

Advanced Perforation Strategies for Maximizing Heat Exchanger Efficiency and Heat Transfer Rates

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Abstract: Heat exchangers, which are essential to numerous industrial processes, facilitate efficient thermal energy transfer between fluid streams. The rising demand for better thermal performance and system compactness has rendered optimizing internal structures—most importantly, baffle configuration—a primary goal. This study investigates the influence of different perforated and non-perforated baffle geometries on the performance of a double-tube heat exchanger (DTHE) for better fluid dynamics and heat transfer efficiency. The major aim of this study is to analyse the convective heat transfer and pressure drop behaviour in a DTHE fitted with structured single-sided perforated baffles (SSPB) through computational fluid dynamics (CFD). It aims at formulating an optimum model through examining various geometries of the baffles and comparing how they influence the performance of the system to a reference condition where there are no baffles. Out of all the tested configurations, triangular perforated baffles demonstrated the largest improvements, increasing shell-side cooling by 9.40% and decreasing tube-side temperature by 12.85%. Other notable results show the importance of geometric optimization, including improvements from the square of and rhombus perforations. By striking a balance between improved heat transfer and controllable pressure drop increases, perforated designs typically performed better than non-perforated baffles. Utilizing both heat and velocity distribution analyses, CFD simulations carried out in ANSYS Workbench demonstrated distinct performance differences among eight baffle configurations. The efficiency of the optimized perforation patterns was confirmed by quantitative data collected from inlets and outlets on the tube and shell sides. Compared flow disruption and thermal mixing were indicated by the triangular hole configuration, which also produced the best velocity profiles and the highest heat transfer efficiency. This study demonstrates that improving DTHE performance requires careful consideration of perforation design and baffle geometry. The study offers practical insights for baffle configuration optimization through a systematic comparison of various shapes and alignments. The study makes an important contribution towards the field of developed thermal system design since the results support the use of computationally optimized perforated baffles to improve energy efficiency.

Keywords: Double-Tube Heat Exchanger (DTHE), Perforated Baffles, Heat Transfer Enhancement, Computational Fluid Dynamics (CFD), Thermal Performance, Fluid Dynamics, Baffle Geometry Optimization, Energy Efficiency, ANSYS Workbench, Pressure Drop Analysis.

I. Introduction

In applications such as electrical power generation, HVAC, chemical production, and refrigeration, heat exchangers are integral parts of industrial thermal control systems that enable effective heat transfer between fluid streams. Their effectiveness directly affects operational expenses, energy usage, and environmental responsibility. By enhancing perforation designs in items such as tubes, plates, and fins, recent development aims at enhanced efficiency by enhancing heat transfer, pressure drop reduction, and fouling minimization. This research examines the ways these design methods can enhance system reliability and energy efficiency in various heat exchanger applications [1].

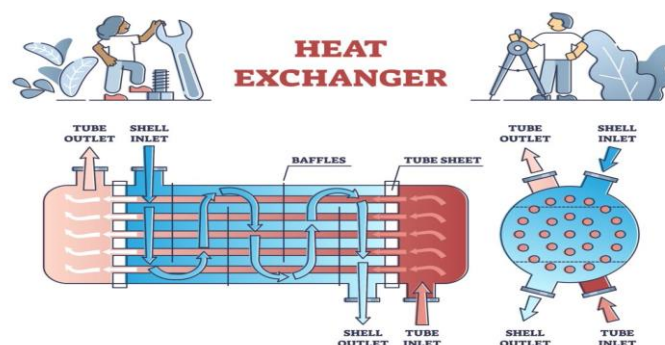


Figure 1. Heat Exchanger [1]

Heat exchangers, whose advantages include energy saving, flexibility, compact size, and accurate control of the temperature, play a crucial role in effective transfer of thermal energy in several applications. Due to their

ability to save fuel and enhance efficiency, they are used in systems such as air conditioners, power plants, and car engines [2]. Nevertheless, issues such as corrosion, fouling, pressure losses, and high upfront costs may influence how efficient they are and how long they last. Heat exchangers play a vital role in contemporary thermal management systems since, despite these limitations, correct design and maintenance can rectify most problems [3]. Because perforation designs directly affect heat transfer, fluid flow, and pressure fluctuations, they play a critical role in assessing heat exchanger efficiency and operation. Perforations well-designed considering size, shape, distribution, and orientation increase thermal energy transfer, minimize energy losses, provide uniform heat distribution, and reduce pressure and fouling losses. System efficiency may be enhanced by adapting these patterns to target applications and fluid characteristics, and sophisticated analytical tools such as computational fluid dynamics and experimental investigation yield essential information for improvement in designs. Improved thermal performance and energy efficiency in contemporary heat exchangers can be achieved only through this on-going process of optimization [4].



