Sovaran Singh yadav, 2025, 13:3
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

Design and analysis of shell and tube heat exchanger

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Abstract- Power generating, chemical processing, and oil refining are just a few of the many industries that rely on tube and shell heat exchangers because of their versatility, high-pressure handling capacity, and sturdy architecture. Limitations in thermal effectiveness and operational costs caused by problems including flow maldistribution, contamination, and high-pressure drop are common in traditional systems. Analytical and computational approaches to optimising the design and efficiency of shell and tube heat exchangers are investigated in this work. Emphasis is placed on key design considerations including baffle configuration, tube arrangement, material selection, and flow orientation. Analytical models using LMTD, NTU-effectiveness methods, and pressure drop equations are applied to evaluate thermal performance. Additionally, CFD simulations are used to validate and visualize improvements in flow and heat transfer behavior. Case studies highlight the advantages of baffle optimization and AI-assisted predictive diagnostics. The paper also discusses emerging innovations such as the use of nanofluids, additive manufacturing of complex geometries, and smart sensors for real-time monitoring. Challenges related to material constraints, maintenance access, and computational limitations are also addressed. The findings suggest that through integrated design and advanced analysis, tube and shell heat exchangers can be significantly enhanced for modern industrial applications.

Keywords: Tube and shell Heat Exchanger, Heat Transfer, Baffle Optimization, CFD Simulation, Pressure Drop, Nanofluids, Additive Manufacturing, Smart Sensors, Thermal Design, Energy Efficiency.

I. INTRODUCTION

The ability to transfer heat between fluids of different temperatures makes heat exchangers important in numerous industrial contexts. All of these things rely on them: energy, petroleum products, chemical plants, refrigeration, heating, ventilation, and air conditioning, marine systems, and food and drink. The most common type of exchanger for heat is the tube and shell design because it is versatile, resilient, and resistant to a wide range of temperatures and pressures.

Cylindrical shells with tubes make up shell-and-tube heat exchangers. Two fluids—one inside and one outside—circulate through tubes to transfer heat. The design's versatility allows single-pass, multi-pass, U-tube, and floating head variants [1]. Flexible and easy to inspect, disassemble, and clean, they are perfect for gaseous and liquid media.

They can withstand corrosion, pressure changes, and thermal expansion strains, making them popular in industry. They may be scaled to small and large capacities, making them appropriate for laboratory and power plant applications. Classical shell-and-tube heat exchangers have some advantages, but they are less efficient and less reliable.

When fluids flow unevenly, flow maldistribution produces poor heat transfer and hot patches. Thermal stresses can cause mechanical failure or poor thermal performance.

Fouling, which lowers heat transfer coefficients and raises pressure drops, is another concern. Long-term fouling raises operational costs and maintenance shutdowns. Operating temperature and corrosion resistance limit materials choices, resulting in performance, longevity, and cost trade-offs.

Due to these challenges, shell and tube heat exchanger design and analysis must incorporate fluid dynamics, mechanical characteristics, and thermodynamics [2]. Modern computer methods like CFD and FEA are replacing or supplementing empirical methods and human computations. Engineers can model operating conditions, establish the best baffle spacing and orientation, predict pressure drops, and identify fouling hotspots using these methods. This allows heat exchanger functioning optimisation before production or usage. Energy efficiency, sustainability, and environmental compliance are driving demand for heat exchanger designs that reduce operational costs and environmental impact. Increasing heat transfer efficiency and reducing thermal losses can substantially reduce energy waste for businesses. This study analyses and designs performance-optimized shell-and-tube heat exchangers. This study uses analytical and computational methods to evaluate thermal efficiency parameters, identify design flaws, and optimise heat exchanger performance.

Methodology

This research uses analytical and computational techniques to improve the efficiency of shell-and-tube heat exchangers. When designing heat exchangers, we used the Log Mean Temperature Difference (LMTD) and Number of Transfer Units (NTU) effectiveness formulas to determine thermal performance indicators such as total heat transfer coefficient and heat duty. We used empirical correlations to calculate tube and shell pressure decreases for fluid dynamics and energy efficiency. CFD simulations using ANSYS Fluent supplemented the analytical work. Detail geometry modelling, mesh creation, and boundary condition setups were used in these simulations.

