEs with a particular focus on conventional and novel baffle designs. Classical segmental and double-segmental baffles are discussed alongside advanced configurations such as wavy, helical, spiral, inclined, porous, disc-and-doughnut, hybrid, and air-injection-assisted baffles. Key performance indicators including heat transfer coefficient, effectiveness, pressure drop, performance evaluation criterion, and exergy efficiency are critically analyzed based on recent experimental, numerical, and optimization-based studies. The review highlights that while traditional baffles enhance heat transfer, they often incur significant pressure penalties, whereas advanced and hybrid baffle geometries provide superior thermo-hydraulic trade-offs through improved flow uniformity and reduced dead zones. In addition, the role of computational fluid dynamics, multi-objective optimization techniques, and design standards such as TEMA, ASME, API, and PED in guiding practical implementation is emphasized. The study consolidates current research trends, identifies key performance trade-offs, and outlines existing gaps, thereby providing valuable guidance for the development of high-efficiency, industry-compliant shell-and-tube heat exchangers.

Keywords- Shell-and-tube heat exchanger; baffle design; thermo-hydraulic performance; pressure drop; heat transfer enhancement; CFD analysis

I. INTRODUCTION

Shell-and-tube heat exchangers are among the most widely used thermal systems in industrial sectors such as power generation, chemical processing, HVAC, petroleum refining, and food industries due to their mechanical robustness, adaptability to high pressure and temperature, and ease of customization. Despite their extensive application, conventional shell-and-tube heat exchangers often suffer from limitations related to poor shell-side flow distribution, bypass streams, dead zones, and non-uniform temperature gradients. These issues significantly reduce thermal effectiveness and increase irreversibility, particularly under high flow-rate or compact design constraints [1].

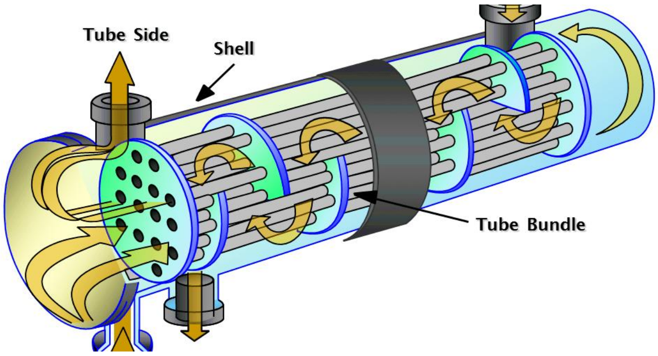

Fig. 1: Shell and Tube Heat Exchanger [9]

1.1 Benefits of shell and tube heat exchangers

Shell-and-tube heat exchangers are highly versatile thermal devices widely used across industries such as refineries, chemical plants, power generation, and manufacturing due to their robust construction and flexible design. Accounting for nearly 65% of industrial heat exchangers, they can be customized to meet diverse process requirements [2]. One of their key advantages is cost-effectiveness, as they are generally more economical than plate-type heat exchangers, particularly for high-pressure and high-temperature applications. These exchangers are capable of handling a wide range of operating temperatures and pressures, owing to the use of durable materials and compliance with standards such as ASME and PED [3]. Their design minimizes pressure losses while ensuring efficient heat transfer and resistance to fouling. Additionally, shell-and-tube heat exchangers offer significant adaptability through variations in tube dimensions, layouts, and configurations. The multi-tube structure effectively accommodates thermal expansion, making them suitable for handling hazardous, flammable, or toxic fluids while maintaining operational safety and long-term reliability [4].

To address these challenges, performance enhancement techniques have become a critical research focus. Among various enhancement approaches, modification of shell-side baffle design has proven to be one of the most effective and economically viable solutions. Baffles not only guide the shell-side fluid across the tube bundle but also play a crucial role in controlling turbulence, pressure drop, vibration, and fouling. Consequently, a systematic review of baffle-induced thermo-hydraulic enhancement is essential to understand design evolution, performance trade-offs, and emerging research trends.

1.2 Types of Shell and Tube Heat Exchangers

The Tubular Exchangers Manufacturers Association (TEMA) provides widely accepted standards that govern the design, construction, and application of shell-and-tube heat exchangers. These guidelines ensure uniformity, safety, and reliability across industrial practices [5]. TEMA classifies shell-and-tube heat exchangers into three primary categories based on service requirements and construction robustness: Class B, intended for chemical processing applications; Class C, designed for general commercial and moderate-duty services; and Class R, developed for petroleum, refinery, and large-scale industrial operations where severe pressure and temperature conditions are common [6].

