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Improving Heat Transfer Efficiency in Double Pipe Heat Exchangers: An Extensive Investigation of Baffle Configurations

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Abstract: *Heat exchangers play a pivotal role in various industrial and domestic applications, facilitating heat transfer between fluid mediums. This research delves into the performance enhancement of double pipe heat exchangers (DTHE) through the systematic investigation of different baffle configurations. By employing computational fluid dynamics (CFD) analysis, convective heat transfer and pressure drop within an annulus equipped with Single-Sided Perforated Baffles (SSPBs) are examined using water as the working fluid. The study encompasses the development and comparison of a proposed SSPB model with existing experimental results, aiming to optimize geometrical parameters. The methodology involves meticulously designed simulations and rigorous analysis to elucidate the influence of baffle configurations on heat transfer efficiency and fluid dynamics within the DTHE. Comparative results highlight the impact of various baffle designs on temperature distribution, heat transfer rates, and fluid flow characteristics. Insights from this study contribute to advancements in heat exchanger design and optimization.*

Keywords: *Heat exchanger, Double pipe heat exchanger (DTHE), Baffle configurations, Computational fluid dynamics (CFD), Heat transfer enhancement, Thermal performance factor (TPF).*

I. INTRODUCTION

A heat exchanger is a device designed for the transfer of heat from one source to a fluid medium. This system is integral in both heating and cooling operations. In some designs, a solid barrier is present to avoid the mixing of fluids, while in others, the fluids may directly interact. These systems find extensive application in various fields such as residential heating, air conditioning systems, industrial processes in power plants, chemical and petrochemical industries, oil refineries, processing of natural gas, and in wastewater treatment facilities. Internal combustion engines are a classic example of a heat exchanger, since ambient air passes over radiator coils to dissipate heat while a cooling fluid, such as engine coolant, circulates through them. The coolant cools and the air warms as a result of this action. Heat sinks, a type of passive heat exchanger that releases heat into a fluid medium, usually air or a liquid coolant, are another well-known application for them.

Figure 1 Tubular heat exchanger

A. *Heat Exchanger Having Different Types of Baffles Used to Enhance the Heat Transfer Rate*

Double pipe heat exchangers, recognized for their simplicity, are a basic type of heat exchanger commonly used in industrial settings. Their cost-effectiveness in terms of both design and upkeep makes them an attractive option for smallersca8le industries. Despite this, the relatively low efficiency and considerable space requirement when scaled up have prompted contemporary industries to opt for more efficient alternatives such as shell and tube or plate heat exchangers. Nonetheless, the straightforward design of double pipe heat exchangers makes them ideal for educational purposes, serving as an introductory tool for teaching the principles of heat exchanger design, which are universally applicable across different types of heat exchangers.