These models helped us comprehend pressure gradients, velocity profiles, and temperature distributions in varied configurations. Comparing performance of the baseline model, improved baffle configurations, and CFD-validated designs. Industrial case studies showed the practical benefits of the proposed design modifications, supporting the results. This integrated methodology assessed hydraulic and thermal performance to verify the modifications' feasibility and benefits.

II. DESIGN CONSIDERATIONS AND COMPONENT OVERVIEW

Complex shell-and-tube heat exchangers efficiently transfer heat between fluids.
The exchanger's critical components determine its thermal performance, mechanical strength, and operational reliability. Before performing a performance study or optimisation research, you must understand these components and their configurations.

Tube and shell Configuration

This heat exchanger's shell retains the tube bundle and controls fluid flow along its side. Inner shell tube networks carry tube-side fluid. A fluid circulates inside the tubes and above them via the shell, allowing heat exchange across the tube walls. Choosing the right length, diameter, and number of tubes affects heat transfer surface area and pressure drop.

Tube sheets—thick slabs with holes—hold tube ends [3]. They provide mechanical support and prevent fluid mixing. Tube sheets are securely joined by welding or expanding tubes. For long-term performance, tube sheet design must address thermal stresses, corrosion, and fouling. Perpendicular baffles direct fluid flow from the shell side across the tube bundle zigzag-style. Avoiding stagnant flow zones boosts heat transfer and turbulence. Baffles stabilise tubes and decrease fluid flow-induced sagging. Heat transfer and pressure loss are improved by optimising baffle cut and spacing at 15–45% of shell diameter.

Spacers and tie rods through each baffle and onto support plates prevent the construction from collapsing during operation. Applications alter shell-and-tube heat exchanger geometry. The tube's end-to-end fluid flow makes it suitable for low-pressure applications with negligible thermal expansion. A multipass design increases heat transfer area and reduces bulk by changing fluid direction multiple times in the tube bundle [4]. U-shaped bent tubes enable side-by-side fluid introduction and removal. This arrangement facilitates thermal expansion without stressing the tube sheet, making it appropriate for high temperatures. Inside U-tubes are hard to clean. A floating head lets one tube sheet move axially.

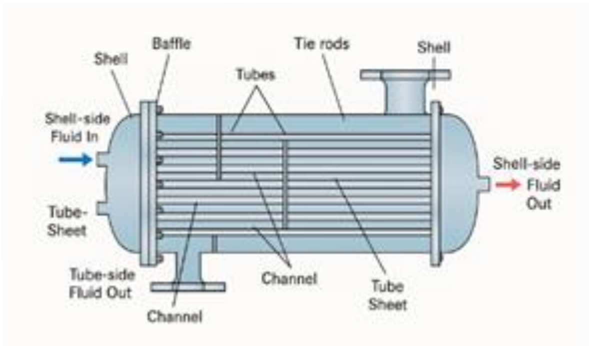

Figure 1: Schematic diagram of a tube and shell heat exchange

Thermal expansion stress disappears but mechanical complexity and expense increase. Process demands should determine configuration based on performance, maintenance, and cost.

Governing Design Parameters

A tube and shell heat exchanger's effectiveness depends on several design characteristics that must be carefully selected to enhance heat transmission and minimise pressure drop and material cost. The arrangement of tubes is crucial to tube bundle design. Tubes can have square or triangular pitches. When the pitch is triangular, the shell-side fluid turbulence improves heat transfer and increases tube density with the same shell diameter. Cleaning tubes is difficult due to limited access. Although square pitch designs have a lower heat transfer coefficient, mechanical cleaning and maintenance are easier [5]. Baffle cut and spacing affect shell-side flow dynamics. Pressure decreases increase with closer baffle spacing, while heat transmission and turbulence improve. Baffle spacing is commonly 20–100% of shell diameter. Baffle cuts affect flow and pressure loss because the deleted section allows fluid passage. Smaller cuts increase heat transmission and turbulence, while larger cuts reduce pressure drop. Tube material is another important design element.