Figure 2 Understanding Perforation Patterns in Heat Exchangers

Since they are inexpensive and easy to maintain, double pipe heat exchangers are among the most common in industrial applications, and small companies especially prefer them. Although they have simple constructions and are perfect for illustrating the basics of heat exchanger operation, their high space usage and relatively low efficiency have rendered more sophisticated alternatives like shell and tube or plate heat exchangers the norm for current industries [5]. Heat exchangers permit heat to be transferred between two fluids of different temperatures without permitting them to get mixed. Heat exchangers, which operate autonomously of external mechanical work or heat interactions, find common application in a range of applications from home heating, air conditioning, to large-scale chemical process and power generation. Convection of each fluid and conduction through the dividing wall are the typical heat transfer mechanisms. The total effectiveness is often measured with the total heat transfer coefficient, or U , which includes all affecting factors [6].

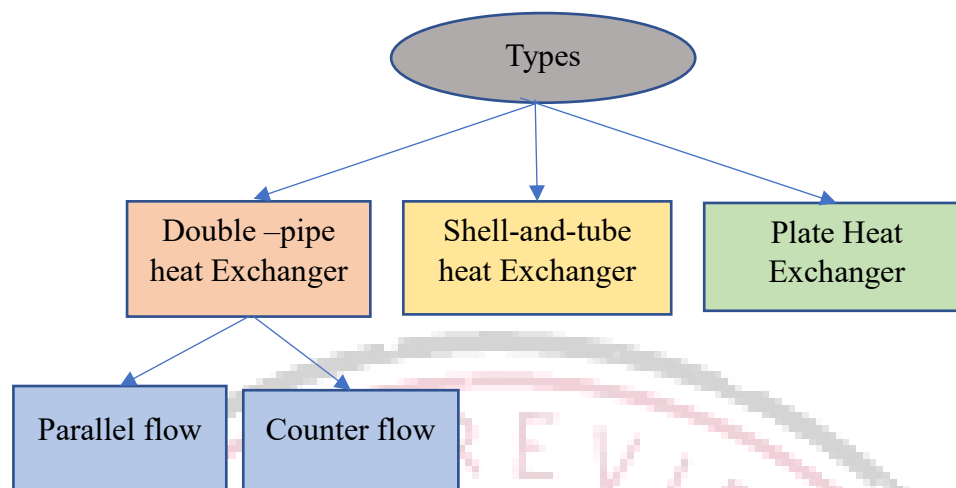


Figure 3 Types of Heat Exchanger

Due to their simplicity of installation, cheapness, and flexibility, double pipe heat exchangers are some of the simplest and most used exchangers, especially in small-scale industries and institutes. Due to their simple design, they are very adaptable or maintainable and can operate at high as well as low pressures. While having their own benefits, double pipe heat exchangers take up more space and provide less thermal efficiency compared to such complex units as shell and tube or plate heat exchangers. They may be configured as counter-flow, where the fluids move in opposite directions, or parallel flow, where fluids move in the same direction; the latter is more efficient in enhancing heat transfer due to a greater temperature difference [7]. Improving heat exchanger performance is now an essential goal because of the growing industrial need for effective heat transfer systems, particularly in energy recovery and high heat-flux cooling. More effective heat transfer methods have been created because of the tendency of traditional fluids like water and ethylene glycol to fail during high thermal loads. Methods such as swirl flow and the employment of augmented surfaces or unique fluids minimize energy losses and enhance the general heat transfer coefficient. Minimizing equipment size, reducing operating costs, and achieving sustainability targets are all based on effective heat exchangers. Heavy industrial use is still hindered by experimental data and thermal performance uncertainties, pointing to the necessity for further research and development in the field [8]. Commercial applications utilize more sophisticated systems extensively, including shell and tube and plate heat exchangers. In a shell and tube exchanger, several tubes are contained within a cylindrical shell, and one fluid passes through the tubes and the other through the shell. The configuration and quantity of tubes normally constructed from thermal conducting materials such as steel or aluminum alloys control heat transfer. Conversely, plate heat exchangers (PHEs) employ a series of closely spaced corrugated metal plates that enhance turbulence and superior thermal efficiency. Its module construction makes it simple to tailor and maintain, thereby being convenient and effective for diverse applications in heating, cooling, and temperature adjustment [9].