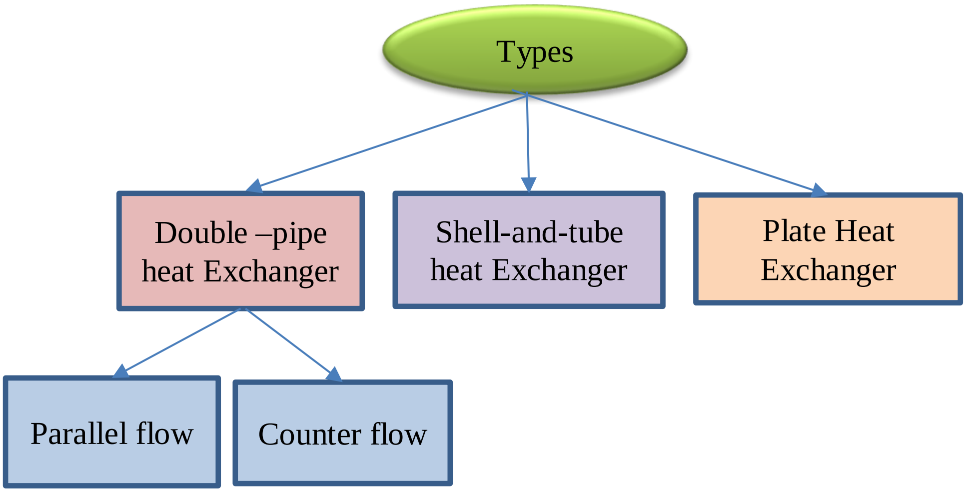


Figure 2 Types of Heat Exchanger

B. *Enhancement Methods for Heat Transfer and Their Thermal Efficiency Metrics*

Heat transfer devices play a crucial role in various industrial and domestic settings, such as in the thermal operations in the pharmaceutical and chemical industries, the boiling and condensation processes in power plants, temperature regulation in dairy production, heating in solar collectors, and cooling in electrical and electronic equipment. Improving the efficiency of heat transfer devices is vital as it leads to savings in energy, materials, and costs. Heat transfer enhancement methods typically aim to lower thermal resistance by either increasing the heat transfer surface area or inducing turbulence within the fluid flow. To expand the surface area, techniques like using rough or extended surfaces are employed, while inserts, winglets, and turbulators are utilized to create turbulence. Such alterations typically result in higher pumping power requirements, potentially elevating operating expenses (Manglik, 2003). To assess the efficiency of heat transfer enhancement techniques, the Thermal Performance Factor (TPF) is used. TPF measures how the change in heat transfer rate corresponds with the variation in friction factor. Twisted tape inserts have gained prominence as heat transfer enhancement components in recent decades, especially in the context of heat exchangers where their usage has been instrumental in reducing both size and cost. Their effectiveness varies based on the specific application, with twisted tapes being employed in various configurations. These configurations include different twist directions, twist ratios, perforated inserts, full and short tape inserts, tight and loose tape inserts, along with inserts with peripheral cuts, among others. The choice of configuration depends on the particular heat transfer requirements of the application at hand.

C. *Influence of Staggered and Partially Tilted Perforated Baffles on Heat Transfer*

In recent times, extensive research has been carried out for developing heat transfer enhancement techniques that address the challenge posed by thermal boundary layers forming on heat transfer surfaces. The objective is to enhance heat transfer effectiveness while minimizing friction losses. These techniques, known as passive methods, involve modifying the surface geometry by introducing turbulence promoters. These promoters can take various forms, including baffles, corrugations, dimples, fins, grooves, ribs, protrusions, rings, twisted tapes, winglets, wires, or combinations of these modifications. By altering the flow structure and pattern, these geometry modifications improve heat transfer. However, they also lead to increased pumping power requirements and operating costs due to higher pressure drops. These passive techniques find applications in various fields, including gas turbine blade cooling systems. Moreover, they are widely utilized in the manufacturing of several types of heat exchangers, that are integral components in numerous industrial sectors such as solar heating, air conditioning, refrigeration, pharmaceuticals, waste heat recovery, automotive radiator systems, and electronics cooling. The ultimate goal is to create compact and highly efficient heat exchangers [1].

The practice of using baffles as turbulators to create surface roughness is a frequently utilized passive method to improve heat transfer within cooling channels. This method offers a significant boost in heat transfer compared to other approaches, albeit at the cost of a relatively higher pressure drop. Numerous studies have delved into the application of this technique. For example, Kwankaomeng et al. conducted research on enhancing heat transfer in a square channel with isothermal walls under laminar flow conditions. They achieved this by placing baffles on the lower surface at a 30° angle. The study involved varying the heights of the baffles and employing different pitch lengths for a comprehensive numerical analysis.

In another research conducted by Eiamsa-ard et al., an experimental investigation was undertaken to examine the thermal characteristics of turbulent flow. This study covered a broad range of Reynolds numbers, spanning from 4000 to 20,000, within a rectangular channel. The channel was equipped with innovative twisted baffles placed on the bottom surface. The primary objective of this investigation was to analyze the influence of various geometric parameters, particularly the pitch and twist ratios, on heat transfer enhancement. Furthermore, the study conducted a comprehensive comparative analysis between two types of baffles: the angled and transverse configurations. This research aimed to provide valuable insights into the impact of these geometric variables on heat transfer efficiency within the rectangular channel. The results revealed that angled twisted baffles exhibited the highest thermal performance among the considered cases [1].