A tube material with high thermal conductivity that won't corrode, erode, or scale is needed for heat transmission. Carbon steel, titanium, copper alloys, and stainless steel are used. Titanium and high-nickel alloys are best for severe circumstances despite the cost. Pressure and corrosion allowance determine tube wall thickness. You can define counterflow or parallel flow between tube and shell sides. In a counterflow design, hot and cold fluids move in opposite directions to increase mean temperature differential and thermal efficiency. This design is efficient enough for most industrial situations. Parallel flow arrangements are simpler to design and construct but less thermally efficient, making them appropriate for smaller temperature fluctuations or specialised applications.

Last, heat transfer area, pressure drop, and space restrictions determine shell diameter and tube length. Although the shell diameter remains constant, a longer tube length increases heat transfer surface area, which may increase side pressure drop [6]. With bigger shell diameters, capacity and tubes improve, but cost and structural support increase. tube and shell heat exchanger design must include thermal performance, mechanical strength, pressure drop, maintenance readiness, and cost. To develop effective heat exchangers, we must understand each part's function and how key parameters affect heat transport.

By studying these parameters, engineers can improve designs to meet process needs and improve operational reliability and energy efficiency.

III. ANALYTICAL & COMPUTATIONAL ANALYSIS

One can evaluate a tube and shell heat exchanger's thermal and hydraulic parameters using analytical and cutting-edge computer methods. CFD and FEA allow realistic simulations, whereas analytical methods define baseline design parameters and reveal exchanger thermal behaviour. Below are the main methods for assessing tube and shell heat exchanger efficiency in terms of heat transfer, pressure decreases, and fluid flow.

Heat Transfer Calculations

Heat transfer calculations are crucial to heat exchanger design and performance. LMTD and NTU-Efficiency are prominent thermal design methods for tube and shell heat exchangers.

If you know the fluid temperatures entering and leaving the system, use LMTD. It measures heat transfer force per heat exchanger area [7].

The following LMTD describes a counterflow or parallel heat exchanger:

$$\text{LMTD} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)}$$

- **Where:**
- **Th,in and Th,out:** Inlet and outlet temperatures of the hot fluid
- **Tc,in and Tc,out:** Inlet and outlet temperatures of the cold fluid

The rate of heat transfer is then calculated using:

$$Q = U \cdot A \cdot \text{LMTD}$$

- **Where:**
- **Q:** Heat transfer rate (W)
- **A:** Heat transfer area (m^2)
- **U:** Overall heat transfer coefficient ($W/m^2 \cdot K$)

The overall heat transfer coefficient (U) accounts for the resistances to heat transfer on both the tube-side and shell-side, as well as the tube wall. It is calculated using:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{t}{k} + \frac{1}{h_o}$$

- **Where:**
- **Hi h_i and ho**: Convective heat transfer coefficients on the inside and outside of the tubes
- **t:** Wall thickness of the tube
- **k:** Thermal conductivity of the tube material

In cases where outlet temperatures are unknown or for optimization scenarios, the NTU-effectiveness method is used. This method relates the exchanger's effectiveness (ε) to the NTU:

$$\text{NTU} = \frac{UA}{C_{min}}, \quad \varepsilon = \frac{Q}{Q_{max}} = f(\text{NTU}, C_r)$$

Where:

- **Cmin:** Minimum of the heat capacity rates of hot and cold fluids
- Cr=Cmin/CmaxC_r = C_{min}/C_{max}Cr=Cmin/Cmax: Capacity ratio

The effectiveness-NTU relations differ based on the flow arrangement (counterflow, parallel flow, crossflow) and are used to predict performance when temperature data is limited.

Pressure Drop Analysis

Equally important as heat transfer is minimising pressure drop, which affects pumping power and operational cost [8]. Frictional resistance in the tube and shell s lowers fluid pressure.