To simplify identification and selection, TEMA introduced a three-letter designation system (such as BEM, AEM, or NEN) that defines the exchanger’s configuration. The first letter specifies the front-end stationary head type, indicating how the tube sheet is connected to the shell and channel [7]. The second letter represents the shell type, describing inlet and outlet arrangements and the presence of internal flow-directing elements such as baffles. The third letter denotes the rear-end head type, which determines how the tube bundle accommodates thermal expansion and how the channel is sealed. For instance, a BEM exchanger consists of a bonnet-type front head, a single-pass shell, and a fixed tube sheet [8].

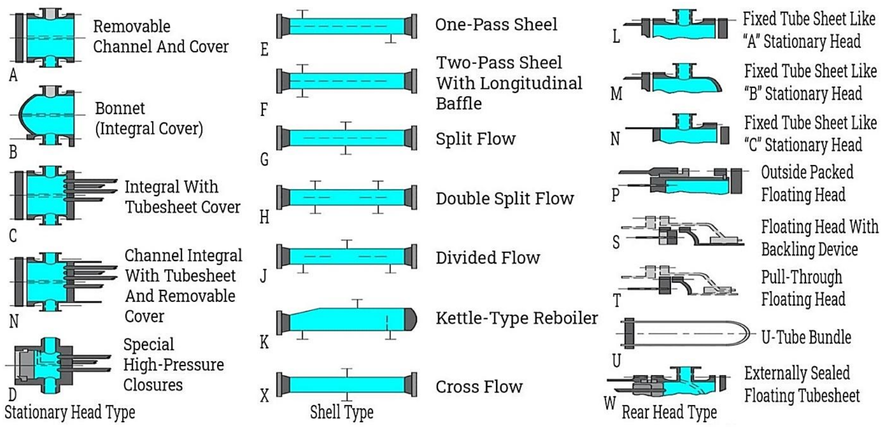

Fig. 2: Different types of shell & tube heat exchanger configuration [10]

Shell-and-tube heat exchangers are also classified based on flow arrangement, which significantly affects thermal performance. The three main flow types are parallel flow, counterflow, and crossflow. In parallel flow, both fluids enter from the same end and move in the same direction, resulting in uniform temperature changes but lower thermal efficiency [11]. Counterflow, where fluids move in opposite directions, is the most efficient arrangement, maintaining a higher temperature gradient along the exchanger length. Crossflow configurations involve fluids moving perpendicular to each other and are commonly used in applications such as steam condensers, where one fluid undergoes a phase change [12].

Based on mechanical construction, several major exchanger types are defined under TEMA. Fixed tube sheet heat exchangers (TEMA Type M) are among the simplest and most economical designs, with tubes welded to stationary tube sheets at both ends [13]. While cost-effective and easy to maintain, they are less suitable for large temperature differences unless expansion joints are used. U-tube heat exchangers employ U-shaped tubes that allow free thermal expansion, making them suitable for high temperature differentials; however, tube-side cleaning is more challenging [14].

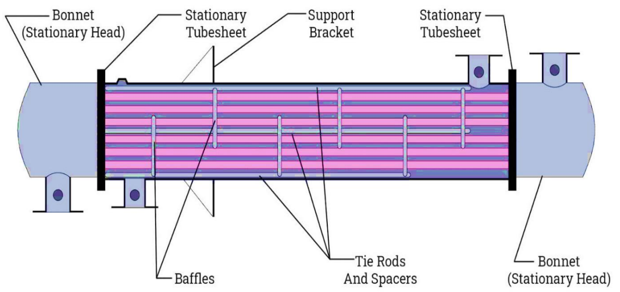

Fig. 3: Fixed Tube Sheet TEMA Type M [13]

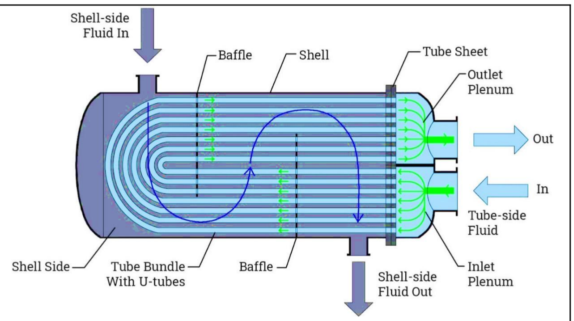

Fig. 4: U-tube shell and tube heat exchanger [14]

Floating head heat exchangers (TEMA Type S) provide greater flexibility by allowing one end of the tube bundle to move freely, accommodating thermal expansion and simplifying cleaning and inspection. Floating head designs are further categorized into Types P, W, S, and T, each employing different sealing and structural mechanisms such as stuffing boxes, lantern rings, backing devices, or pull-through bundles. These configurations are preferred in applications requiring frequent maintenance or handling large thermal stresses [15-18].