II. LITERATURE REVIEW

Omidi et al. [2]: This study provides an overview of double pipe heat exchangers and discusses recent advancements in enhancing their efficiency. It emphasizes the simplicity and versatility of this type of heat exchanger, which has made it popular across industries. The study reviews techniques to augment heat transfer rates, including the use of nanofluids and passive methodologies.

Bahmani et al. [3]: This research investigates heat transfer and turbulent flow characteristics in a double pipe heat exchanger using water/alumina nanofluid. Computational techniques are employed to analyze factors such as nanoparticle concentration, flow direction, and Reynolds number, revealing significant improvements in heat transfer efficiency with increased nanoparticle concentration and Reynolds number.

Swamee et al. [4]: The focus of this study is on optimizing the design of double pipe heat exchangers using geometric programming principles. By determining optimal values for parameters like pipe diameters and flow rates, the study aims to achieve specified performance metrics while minimizing costs.

Dizaji et al. [5]: This research investigates the thermal and frictional properties of double pipe heat exchangers with corrugated inner and outer tubes. Different tube configurations are explored, with findings suggesting that specific corrugation patterns lead to improved heat transfer performance.

Córcoles et al. [6]: This study employs advanced methodologies, including Response Surface Methodology and computational fluid dynamics, to analyze the thermal dynamics of double pipe heat exchangers using nanofluids. Significant enhancements in heat transfer efficiency are observed with increased Reynolds number and nanoparticle concentration.

Shirvan et al. [7]: The research focuses on a numerical analysis of double pipe heat exchangers filled with a porous medium. Sensitivity analysis reveals the impact of various parameters such as Reynolds number and porous substrate thickness on heat transfer performance.

Xiong et al. [8]: This study explores the influence of different turbulator designs on heat transfer and turbulent flow characteristics in double pipe heat exchangers. Computational simulations highlight the effectiveness of specific turbulator configurations in enhancing heat exchange efficiency.

Kavitha et al. [9]: The impact of copper oxide nanofluids on heat transfer enhancement in double pipe heat exchangers is investigated. Experimental findings demonstrate improved thermal performance with increased nanoparticle concentration and thermal conductivity.

Salem et al. [10]: This experimental investigation focuses on convective heat transfer characteristics and pressure drop in double pipe heat exchangers with perforated baffles. Correlations are derived to understand the relationship between various parameters and heat transfer efficiency.

III. OBJECTIVES

The objective of the proposed work is

- To conduct a Computational Fluid Dynamics (CFD) analysis to examine convective heat transfer and pressure drop within an annulus equipped with perforated Single-Sided Perforated Baffles (SSPBs) aligned along the inner heated tube surface, employing water as the working fluid.
- To develop a proposed model for SSPB with optimised geometrical parameters and compare with existing base experimental results.

IV. METHODOLOGY

The research methodology applied in this study follows a systematic and meticulously designed series of steps. These steps are specifically crafted to facilitate a thorough and accurate analysis of the double-tube heat exchanger (DTHE) across a range of different baffle configurations. This methodical approach ensures that the investigation is conducted in a rigorous and organized manner, allowing for a comprehensive examination of the DTHE's performance under varying baffle configurations. The structured nature of the research methodology enables precise data collection, analysis, and interpretation, ultimately contributing to the reliability and robustness of the study's findings. The key stages of this approach can be elaborated as follows.