Tube-side pressure decrease is:

$$\Delta P_t = f_t \cdot \frac{L}{D} \cdot \frac{\rho v^2}{2} + \text{losses due to fittings}$$

- **Where:**
- **ft:** Friction factor (based on Reynolds number)
- **L:** Tube length
- **D:** Tube diameter
- **ρ\rhoρ**: Fluid density
- **v:** Velocity of fluid

The shell side pressure decrease is compounded by baffle flow and tube bundle flow. Bell-Delaware, which accounts for baffle configuration, bypass flow, and leakage, is popular. An easy approach to compute shell pressure decrease:

$$\Delta P_s = N_b \cdot \left(\frac{\rho v_s^2}{2} \cdot K\right)$$

Where:

- **Nb**: Number of baffle spaces
- **K:** Empirical loss coefficient
- **vs:** Cross-flow velocity

Energy efficiency and pumping system wear are improved by limiting pressure drop. Heat transmission improves with more turbulence, but designers must consider the pressure losses.

CFD Simulation or Finite Element Modeling
CFD and FEA are increasingly used in tube and shell heat exchanger design to investigate fluid flow, temperature distribution, and stress behaviour. Common programs include SolidWorks Flow Simulation, ANSYS Fluent, and COMSOL Multiphysics. CFD simulations begin with heat exchanger domain geometry and meshing [9]. The tube and shell s are surrounded by a fine-grained mesh to capture temperature and velocity gradients. Mesh quality—skewness, aspect ratio, and orthogonality—determines solution correctness and stability. Operating characteristics including input velocities, temperatures, pressure outlets, and thermal wall conditions determine boundary conditions. To simulate realistic flow characteristics, turbulence models like k-ε or k-ϋ SST are used.

After calculating the solution, the CFD application illustrates recirculation, hot spot, and dead zone areas utilising streamlines, velocity vectors, and temperature contours.

Results often show:

- Velocity contours indicating flow acceleration and deceleration around baffles and tubes
- Temperature gradients showing thermal performance and mixing behavior
- Pressure distribution that highlights areas of high resistance and flow separation.
- These data can inform iterative design modifications to materials, flow pattern, and baffle spacing.

  FEA and other approaches can represent thermal expansion mechanical stresses, especially in high-pressure or high-temperature settings. Finally, robust tube and shell heat exchangers require computational and analytical methodologies. Heat transfer calculations utilising LMTD and NTU methods give theoretical foundation, while pressure drop analysis ensures energy efficiency. Modern heat exchanger design and performance analysis benefit from computational technologies that enable visualisation and exact optimisation.

IV. PERFORMANCE ENHANCEMENT TECHNIQUES

Find a balance between thermal efficiency, mechanical integrity, and maintainability to optimise tube and shell heat exchanger performance. Engineers concentrate design improvements and performance optimisation when energy demands and operational limits rise in industrial operations [10]. Three key areas for improvement are baffle design, flow-induced vibration abatement, and fouling resistance. This section discusses optimising these parts to improve heat exchanger performance without sacrificing durability or efficiency.

Baffle Design Optimization
Baffles guide fluid from the shell side across the tube bundle in shell-and-tube heat exchangers to promote turbulence and heat transmission.
Baffle spacing and cut drastically alter shell flow dynamics. Shell convective heat transfer coefficient improves with closer baffle spacing as turbulence increases. Higher turbulence disrupts the thermal boundary layer around the tubes, improving heat exchange [11].

This benefit comes at the expense of larger pressure drop, which requires more pumping power and energy. Despite reducing pressure loss, increasing baffle spacing causes greater laminar flow, which lowers thermal performance. Baffle cuts, which are 15–45% of the shell diameter, further affect flow dispersion. Larger cuts improve heat transmission and turbulence but may produce flow maldistribution. Optimised baffle shape like helical or segmental baffles improves flow uniformity, pressure drop, and thermal efficacy.

Flow-Induced Vibration Mitigation
Flow-induced vibration from fluids moving quickly over bundles of tubes can harm heat exchanger mechanical components. Vibrations can induce tube wear and rupture, causing costly shutdowns and safety hazards. Typical vibration reasons are vortex shedding, fluidelastic instability, and turbulent buffeting.