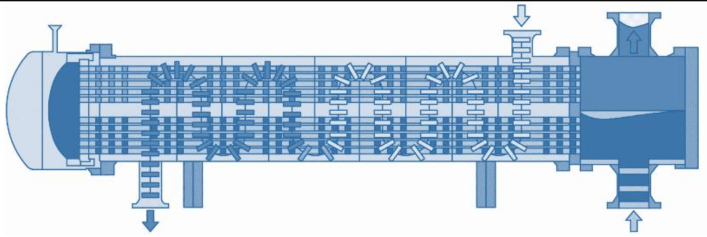

Fig. 5: Floating Head Heat Exchanger TEMA Type S [15]

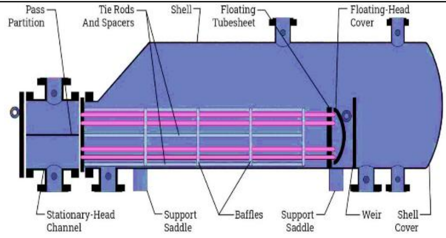

Fig. 6: TEMA Type T or Type AKT [16]

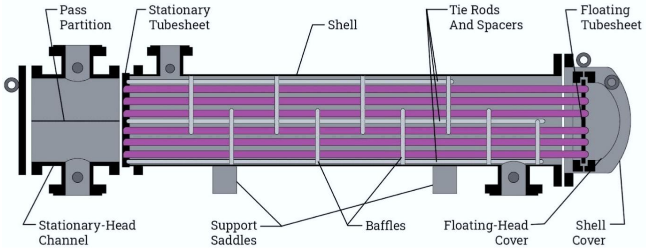

Fig. 7: TEMA Type S or Type AES [17]

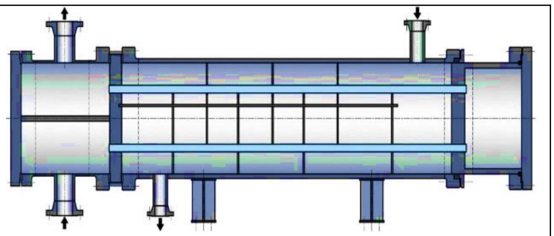

Fig. 8: TEMA Type P or Type AEP [18]

In specialized applications involving viscous or sticky fluids, scraped surface heat exchangers are employed. These exchangers incorporate rotating, spring-loaded scraping blades that continuously remove fouling deposits from heat transfer surfaces, ensuring consistent performance. They are particularly useful in food processing, pharmaceuticals, and polymer industries. Overall, TEMA standards provide a comprehensive framework for selecting appropriate shell-and-tube heat exchanger designs, balancing thermal performance, mechanical integrity, maintainability, and cost across a wide range of industrial applications.

II. FUNDAMENTALS OF THERMO-HYDRAULIC PERFORMANCE IN SHELL-AND-TUBE HEAT EXCHANGERS

2.1 Heat Transfer Mechanisms and Performance Parameters

The thermo-hydraulic performance of shell-and-tube heat exchangers is governed by coupled conduction and convection heat transfer processes between tube-side and shell-side fluids. Key performance indicators include heat transfer rate, overall heat transfer coefficient, effectiveness, Nusselt number, logarithmic mean temperature difference, and shell-side pressure drop. These parameters are interdependent and strongly influenced by flow regime, fluid properties, and internal geometry. An increase in turbulence generally enhances heat transfer coefficients but simultaneously raises pressure drop, leading to higher pumping power requirements. Therefore, the objective of thermo-hydraulic optimization is not merely maximizing heat transfer but achieving an optimal balance between thermal enhancement and hydraulic penalty [19].