II. Literature Review

The significance of heat transfer in fields like electronics, thermal management of batteries, and renewable energy was emphasized by **Ashwani Kumar et al. (2025)** [10]. Study included advanced techniques that facilitate enhanced heat transfer and system adaptability, such as additive manufacturing, nanomaterials, metamaterials, and artificial intelligence-based thermal management systems. The increasing demand for sustainable and efficient heat transfer systems was underscored by **Ali Alahmer et al. (2025)** [11]. They discussed nanofluids, hybrid nanofluids, phase change materials (PCMs), and solar thermal systems. CFD applications and passive/active cooling techniques were revealed to contribute significantly to efficient performance in heat exchangers and for developing future energy applications. **LePree et al. (2025)** [12] discussed about new heat exchanger design innovations that seek to increase energy efficiency and decrease costs in the chemical industry. The research emphasized the importance of efficient, sustainable heat exchange technologies to enable environmentally friendly industrial processes. **Chunlan Pan et al. (2024)** [13] proposed magnetic turbulators and electromagnetic vibration (EMV) methods to improve heat exchanger performance. Perforated magnetic turbulators enhanced the heat transfer by as much as 150%, but the optimum performance was obtained with 2 mm holes spaced 12 mm apart, although at the expense of greater pressure drops. **A. Vaisi et al. (2023)** [14] performed an experimental investigation on finned double-pipe heat exchangers with different perforated tube inserts. Out of all the configurations, a single top-row perforation pattern resulted in the greatest heat transfer improvement (73%) and a maximum thermal performance factor (TPF) of 1.42, especially at elevated Reynolds numbers. **Atiqur Rahman et al. (2023)** [15] investigated a new design of baffle plate for tubular heat exchangers. With the utilization of rectangular deflectors and the variation of pitch ratios and

angles, they attained a 41.49% enhancement in thermal-fluidic performance with the best results at a 30° deflector angle and pitch ratio of 1. **Maha A. Hussein et al. (2022) [16]** investigated the influence of segmental baffles with semi-circular perforations on a double-pipe air–water heat exchanger. Baffles with 20 mm perforation resulted in an 80.6% enhancement of the overall heat transfer coefficient, showing the significant effect of perforation diameter on performance. **Stergaard, D. S. et al. (2022) [17]** concentrated on district heating networks and advised reducing supply and return temperatures to enhance efficiency. Combining heat pumps and renewables, the tactic could bring up to 300% return on investment for district heating companies and foster green energy habits.

Table 1 Comparative Summary of Recent Advances in Heat Transfer and Heat Exchanger Technologies

Author(s) & Year	Focus Area	Methods Used	Key Findings	Application Area	Performance Metrics
Ashwani Kumar et al. (2025) [10]	Advanced heat transfer methods, materials, AI integration	Experimental and computational review	AI, additive manufacturing, and nanomaterials enhance performance	Electronics, battery systems, renewable energy	Enhanced thermal management via AI and materials
Ali Alahmer et al. (2025) [11]	Nanofluids, hybrid nanofluids, PCMs, CFD	Review and modelling techniques	Nanofluids and hybrid PCMs improve thermal performance significantly	Energy systems, solar tech, heat exchangers	Improved thermal efficiency with advanced fluids
LePree et al. (2025) [12]	Industrial heat exchange efficiency and sustainability	Industry analysis and design trends	New technologies boost efficiency, reliability, and sustainability	Chemical and process industries	Energy savings and process sustainability
Chunlan Pan et al. (2024) [13]	Magnetic turbulators and EMV in heat exchangers	Experimental with magnetic turbulators	Perforated turbulators improved heat transfer by up to 156%, but increased pressure drops	Heat exchangers in industrial cooling	Heat transfers up to 156% higher with 2.06 TEF
A. Vaisi et al. (2023) [14]	Perforated inserts in finned double-pipe exchangers	Experimental with varied perforation patterns	Top-row perforation gave highest heat transfer enhancement (73%)	Finned double-pipe heat exchangers	Up to 73% enhancement in heat transfer coefficient
Atiqur Rahman et al. (2023) [15]	Novel baffle plate design with swirling flow	Experimental with variable deflector angles and pitch	41.49% improvement in thermal-fluidic performance with optimized baffle setup	Tubular heat exchangers with flow modifiers	41.49% improvement in thermal-fluidic performance
Maha A. Hussein et al. (2022) [16]	Segmental baffles with perforations and fins	Experimental with varying perforation diameters	80.6% improvement in overall heat transfer coefficient with 20 mm perforated baffles	Air–water heat exchangers	80.6% improvement in overall heat transfer coefficient
Stergaard, D. S. et al. (2022) [17]	Low-temperature district heating systems	Industry data and economic analysis	300% ROI by lowering heating temps through district-wide temperature reductions	District heating networks	300% ROI by lowering supply/return temperatures