These consequences are mitigated by several design methods. Staggered tubes prevent coherent vortex patterns and reduce resonance. Use intermediate tube supports or improve baffle spacing to further restrain tubes from vibrational damage. In the design phase, computational analysis methods like FEA can model dynamic loading scenarios and find vibration hotspots. Vibration reduction enhances heat exchanger reliability, longevity, and maintenance costs.

Fouling Resistance and Cleaning Mechanisms

tube and shell heat exchangers suffer from fouling, which deposits unwanted chemicals on heat transfer surfaces. Fouling decreases heat conductivity, increases pressure loss, and can collapse the system if not regulated. Shell-side flow design is crucial for fouling resistance. Optimal baffle layouts provide turbulent flow regimes that limit foulant residence time on tube surfaces and avoid particle deposition [12] . Coatings and smooth interiors can also avoid fouling. Importantly, the heat exchanger must meet Tubular Exchanger Manufacturers Association (TEM) standards, which simplify cleaning and maintenance. Cleaning ports, floating heads, and detachable tube bundles enable mechanical or chemical cleaning for operational continuity. Scheduling frequent maintenance and real-time fouling detection can improve exchanger dependability. Use fouling-resistant surface treatments and materials like titanium or PTFE coatings in fouling-prone locations. Effective baffle design, structural stability against flow-induced vibration, and proactive fouling control increase tube and shell heat exchanger performance. The exchanger's thermal performance, durability, and operational efficiency improve.

V. CASE STUDIES OR COMPARATIVE ANALYSIS

Verifying tube and shell heat exchanger design with case studies and simulations provides valuable insights.This section compares design revisions based on performance variables such heat transfer coefficient (U), pressure drop (ΔP), and heat duty. This broad and technically informed analysis is based on published studies and established computational fluid dynamics (CFD) models from industrial applications including power plants and chemical processing units. A frequently cited petrochemical refinery case study involved a heat exchanger that warmed crude oil before distillation [13]. Traditional segmental baffles and a fixed tube sheet configuration were used in the base design.

Due to fouling and vibration-related operating inefficiencies and high maintenance costs, baffle optimisation and flow reconfiguration were recommended. CFD simulations were used to test and alter the design for thermal distribution and flow.

Design Variation	U (W/m²·K)	ΔP (kPa)	Heat Duty (kW)
Base Case	510	30	1400
Optimized Baffle	620 (+21%)	35 (+16%)	1700 (+21%)
CFD Verified Model	610 (+19%)	33 (+10%)	1680 (+20%)

The basic case heat exchanger delivered 1400 kW heat duty, 510 W/m²·K heat transfer coefficient, and 30 kPa shell-side pressure drop. It was fine for continuous operations, but fouling and poor heat usage caused it to degrade over time. Ideal baffle design used 25% shorter segmental baffles with reduced spacing to enhance turbulence and minimise pressure losses. The adjustment improved heat transmission by 21%, with the overall heat transfer coefficient rising to 620 W/m²·K from the baseline. However, intensified turbulence boosted pressure loss to 35 kPa. The design's thermal advantage was shown by the heat duty rising to 1700 kW.

The performance was optimised with an ANSYS Fluent CFD-verified model. Real-time boundary conditions in the simulation included entrance velocities, temperature gradients, and turbulence. Mesh independence studies verified accuracy and numerical stability [14]. The CFD model outperformed the optimal design, with a lower pressure drop of 33 kPa and a heat transfer coefficient of 610 W/m²·K, resulting in a greater energy efficiency balance. The optimised design had a heat duty of 1680 kW and a heat transfer coefficient of 611

This comparative study indicates that changing baffle shape and flow design can improve heat exchanger performance. However, pressure drop penalties and structural integrity must be considered while assessing these advances.

Computational fluid dynamics (CFD) models help designers avoid dead zones, vortex formation, and hot spots by replicating flow dynamics. The procedure is more reliable, cheaper, and maintained less often. Chemical facilities, refineries, and thermal power stations are demanding industrial environments. Heat exchangers should use analytical design and computational validation for efficiency and sustainability.