2.2 Working Principle of Shell-and-Tube Heat Exchanger

Shell-and-tube heat exchangers are widely used industrial devices designed to transfer thermal energy efficiently between two fluids without allowing them to mix. Their operation is based on indirect heat transfer, where one fluid flows through a bundle of tubes while the second fluid circulates around the tubes within an enclosing shell. Heat is transferred across the tube walls due to the temperature difference between the fluids, moving naturally from the hotter fluid to the colder one. Materials with high thermal conductivity and corrosion resistance, such as stainless steel, copper, or titanium, are commonly used to enhance performance and durability. The arrangement of the tube bundle, flow configuration (parallel, counterflow, or crossflow), and use of baffles help maximize heat transfer efficiency and control pressure drop. Proper allocation of hot and cold fluids between the shell and tube sides is crucial, especially when pressure differences exist, ensuring safe, reliable, and efficient operation across diverse industrial applications [20].

2.3 Shell-Side Flow Behavior and Role of Baffles

Shell-side flow behavior is inherently complex due to flow separation, recirculation, and cross-flow patterns around tube bundles. Without baffles, shell-side fluid tends to follow the path of least resistance, resulting in bypass streams and stagnant regions. Baffles are introduced to redirect the flow, increase residence time, and promote cross-flow across the tubes.

The effectiveness of a baffle configuration depends on parameters such as baffle cut, spacing, orientation, and geometry. Improper baffle design may lead to excessive pressure drop, flow-induced vibration, and maintenance challenges, highlighting the importance of optimized baffle selection in exchanger design. Fluid flow configuration on the shell and tube sides plays a critical role in determining the thermal and hydraulic performance of shell-and-tube heat exchangers. On the shell side, baffles are installed to guide the fluid across the tube bundle in a zig-zag path, enhancing turbulence and increasing the shell-side heat transfer coefficient. This side is typically selected for high flow rates, viscous fluids, or applications involving large heat loads, as the induced turbulence also helps reduce fouling. In contrast, the tube side is designed for flexibility and ease of maintenance, often accommodating high-pressure or corrosive fluids using specialized tube materials. Turbulators may be employed to enhance mixing and heat transfer within the tubes. While tube-side flow usually experiences lower pressure drop and turbulence compared to the shell side, multi-pass arrangements allow adaptation to varied industrial operating conditions.

III. CONVENTIONAL BAFFLE DESIGNS AND THEIR THERMO-HYDRAULIC CHARACTERISTICS

3.1 Segmental and Double-Segmental Baffles

Segmental baffles are the most commonly used configuration due to their simplicity and ease of fabrication. They force the shell-side fluid to flow in a zig-zag pattern, significantly enhancing turbulence and heat transfer. However, conventional segmental baffles often create dead zones behind the baffle plates and induce high pressure drops, particularly at small baffle spacing. Double-segmental baffles were developed to mitigate some of these drawbacks by reducing flow blockage and tube vibration. While they offer lower pressure drop than single segmental baffles, their thermal enhancement is generally limited, making them less suitable for compact or high-performance applications.

Baffles are key structural and thermal components in shell-and-tube heat exchangers, installed on the shell side to direct fluid flow across the tube bundle. By increasing flow velocity and turbulence, baffles significantly enhance heat transfer coefficients and help reduce fouling through disruption of laminar flow. The spacing, geometry, and cut of baffles strongly influence exchanger performance, affecting heat transfer rate, pressure drop, and mechanical stability. In long horizontal exchangers, baffles also provide essential support to the tube bundle, minimizing vibration-induced damage and extending service life.

Tie rods and spacers complement baffles by maintaining their alignment and spacing within the shell. Anchored to the tube sheets, tie rods run along the bundle length to resist pressure and flow-induced vibrations. Proper design and installation of tie rods and spacers ensure stable flow patterns, prevent baffle displacement, and contribute to the overall mechanical reliability and safe operation of shell-and-tube heat exchangers in industrial environments.

3.2 Limitations of Traditional Baffle Configurations

Although conventional baffles improve heat transfer compared to no-baffle arrangements, they exhibit inherent limitations such as non-uniform flow distribution, increased fouling risk, and mechanical stress on tubes. These limitations have motivated researchers to explore alternative baffle geometries that can sustain high thermal performance while reducing hydraulic losses and operational issues.

IV. NOVEL AND ADVANCED BAFFLE DESIGNS FOR PERFORMANCE ENHANCEMENT

4.1 Wavy, Helical, and Spiral Baffle Configurations

Novel baffle designs such as wavy, helical, spiral, and inclined baffles have gained significant attention due to their ability to generate continuous swirling flow along the shell side. Unlike segmental baffles, these configurations minimize flow separation and dead zones, resulting in more uniform temperature fields and reduced pressure drop.