III. Objectives

The objectives of the proposed study are:

- Using water as the working fluid, computational fluid dynamics is used to study convective heat transfer and pressure drop properties inside a space annulus with perforated SSPB baffles oriented along the inner heated tube surface.

- To enhance the SSPB model, we'll be using refined geometric parameters to optimize it and compare its performance against the current baseline experimental results.

IV. Methodology

This study takes a deep dive into how different baffle configurations affect the thermal efficiency and fluid dynamics of double-tube heat exchangers (DTHE). It explores both baffle and non-baffle systems, aiming to optimize heat transfer processes. The research highlights how these structural tweaks influence fluid flow and thermal performance. By following a thorough and systematic approach, the study identifies key challenges and opportunities, providing essential insights for improving DTHE design and boosting overall system efficiency. The investigation into thermal and fluid performance across various baffle setups is conducted with a detailed and methodical strategy. It all starts with creating precise 3D CAD models, which are then incorporated into intricate Computational Fluid Dynamics (CFD) simulations using ANSYS Workbench. To ensure the CAD models are ready for simulation, they undergo a cleanup process in Design Modeler to fix any geometrical errors. Next, careful attention is given to mesh generation to ensure both density and quality are up to par. The Fluent solver is then employed to set boundary conditions, turbulence models (like realizable k-epsilon), and material properties, all aimed at accurately mimicking real-world conditions.