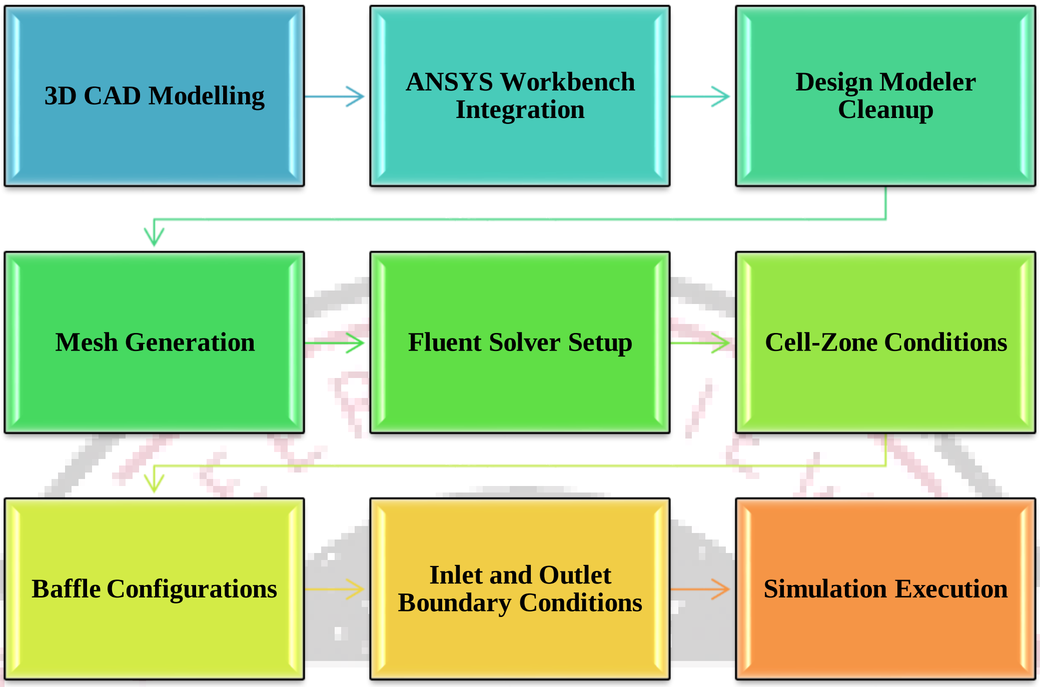
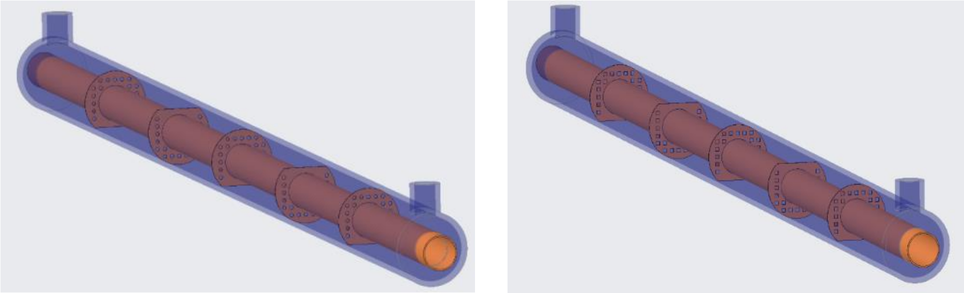