Helical and spiral baffles, in particular, promote near-axial flow with secondary swirling motion, which enhances heat transfer while lowering shell-side pressure loss. Wavy baffles introduce periodic acceleration and deceleration of the flow, improving mixing intensity without excessive hydraulic penalties.

4.2 Hybrid and Modified Baffle Concepts

Recent studies have proposed hybrid baffle designs that combine features of multiple configurations, such as segmented-wavy or half-segmental spiral baffles. These designs aim to exploit the advantages of both cross-flow turbulence and continuous flow guidance. Such hybrid concepts demonstrate improved thermo-hydraulic performance and structural stability, making them promising candidates for next-generation heat exchangers.

Recent studies have focused on improving the thermo-hydraulic performance of shell-and-tube heat exchangers through innovative baffle designs and optimization strategies. A hybrid trefoil–three-zonal baffle demonstrated a favorable trade-off between heat transfer and pressure drop, achieving a 13.07% improvement in heat transfer per unit pressure drop while reducing pressure loss by up to 17.7%, compared with conventional baffles that showed higher heat exchange (16.67%) at the cost of a peak pressure drop of 41.46% [21]. Similarly, a single-shell-pass exchanger with inclined, crossed semi-elliptical baffles reduced pressure drop by 44–49% relative to segmental and helical baffles, while improving the performance evaluation factor by 1.48–1.70 times under equal pump power [22]. Broad review efforts further indicate that passive enhancement techniques dominate the field (47.8%), followed by nanofluids and air injection, with air bubbles increasing the overall heat transfer coefficient by up to 452% and TiO_2 nanofluids yielding a maximum improvement of 175.9% [23].

Optimization-oriented and CFD-based investigations reveal that geometric tuning of baffles plays a decisive role in performance enhancement. Genetic-algorithm-based optimization of baffle angles yielded heat transfer improvements of up to 19.5% over conventional cross-arranged baffles due to enhanced flow mixing [24]. Comparative CFD studies showed that segmental and wavy baffles increased exchanger effectiveness to 1.2–1.23 times and improved overall heat transfer coefficients by up to 1.38, albeit with increased pressure drops reaching 406 Pa for wavy baffles [25]. Introducing air injection with disc-and-ring baffles led to effectiveness enhancements of 202–231% while maintaining lower pressure drops and more uniform flow fields [26]. Among various baffle types, disc-and-doughnut configurations achieved the highest performance evaluation criteria despite moderate pressure-drop penalties [27], whereas inclined baffles around 25°–30° provided optimal PEC values depending on baffle count [28]. Advanced designs such as porous baffles optimized via response surface methods [29] and double-shell exchangers with elliptical tubes and flower baffles, which achieved a 121% increase in shell-side temperature drop and a 69% reduction in pressure loss, highlight the strong potential of integrated geometric innovations for next-generation heat exchanger design [30].

Table 1: Parametric Comparison of Baffle-Based Performance Enhancement Studies in STHE

Ref. No.	Baffle Type	Heat Exchanger Type	Key Performance Parameters	Heat Transfer Enhancement	Pressure Drop Impact	Performance Evaluation	Optimization Method
[21]	Hybrid trefoil–three-zonal baffle	STHE	ε, U, ΔP, PEC	+16.67% (conv.), +13.07% per ΔP	ΔP reduced up to 17.7%	Improved thermo-hydraulic balance	CFD–experimental validation
[22]	Inclined semi-ellipse crossed baffles	Single-shell-pass STHE	U, ΔP, PEC	PEC ↑ 1.48–1.70×	ΔP ↓ 44–49%	Superior to SG & CH baffles	Finite volume formulation
[23]	Passive, nanofluid & air injection methods	STHE	U, NTU, exergy, ΔP	U ↑ up to 452%	Method-dependent	Passive methods most effective	Statistical literature synthesis
[24]	Optimized inclined baffle angles	STHE	U, ΔP, PEC	+5.5% to +19.5%	Moderate increase	Optimized PEC	Genetic Algorithm