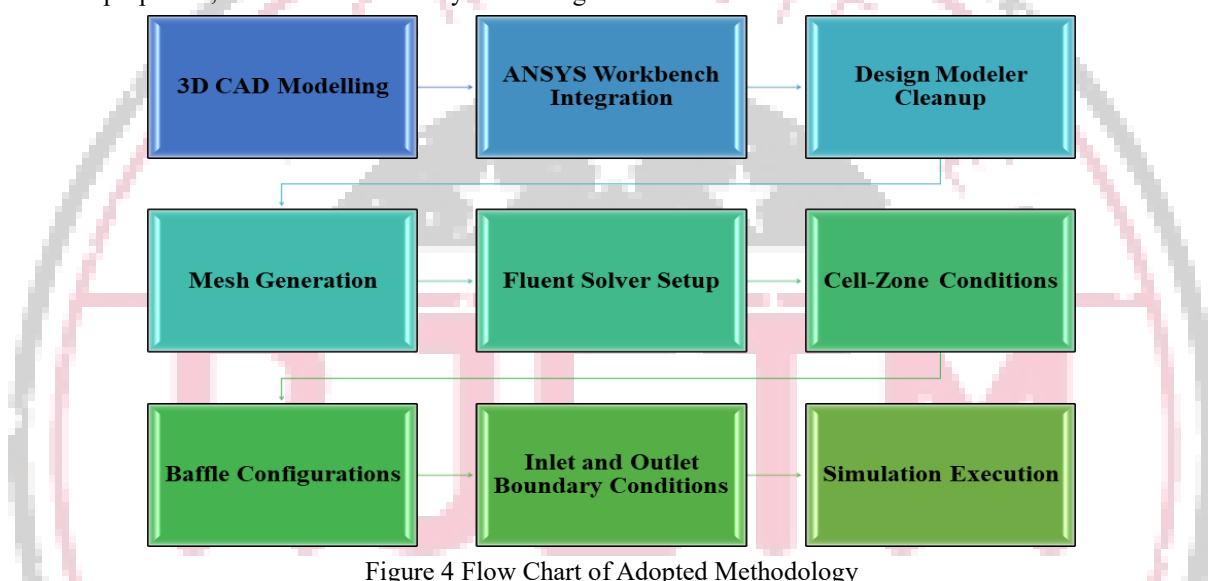


Figure 4 Flow Chart of Adopted Methodology

The method also includes setting realistic inlet and outlet conditions, experimenting with various baffle designs like perforated patterns in different shapes and alignments and distinguishing between fluid and solid areas. To analyse temperature and velocity profiles across all setups, simulations are run. This organized approach allows for a comprehensive understanding of how different baffle configurations impact heat transfer and fluid dynamics. Finally, the study offers valuable insights into the most effective baffle designs, enhancing DTHE design and boosting overall thermal efficiency.

A. Cases Examined in This Study

In this analytical study, we dive into the heating and fluid dynamics of a double-tube heat exchanger (DTHE) featuring eight unique baffle designs. Each configuration is crafted to demonstrate how variations in geometry can influence heat transfer efficiency. Starting with Case 1, which serves as our control scenario, we observe fluid flow and natural heat transfer without any baffles to interfere. To focus solely on the effects of obstruction, Case 2 introduces solid baffles that lack any holes. Then, in Case 3, we add baffles with evenly spaced circular holes to assess how these perforations impact fluid movement and thermal behaviour. Moving on to Case 4, we swap the circular holes for square ones, which introduce sharper edges that could change heat distribution and flow turbulence. Case 5 explores the effects of elongated openings by incorporating elliptical holes with their longer axis oriented horizontally. In Case 6, we experiment with triangular perforations, adding a geometric twist that might lead to distinct thermal-fluid dynamics. Case 7 features rhombus-shaped holes with an inclined design, predicting specific flow patterns and thermal responses. Finally, Case 8 allows us to compare how the alignment of perforations affects the overall performance of the DTHE, similar to Case 5 but with vertically oriented elliptical holes. Together, these configurations aim to deepen our understanding of how baffle geometry influences fluid behaviour and energy exchange, potentially paving the way for the creation of more efficient heat exchangers.