VI. CHALLENGES AND LIMITATIONS

Despite its widespread use in power plants, oil refineries, chemical industries, and HVAC applications, tube and shell heat exchangers have practical design and optimisation limitations. The design trade-off between minimalism and maintenance is significant.

Due to space constraints, designers often chose smaller heat exchangers with denser tube designs and tighter baffle spacing to optimise heat transfer. Cleaning, inspecting, and repairing might be difficult with limited inside access. Denser designs also experience greater fouling and vibration, which reduce operational longevity and downtime. Material selection is harder in high-temperature or corrosive environments [15]. Titanium, copper alloys, and stainless steel are popular due to their high cost, heat conductivity, and corrosion resistance. Even corrosion-resistant materials can fail after prolonged chemical fluid or pH exposure. Mineral scaling, microbial growth, and particle deposition cause continual fouling. Smooth surfaces and coatings reduce fouling, but they degrade over time, lowering thermal performance and increasing pressure drop. Computational Fluid Dynamics (CFD) analysis offers pros and cons. High-fidelity computational fluid dynamics (CFD) simulations of turbulent, multi-phase, or transient flows with thin meshes require a lot of processing power. Due to idealised assumptions and oversimplified boundary conditions, these simulations may not capture all operational dynamics even after hours or days. This causes CFD model validation with experimental data to take time and money. Finally, better heat exchanger designs' cost-effectiveness is a major barrier to adoption, especially in smaller or more price-conscious enterprises. Real-time monitoring, improved baffle structures, and high-end materials may increase operational and capital costs. Due to the long payback period, many applications may not be able to justify these characteristics, which may improve efficiency and reliability. Thus, designers must balance technological excellence and profitability.

VII. FUTURE TRENDS AND INNOVATION

Heat exchanger design is advancing rapidly due to manufacturing, smart technologies, and novel materials, despite many obstacles. The integration of ML and AI into design and maintenance is interesting new study. AI algorithms can generate predictive maintenance schedules that save downtime and prevent catastrophic breakdowns by assessing vast databases of operating variables like temperatures, flow rates, and fouling trends.

AI-powered thermal design tools can automate optimisation by running several simulations to find the best configuration for operating conditions, reducing engineering time. Another exciting discovery is heat exchangers using nanofluids. Nanoparticles like Al_2O_3, CuO, or TiO_2 enhance heat conductivity and convection in fluids. These fluids can boost the exchanger's heat transfer coefficient, especially in tiny or high-performance systems. However, stability, cost, and tube wall erosion remain issues. 3D printing will also change heat exchanger construction. This allows precise manufacture of complex geometries like spiral tubes, integrated flow diverters, and lattice-structured baffles that would be too expensive or impossible to make with conventional methods. This opens up new application-specific exchanger designs that are lightweight, efficient, and customised.

Iteration and prototyping are easier with 3D printing since it reduces manufacturing time and material waste.Future smart heat exchangers will have embedded sensors to monitor temperature, pressure, vibration, and fouling in real time. These sensors can provide data to a cloud-based dashboard or central control system for remote diagnostics, performance monitoring, and anomaly detection. Power plants and defence equipment are mission-critical systems that could benefit from real-time thermal management optimisation and accident prevention. Digital twin simulations use sensor data and AI models to simulate heat exchanger performance and find trouble points.

VIII. CONCLUSION

Thermal management systems still require tube and shell heat exchangers for energy production and process industries. Their durability, adaptability to various temperature loads, and high-pressure fluid handling flexibility make them essential in all industries. Due to demands for energy efficiency, compact design, and environmental sustainability, heat exchanger design is becoming more important. This research examined tube and shell heat exchanger structural and analytical features, focussing on baffle optimisation, pressure drop management, and heat transfer augmentation. Engineers must consider maintenance restrictions, material choices, financial feasibility, trade-offs, and practical limitations when designing. As shown in the paper, computational modelling and CFD simulations improve performance validation and design refinement.