[25]	Segmental & wavy baffles	Counter-flow STHE	ε, Uo, ΔP, exergy	ε ↑ 1.2–1.23, Uo ↑ 1.38	ΔP ↑ to 406 Pa	Trade-off evident	CFD (FLUENT 22R1)
[26]	Disc–ring baffles with air injection	Vertical STHE	NTU, ε, U, ΔP, PEC	ε ↑ 202–231%	Minimum ΔP for DRCHB	Excellent PEC	Air bubble injection
[27]	Segmental, Helical, Disc–Doughnut, Flower	STHE	OHT, ΔP, PEC	OHT ↑ 21–29%	ΔP ↓ 14–28%	Disc–Doughnut best PEC	CFD analysis
[28]	Inclined baffles (0°–30°)	STHE	OHT, HTC, ΔP, PEC	OHT ↑ up to 17%	ΔP ↑ 138–141%	8 baffles optimal	Parametric CFD study
[29]	Porous baffles	STHE	Q, ΔP	Heat transfer ↑ 84.5%	ΔP dominated by cut (89.5%)	Multi-objective optimum	Response Surface Method
[30]	Flower baffles + elliptical tubes + double shell	Novel STHE	ΔT, ΔP, flow fields	ΔT ↑ 121%	ΔP ↓ 69%	Highly improved efficiency	CFD + prototype validation

V. DESIGN STANDARDS, PRACTICAL CONSIDERATIONS, AND FUTURE RESEARCH DIRECTIONS

5.1 Industrial Design Codes and Constraints

The practical implementation of advanced baffle designs must comply with established standards such as TEMA, ASME, API, and relevant national codes. These standards impose constraints related to mechanical integrity, allowable pressure drop, vibration limits, and manufacturability. Consequently, not all high-performance baffle designs reported in academic studies are directly transferable to industrial practice without further validation.

5.2 Standards and Regulations for shell and tube heat exchangers

Shell-and-tube heat exchangers play a vital role in regulated industries such as food, beverage, dairy, and pharmaceuticals, where product safety, hygiene, and process consistency are critical. Equipment used in these sectors must comply with Food and Drug Administration (FDA) requirements to ensure sanitary operation and prevent contamination. A key framework supporting hygienic design is the 3-A Sanitary Standards (3-ASSI), developed collaboratively by manufacturers, sanitarians, and processors. These standards define nearly 70 sanitary requirements covering equipment categories such as heat exchangers, pumps, valves, vessels, fillers, and dairy-processing machinery, ensuring cleanability, material compatibility, and operational safety.

In energy and heavy industrial sectors, additional standards govern mechanical strength and operational reliability. The American Petroleum Institute (API) Standard 660 specifies requirements for the design, materials, fabrication, inspection, and testing of shell-and-tube heat exchangers used in petroleum and petrochemical applications. Similarly, the Tubular Exchangers Manufacturers Association (TEMA) provides the most widely adopted design classifications and configuration guidelines, categorizing exchangers based on service severity and durability requirements. For pressure containment and material integrity, ASME Boiler and Pressure Vessel Code Section VIII is commonly applied, with related sections addressing material specifications and nondestructive testing.

For international compliance, the Pressure Equipment Directive (PED) ensures safety and conformity of pressure equipment used in global markets. In Canada, shell-and-tube heat exchangers require Canadian Registration Number (CRN) approval, which varies by province. In India, IS 4503:1967 and IS 10746 serve as foundational standards, often used alongside TEMA and ASME codes in industrial practice. Together, these standards ensure safe, reliable, and compliant heat exchanger design across diverse applications and regulatory environments.

VI. CONCLUSION

This review demonstrates that shell-side baffle design plays a decisive role in enhancing the thermo-hydraulic performance of shell-and-tube heat exchangers. Conventional segmental and double-segmental baffles, while simple and widely adopted, are associated with flow maldistribution, high pressure drop, and vibration issues. In contrast, novel baffle configurations such as wavy, helical, inclined, porous, disc-and-doughnut, and hybrid designs significantly improve heat transfer performance while offering reduced hydraulic penalties and improved performance evaluation criteria. The integration of CFD-based analysis and optimization techniques, including genetic algorithms and response surface methods, has enabled systematic identification of optimal baffle geometries under competing thermal and hydraulic constraints. Despite notable progress, several challenges remain. Future research should focus on long-term fouling behavior, vibration characteristics, and manufacturability of advanced baffle designs under industrial operating conditions. The combined use of hybrid baffles with nanofluids, surface coatings, or air-injection techniques offers promising avenues for further enhancement. Moreover, the application of additive manufacturing and data-driven optimization methods, such as machine learning, can enable highly customized and compact exchanger designs. Ensuring compliance with international design codes while achieving scalability and cost-effectiveness will be crucial for translating advanced baffle concepts from laboratory-scale studies to real-world industrial applications.