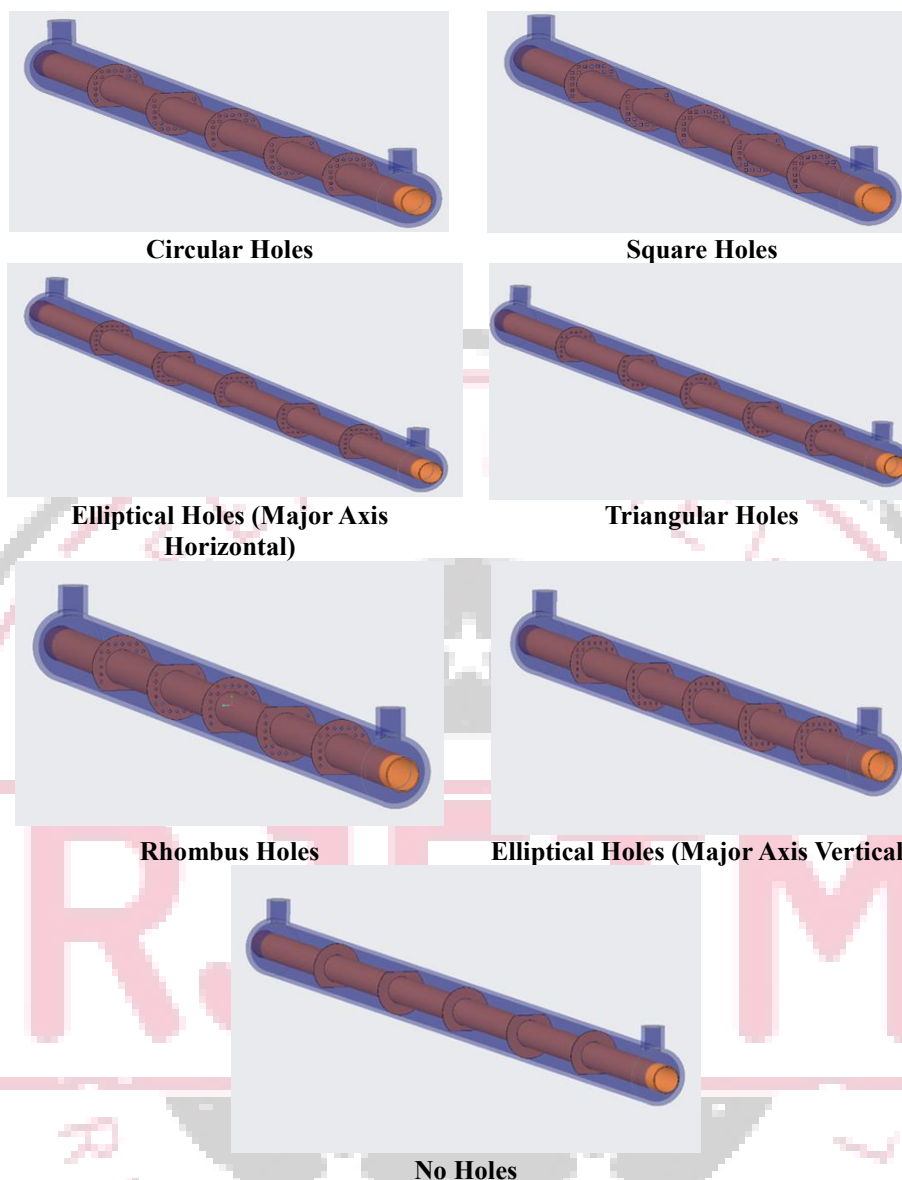


Figure 5 Specific CASES Considered in this Study

The impact of various baffle configurations on the thermal and fluid performance of a double-tube heat exchanger (DTHE) is methodically investigated in this work, beginning with a baseline situation in which there are no baffles. To ensure correct geometry in simulation, a detailed 3D CAD model of the DTHE was made and refined in ANSYS Workbench. Mesh generation and CFD configuration were conducted with great care, including real-world boundary conditions, material characteristics (copper, PVC, and water), and the realizable k-epsilon turbulence model. The simulation configuration included gravity, energy equations, and cell-zone distinction, with mass flow rates and temperatures for the inner tube and outer casing specified. This initial configuration allowed for realistic simulation of heat transfer and fluid flow to become the basis for comparative evaluation across a wide range of baffle designs and to aid in the optimization of heat exchanger performance.

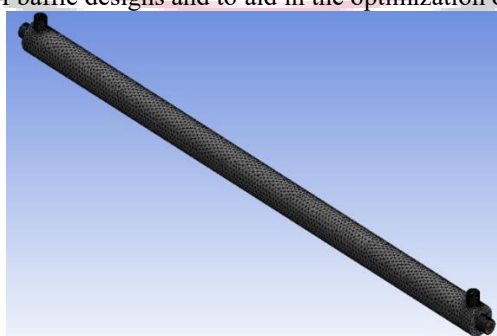


Figure 6 Meshing of DTHE

Table 2 Boundary conditions for DTHE

Component	Condition	Details
Inner Tube (Copper)	Inlet	Mass Flow Rate: 0.1343 kg/s Temperature: 50°C
	Outlet	Pressure Outlet
Outer Shell (PVC)	Inlet (opposite to shell)	Mass Flow Rate: 0.2 kg/s
	Outlet	Pressure Outlet



Figure 7 Meshing of DTHE

All those boundary conditions define specific settings for which the inner tube (being made of copper) and the housing (needing to be made of PVC) would be subjected to influence such simulation of a double-tube heat exchanger (DTHE).

V. Result and Discussion

The section on results introduces a descriptive analysis of the thermal and fluid dynamics in the double-tube heat exchanger (DTHE) in the baseline condition without baffles. Temperature pattern and fluid velocity profiles were graphically displayed to enable easy observation of the impact of the absence of baffles on heat transfer and flow behaviour. Liquid flow patterns were investigated in the study, observing the extent to which the absence of flow-guiding structures impacted thermal performance. Quantitative temperature and velocity measurements were made at both inlet and outlet on both tube and shell sides, providing an overall assessment of the DTHE's baseline performance.

A. Comparative Results

1. Comparative Results for Temperature

To compare the results for all cases where temperature readings were recorded at both the tube side outlet and the shell side outlet, it is essential to consider the variations in temperature under the specified inlet conditions of 50°C for the tube side and 15°C for the shell side.