Figure 3 Flow Chart of Adopted Methodology

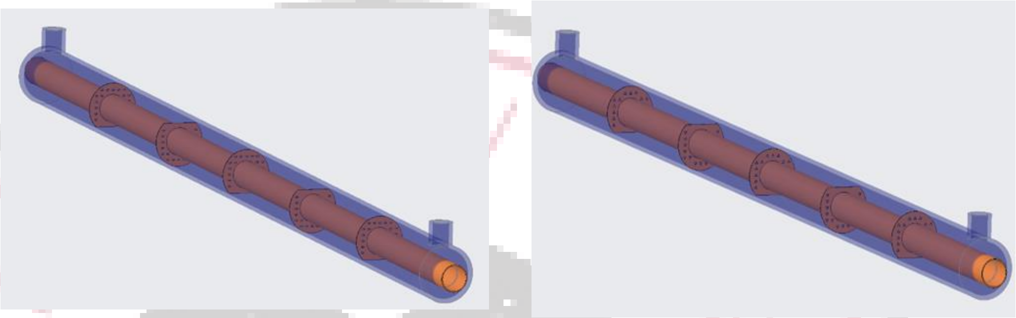
A. *CASES Considered in this Study*

The research investigation involves a meticulously structured exploration of various baffle configurations within the context of the double-tube heat exchanger (DTHE). These distinct configurations have been thoughtfully selected to comprehensively assess their impact on the DTHE's performance. Here is an elaboration of each specific case:

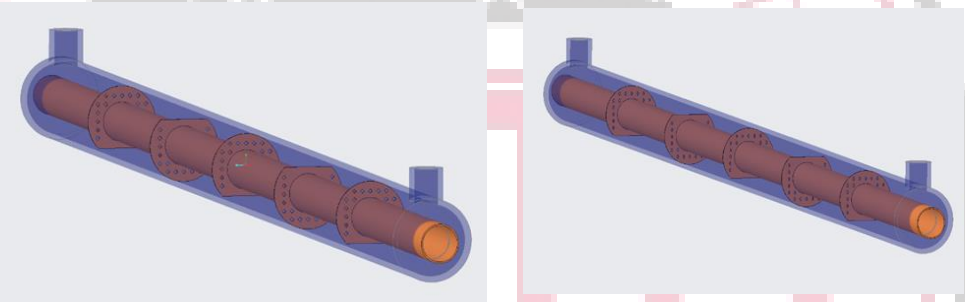
- Case 1: **No Baffles -** In this scenario, the DTHE operates without any baffles. This case serves as a baseline for understanding the natural heat transfer and fluid dynamics within the heat exchanger, without the presence of any disrupting elements.
- Case 2: **Baffles with No Holes -** Baffles are introduced into the DTHE, but they do not feature any perforations or holes. This configuration tests the impact of baffles themselves on heat transfer and fluid flow, without the additional complexity of holes.
- Case 3: **Baffles with Circular Holes -** The baffles in this case are equipped with circular holes. Circular perforations are known for their uniformity, and this configuration investigates their influence on heat exchanger performance.
- Case 4: **Baffles with Square Holes -** In this scenario, the baffles are designed with square holes. Square perforations introduce a different geometric element, and their impact on heat transfer and fluid flow is a key focus of this case.
- Case 5: **Baffles with Elliptical Holes (Major Axis Horizontally Aligned) -** Baffles featuring elliptical holes with horizontally aligned major axes are examined in this case. Elliptical perforations introduce asymmetry, and their orientation is of particular interest in assessing their impact on heat exchanger performance.
- Case 6: **Baffles with Triangular Holes -** Triangular holes are incorporated into the baffles in this case. The unique shape of triangular perforations brings a different set of challenges and opportunities, making this configuration noteworthy for analysis.
- Case 7: **Baffles with Rhombus Holes -** The baffles in this case are equipped with rhombus-shaped holes. Rhombus perforations introduce yet another geometric variation, and their impact on heat transfer and fluid dynamics is a focal point of investigation.
- Case 8: **Baffles with Elliptical Holes (Major Axis Vertically Aligned) -** Similar to Case 5, this scenario involves baffles with elliptical holes, but with their major axes aligned vertically. The orientation of the elliptical perforations in this case introduces a different dynamic into the study, exploring the influence of orientation on heat exchanger performance.