References

[1] Syed Maaz Hasan et al. (2025) Performance enhancement of a shell-and-tube heat exchanger using a novel baffle design, Case Studies in Thermal Engineering, Volume 74, October 2025, 106800.https://doi.org/10.1016/j.csite.2025.106800.

[2] Huy Minh Khoi Hoang et al. (2025) A novel shell-and-tube heat exchanger design with alternative inclined baffles, Case Studies in Thermal Engineering Volume 65, January 2025, 105542.https://doi.org/10.1016/j.csite.2024.105542.

[3] Muhammad Waleed et al. (2025) Numerical analysis of shell and tube heat exchanger with combination of different baffles, Case Studies in Thermal Engineering Volume 65, January 2025, 105658.https://doi.org/10.1016/j.csite.2024.105658.

[4] Zhengfeng Shuai et al. (2025) Thermal performance of condensation phase change in the shell side of discontinuous helical baffle heat exchanger, Case Studies in Thermal Engineering Volume 68, April 2025, 105959. https://doi.org/10.1016/j.csite.2025.105959.

[5] Giovanni Di Bono et al. (2025) Systematic comparative analysis of Kern and Bell-Delaware methods for the design of shell-and-tube heat exchangers, Applied Thermal Engineering Volume 278, Part C, 1 November 2025, 127327. https://doi.org/10.1016/j.applthermaleng.2025.127327.

[6] Bailey Spickler et al. (2025) Surface roughness and dimensional evaluation of laser powder bed fusion additively manufactured shell and tube heat exchangers, Thermal Science and Engineering Progress Volume 65, September 2025, 103858. https://doi.org/10.1016/j.tsep.2025.103858.

[7] D. Pardillos-Pobo et al. (2025) Superheater-reheater integration in a one-shell coil-wound heat exchanger: analytical thermo-economic design for CSP, Applied Thermal Engineering Volume 279, Part B, 15 November 2025, 127632. https://doi.org/10.1016/j.applthermaleng.2025.127632.

[8] Samet Gürgen (2025) Shell and tube heat exchanger optimization: A critical literature assessment and fairness-based comparative performance analysis of meta-heuristic algorithms, Case Studies in Thermal Engineering Volume 72, August 2025, 106405. https://doi.org/10.1016/j.csite.2025.106405.

[9] Alyaa Qasim Najm et Al. (2024) Numerical Analysis of Shell and Tube Heat Exchanger with Different Baffle Configurations Performance, International Journal of Heat and Technology, Vol. 42, No. 4, August, 2024, pp. 1327-1336. https://doi.org/10.18280/ijht.420423.

[10] S.A. Marzouk et al. (2024) Effects of baffles and springs in shell and multi-tube heat exchangers: Comparative approach, Case Studies in Thermal Engineering Volume 61, September 2024, 104996. https://doi.org/10.1016/j.csite.2024.104996.

[11] Liang Tang et al. (2024) Investigation of a falling film tube bank heat exchanger with baffle design for water recovery applications, Energy and Built Environment Volume 5, Issue 5, October 2024, Pages 817-828. https://doi.org/10.1016/j.enbenv.2023.06.009.

[12] Parth Prajapati et al. (2024) Energy-economic analysis and optimization of a shell and tube heat exchanger using a multi-objective heat transfer search algorithm, Thermal Science and Engineering Progress Volume 56, December 2024, 103021. https://doi.org/10.1016/j.tsep.2024.103021.

[13] Sumon Saha & Nahid Hasan (2024) Numerical evaluation of thermohydraulic parameters for diverse configurations of shell-and-tube heat exchanger, Results in Engineering Volume 23, September 2024, 102509. https://doi.org/10.1016/j.rineng.2024.102509.

[14] Md Atiqur Rahman (2024) Thermo-fluid performance of axially perforated multiple rectangular flow deflector-type baffle plate in an tubular heat exchanger, Applications in Engineering Science Volume 20, December 2024, 100197. https://doi.org/10.1016/j.apples.2024.100197.

[15] Seyed Ali Abtahi Mehrjardi et al. (2024) Performance increasement in shell-and-tube heat exchangers reinforced with dimpled tubes: A correlation-based approach, International Journal of Heat and Mass Transfer Volume 226, July 2024, 125489. https://doi.org/10.1016/j.ijheatmasstransfer.2024.125489.

[16] Sreejesh S.R. Chandran et al. (2024) Empirical correlation to analyze performance of shell and tube heat exchanger using TiO2 Nanofluid-DI water in solar water heater, Case Studies in Thermal Engineering Volume 60, August 2024, 104652. https://doi.org/10.1016/j.csite.2024.104652.