Table 3 Comparative Analysis of Baffle Configurations in Heat Exchanger Performance

S. No.	Baffle Configuration	Tube side TS	Shell side SS	% Reduction TS	% Accession SS
1	W/o Baffle	48.44	18.54	3.12	3.54
2	No Hole	44.75	19.14	10.494	4.14
3	Circular	44.57	19.90	10.856	4.90
4	Square	43.88	20.93	12.24	5.93
5	Elliptical horizontal	44.78	20.51	10.44	5.51
6	Triangle	43.57	24.40	12.852	9.40
7	Rhombus	44.18	20.70	11.646	5.70
8	Elliptical vertical	44.38	19.80	11.244	4.80

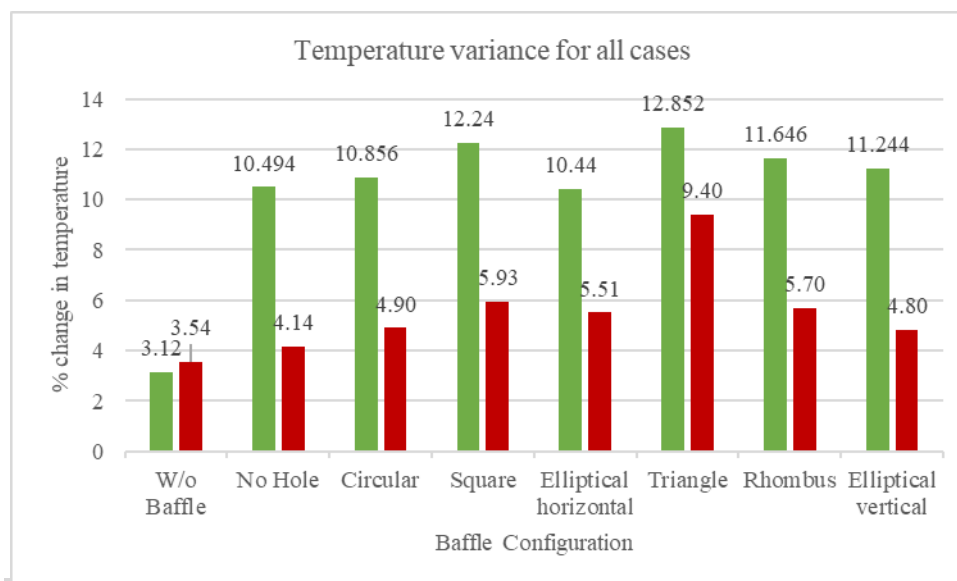


Figure 8 Comparative results for temperature

When the various configurations of baffles in a double-tube heat exchanger are being analyzed, the factors of temperature distribution and its effect upon heat transfer efficiency provide necessary insight. Here, it could be seen that temperature variation has changed from tube side to shell side as the two opposing fluids flow and interacts with the walls and baffles of heat exchangers. Case 1 was established in the absence of baffles at which the amounts of temperature reduction on both sides, moderate at best, became reference values for evaluating every other arrangement. Case 2, that of baffles without holes, showed an improvement of about 10.44% tube side temperature reduction and 4.14% shell side temperature reduction, thus underscoring the merits of solid baffles in heat transfer. Further improvement was realized in Case 3 with baffles with circular holes achieving a 10.856% reduction in temperature on the tube side and a 4.90% reduction on the shell side, again suggesting the effect of circular perforations. The combination of square holes in Case 4 resulted in 12.24% and 5.93% tube-side and shell-side temperature reductions, respectively, implying a more significant heat transfer. Horizontal elliptical perforations used in Case 5 decrease tube side temperature by 10.50%, while the put side is lowered by 5.51%, thus demonstrating their effectiveness. The triangular hole configuration studied in Case 6 appears to be the most effective with a tube side temperature reduction of 12.852% and a shell-side temperature drop of 9.40%, demonstrating the best heat transfer characteristics among all cases. The shaped-rhombus hole patterns performed reasonably here in Case 7 to lose tube-side temperature by 11.646% and shell-side temperature by 5.70%. Lastly, vertically-aligned elliptical hole patterns in Case 8 decreased tube-side temperature by 11.244% and shell-side temperature by 4.80%. These further stresses the importance of baffle perforation geometry in improving heat exchanger performance.

2. Comparative Results for Velocity

These velocity recordings at the two outlet points provide key information regarding how the stencil-type flow-through arrangement imposed on these flow fields, i.e., for the DTHE, under different baffle configurations, and for a constant velocity of 0.26 m/s for the inlet in the tube side and 0.90 m/s in the shell side, the variation in outlet velocity profiles were observed as the core fluids interact with interior parts of the heat exchanger and baffles, thus the effect of various baffle designs on the dynamics of flow.