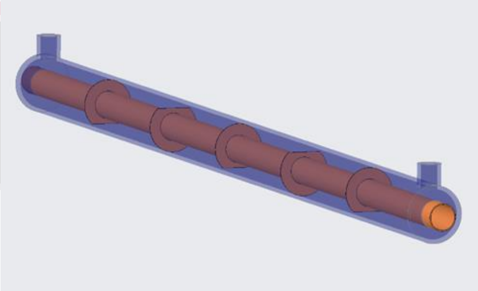
Circular Holes **Square Holes**



Elliptical Holes (Major Axis Horizontal) **Triangular Holes**



Rhombus Holes **Elliptical Holes (Major Axis Vertical)**



No Holes

Figure 4 Specific CASES Considered in this Study

Each of these cases represents a unique configuration that is systematically examined to gain valuable insights into its influence on heat transfer and fluid flow within the DTHE. Through the analysis of these diverse scenarios, the research aims to provide a comprehensive understanding of the intricate dynamics governing the performance of the heat exchanger, ultimately contributing to advancements in heat exchanger design and optimization.

In the initial phase of this study, the focus was on investigating the effects of the absence of baffles on the performance of a double-tube heat exchanger (DTHE). This endeavor commenced with the creation of a highly detailed 3D CAD (Computer-Aided Design) model representing the DTHE without baffles, capturing its intricate geometry and dimensions. Subsequently, the CAD model seamlessly integrated into ANSYS Workbench, a renowned computational fluid dynamics (CFD) analysis platform, to harness its advanced capabilities. Within this environment, the Design Modeler tool was employed to meticulously refine the CAD model, ensuring geometrical accuracy and eliminating any potential anomalies. Mesh generation, another vital step, involved creating a suitable mesh structure to facilitate the heat transfer and simulation of fluid flow within the DTHE. This comprehensive setup laid the foundation for subsequent phases, enabling a systematic exploration of how the absence of baffles impacts the DTHE's performance, all while prioritizing accuracy and precision in the simulation results.

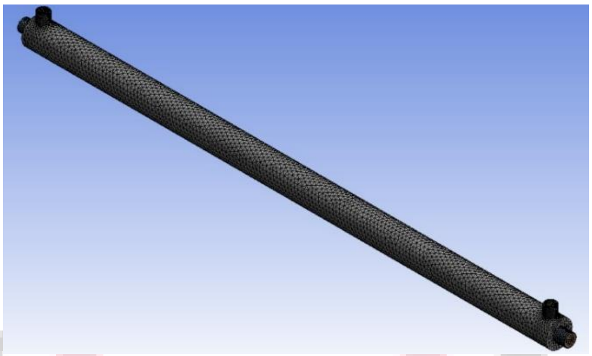


Figure 5 Meshing of DTHE

In the simulation setup, a series of crucial steps and parameters were meticulously configured to accurately replicate the conditions and dynamics within the double-tube heat exchanger (DTHE). To begin, constant pressure-based boundary conditions were applied while ensuring the effect of gravity was incorporated into the simulation. The energy equation was enabled to account for heat transfer phenomena. For modeling turbulence, the k-epsilon model with the realizable scale model and standard wall functions was chosen to accurately capture turbulent flow behavior. Material properties for water liquid, PVC, and copper were sourced from the Fluent material database and integrated into the simulation. In defining cell-zone conditions, the solid domain was specified as PVC for the outer shell, copper for both the inner tube and baffles, and water liquid for the fluid domain.

Boundary conditions were meticulously set for the inner tube (constructed from copper) with an inlet mass flow rate of 0.1343 kg/s at an initial temperature of 50°C, and the outlet was configured as a pressure outlet. Similarly, for the outer shell (comprising PVC), the inlet was defined opposite to the shell inlet, featuring a mass flow rate of 0.2 kg/s, and the outlet was designated as a pressure outlet. These detailed configurations ensured the simulation accurately represented the real-world operating conditions of the DTHE, enabling a comprehensive analysis of its heat transfer and fluid flow performance under various baffle configurations.

Table 1 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 6 Fluent Solver Boundary Conditions

These boundary conditions outline the specific settings applied to the inner tube (made of copper) and the outer shell (constructed from PVC) within the double-tube heat exchanger (DTHE) simulation.