[17] Parth Prajapati et al. (2024) Thermodynamic evaluation of shell and tube heat exchanger through advanced exergy analysis, Energy Volume 292, 1 April 2024, 130421.https://doi.org/10.1016/j.energy.2024.130421.

[18] Amnart Boonloi et al. (2024) Performance improvement in a heat exchanger tube using discrete X–V baffle (DXVB) turbulators, Case Studies in Thermal Engineering Volume 54, February 2024, 103999. https://doi.org/10.1016/j.csite.2024.103999.

[19] Dheyaa J. Jasim et al. (2024) Hydrothermal behaviour of hybrid nanofluid flow in two types of shell and helical coil tube heat exchangers with a new design. Numerical approach, International Journal of Thermofluids Volume 24, November 2024, 100902. https://doi.org/10.1016/j.ijft.2024.100902.

[20] Yuyang Yuan et al. (2024) Numerical simulation and multi-objective optimization design of conjugate heat transfer in novel double shell-passes multi-layer helically coiled tubes heat exchangers, Case Studies in Thermal Engineering Volume 62, October 2024, 105155. https://doi.org/10.1016/j.csite.2024.105155.

[21] Hasan, S. M., Iqbal, S., Khan, I., Javaid, A., & Sajid, M. (2025). Performance enhancement of a shell-and-tube heat exchanger using a novel baffle design. *Case Studies in Thermal Engineering*, 106800. https://doi.org/10.1016/j.csite.2025.106800

[22] Hoang, H. M. K., Cao, H. L., Pham, P. M. Q., Hajjar, A., & Nguyen, V. L. (2025). A novel shell-and-tube heat exchanger design with alternative inclined baffles. *Case Studies in Thermal Engineering*, *65*, 105542. https://doi.org/10.1016/j.csite.2024.105542

[23] Marzouk, S. A., Abou Al-Sood, M. M., El-Said, E. M., Younes, M. M., & El-Fakharany, M. K. (2023). A comprehensive review of methods of heat transfer enhancement in shell and tube heat exchangers. *Journal of Thermal Analysis and Calorimetry*, *148*(15), 7539-7578. https://doi.org/10.1007/s10973-023-12265-3

[24] Dogan, S. (2025). Baffle angle optimization of a typical shell and tube heat exchanger. *Physics of Fluids*, *37*(1). https://doi.org/10.1063/5.0249271

[25] Najm, A. Q., Dakhil, S. F., & Mohammed, A. Q. (2024). Numerical Analysis of Shell and Tube Heat Exchanger with Different Baffle Configurations Performance. *International Journal of Heat & Technology*, *42*(4). DOI: 10.18280/ijht.420423

[26] Al-darraji, A. R., Marzouk, S. A., Aljabr, A., Almehmadi, F. A., Alqaed, S., & Kaood, A. (2024). Enhancement of heat transfer in a vertical shell and tube heat exchanger using air injection and new baffles: Experimental and numerical approach. *Applied Thermal Engineering*, *236*, 121493. https://doi.org/10.1016/j.applthermaleng.2023.121493

[27] Mohammadzadeh, A. M., Jafari, B., & Hosseinzadeh, K. (2024). Comprehensive numerical investigation of the effect of various baffle design and baffle spacing on a shell and tube heat exchanger. *Applied Thermal Engineering*, *249*, 123305. https://doi.org/10.1016/j.applthermaleng.2024.123305

[28] Mohammadzadeh, A. M., Jafari, B., Hosseinzadeh, K., & Paikar, E. (2025). Numerical investigation of segmental baffle design in shell and tube heat exchangers with varying inclination angles and spacing. *Scientific Reports*, *15*(1), 4683. https://doi.org/10.1038/s41598-025-87652-x

[29] Tian, B., Wang, N., Liu, L., Guo, Y., Liu, L., & Shao, S. (2026). A comprehensive investigation of Shell and Tube Heat Exchangers based on porous baffle design and multi-objective parameter optimization. *International Journal of Thermal Sciences*, *221*, 110463. https://doi.org/10.1016/j.ijthermalsci.2025.110463

[30] Chaoui, A., Bouzid, S., Aidi, M., Bordja, L., & Poós, T. (2025). Comparative study of shell-and-tube heat exchanger designs for improved thermal performance and energy efficiency. *Advances in Mechanical Engineering*, *17*(12), 16878132251408726. https://doi.org/10.1177/16878132251408726

[31]