Table 4 Impact of Baffle Configuration on Heat Exchanger Efficiency

S. No.	Baffle Configuration	Tube side TS	Shell side SS	% Reduction TS	% Reduction SS
1	W/o Baffle	0.38	0.950	46.15	5.56
2	No Hole	0.38	1.027	46.15	14.07
3	Circular	0.38	1.030	46.15	14.44
4	Square	0.37	1.080	42.31	20.00
5	Elliptical horizontal	0.38	1.029	46.15	14.31
6	Triangle	0.37	1.120	42.31	24.44
7	Rhombus	0.38	1.050	46.15	16.67

8	Elliptical vertical	0.38	1.040	46.15	15.56
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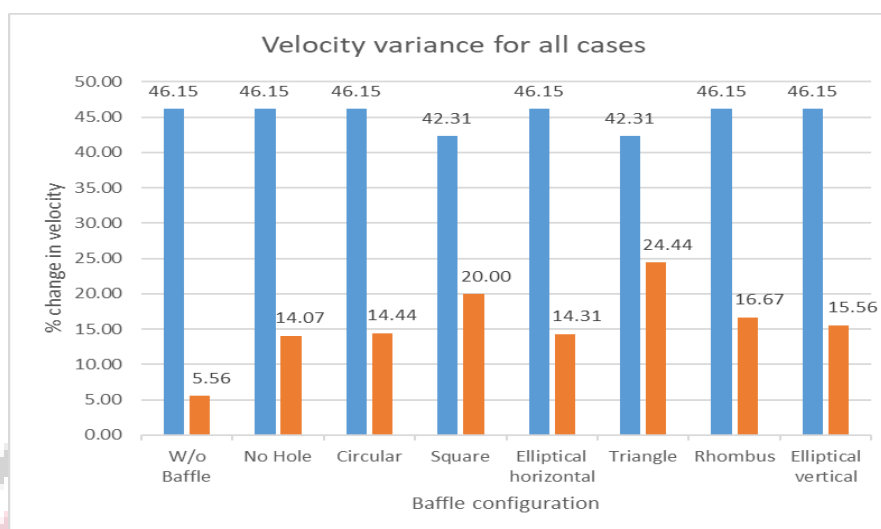


Figure 9 Comparative results for velocity

These complex result interactions of two fluids in counter flow in a double-tube heat exchanger (DTHE) and the various baffle configurations' influences on fluid dynamics can be elucidated through percentage change analyses in fluid velocity into and out of the tube and shell sides of DTHE. Base velocities with no baffle configuration (Case 1) were 0.28 m/s on the tube side and 0.950 m/s on the shell side. The application of simple baffle with no hole (Case 2) resulted in very appreciable improvement in tube side velocity of 0.38 m/s, while shell side velocity of 1.027 m/s was maintained. Circular holes in the baffles (Case 3) further improved flow recording at a tube side velocity of 0.38 m/s and a shell side at 1.030 m/s. square holes (Case 4) demonstrated much improvement measuring tube side velocity of 0.37 m/s and shell side of 1.080 m/s. Triangular holes (Case 6) were the best among the permutations with values recorded for the tube (0.37 m/s) and a significant result for the shell at 1.120 m/s. This indicates that such flow performance is superior. These results justify the importance of baffle configurations on the performance of fluid flow within the DTHE.

VI. Conclusion

This study takes a deep dive into how double-tube heat exchange systems (DTHE) perform in terms of heat and liquid dynamics. It looks closely at how different baffle configurations like solid and perforated baffles with various shapes and orientations affect performance. By leveraging advanced CFD simulations using ANSYS Workbench and detailed 3D CAD modelling, the research reveals just how much baffle design can influence heat transfer rates and fluid flow patterns within the exchanger. The results show that perforated baffles, especially those with optimized designs like circular, triangular, and vertically aligned elliptical holes, can boost thermal performance while tackling pressure drop challenges. Smart baffle design not only enhances system reliability but also improves energy efficiency, as demonstrated by comparing configurations with structured perforations to a baseline case with no baffles. Overall, these findings provide valuable insights for refining DTHE design and contribute to the development of more cost-effective and efficient industrial thermal management systems.

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