As illustrated in comparative case studies, design modification can boost thermal performance by 20% with a minor pressure loss, highlighting the delicate line between efficiency and operational cost. When embedded sensors, additive manufacturing, nanotechnology, and AI come together, heat exchanger technology will advance. These advancements are expected to increase safety, adaptability, lifetime, and remove restrictions. Adaptive control, predictive diagnostics, and higher material performance are the future for tube and shell heat exchangers.

REFERENCE

1. E. J. Fernandes and S. H. Krishanmurthy, "Design and analysis of shell and tube heat exchanger," Int. J. Simul. Multidiscip. Des. Optim., vol. 13, p. 15, 2022.
2. Abd, M. Q. Kareem, and S. Z. Naji, "Performance analysis of shell and tube heat exchanger: Parametric study," Case Stud. Therm. Eng., vol. 12, pp. 563–568, 2018.
3. Fetuga et al., "Numerical analysis of thermal performance of waste heat recovery shell and tube heat exchangers on counter-flow with different tube configurations," Alexandria Eng. J., vol. 64, pp. 859–875, 2023.
4. S. A. Marzouk, M. M. Abou Al-Sood, E. M. El-Said, M. M. Younes, and M. K. El-Fakharany, "A comprehensive review of methods of heat transfer enhancement in shell and tube heat exchangers," J. Therm. Anal. Calorim., vol. 148, no. 15, pp. 7539–7578, 2023.
5. X. Wang, N. Zheng, Z. Liu, and W. Liu, "Numerical analysis and optimization study on shell-side performances of a shell and tube heat exchanger with staggered baffles," Int. J. Heat Mass Transf., vol. 124, pp. 247–259, 2018.
6. R. Chandrasekaran, X. Qian, and L. Seong, "Thermal performance evaluation and analysis of the efficient and sustainability shell and tube heat exchanger system," J. Constr. Proj. Manag. Innov., vol. 11, no. 1, pp. 151–159, 2021.
Arani and R. Moradi, "Shell and tube heat exchanger optimization using new baffle and tube configuration," Appl. Therm. Eng., vol. 157, p. 113736, 2019.
7. D. Tuncer, A. Sözen, A. Khanlari, E. Y. Gürbüz, and H. İ. Variyenli, "Analysis of thermal performance of an improved shell and helically coiled heat exchanger," Appl. Therm. Eng., vol. 184, p. 116272, 2021.
8. Habibullah, M. Atif, M. A. Khan, F. A. Awwad, and E. A. Ismail, "Thermal analysis and performance investigations of shell and tube heat exchanger using numerical simulations," Mod. Phys. Lett. B, vol. 38, no. 16, p. 2341015, 2024.
9. N. Li et al., "Analysing thermal-hydraulic performance and energy efficiency of shell-and-tube heat exchangers with longitudinal flow

based on experiment and numerical simulation," Energy, vol. 202, p. 117757, 2020.

10. V. Safari, B. Kamkari, and A. Gharbi, "Wedge-shaped fins to enhance thermal performance of shell and tube heat exchangers containing phase change material: an experimental study," Therm. Sci. Eng. Prog., vol. 49, p. 102474, 2024.
11. M. H. Mohammadi, H. R. Abbasi, A. Yavarinasab, and H. Pourrahmani, "Thermal optimization of shell and tube heat exchanger using porous baffles," Appl. Therm. Eng., vol. 170, p. 115005, 2020.
12. Hanan, U. Zahid, T. Feroze, and S. Z. Khan, "Analysis of the performance optimisation parameters of shell and tube heat exchanger using CFD," Aust. J. Mech. Eng., vol. 21, no. 3, pp. 830–843, 2023.
13. T. Sengar, M. K. Agrawal, and T. Grover, "Performance Enhancement and Analysis of Shell and Tube Type Heat Exchanger," in IOP Conf. Ser.: Mater. Sci. Eng., vol. 1116, no. 1, p. 012104, 2021.
14. M. B. Shafiq et al., "Thermal performance enhancement of shell and helical coil heat exchanger using MWCNTs/water nanofluid," J. Therm. Anal. Calorim., vol. 147, no. 21, pp. 12111–12126, 2022.