V. RESULT AND DISCUSSION

In the results section, a comprehensive analysis was conducted to evaluate the thermal and fluid dynamics behavior within the double-tube heat exchanger (DTHE) under the specific conditions. Visual representations, including images and visualizations, were presented to illustrate the temperature distribution throughout the DTHE. These visualizations allowed for the clear observation and documentation of temperature variations that occurred as a direct result of the absence of baffles within the heat exchanger. Furthermore, the velocity profile within the fluid domain was also extensively examined, with visual representations showcasing the distribution of fluid velocity. This analysis included a detailed assessment of changes in fluid flow patterns induced by the absence of baffles. To provide a more comprehensive understanding of the results obtained, specific temperature and velocity values were recorded at both the inlet and outlet points for both the tube side and the shell side of the DTHE.

A. Comparative Results

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 2 Baffle Configuration Impact in Double Pipe Heat Exchangers: Tube vs. Shell Side Performance

C.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

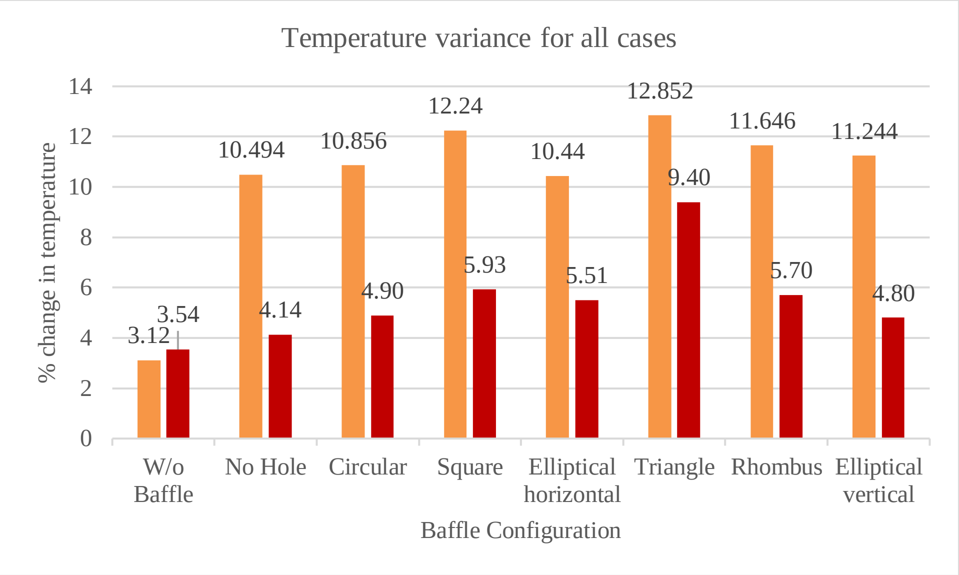


Figure 7 Comparative results for temperature

The analysis of various baffle configurations in the double-tube heat exchanger (DTHE) provides valuable insights into their impact on temperature distribution and heat transfer efficiency. Percentage changes in temperature are observed at both the tube side and shell side as the counter-flowing fluids interact with each other and the heat exchanger's walls and baffles. In the absence of baffles (Case 1), a baseline performance is established, resulting in moderate reductions in both tube and shell side temperatures. This configuration serves as a reference for comparing cases with perforated baffles. Case 2, featuring baffles with no holes, exhibits significant improvement, with a 10.44% reduction in tube side temperature and a 4.14% reduction in shell side temperature, highlighting the effectiveness of simple baffles in enhancing heat transfer. Case 3, employing baffles with circular holes, demonstrates notable improvements with a 10.856% reduction in tube side temperature and a 4.90% reduction in shell side temperature, emphasizing the impact of circular perforations on heat exchange performance. Case 4, utilizing square holes in baffles, achieves substantial improvement with a 12.24% reduction in tube side temperature and a 5.93% reduction in shell side temperature, suggesting the contribution of square perforations to enhanced heat transfer. Case 5, featuring horizontal elliptical holes, shows good improvement, with a 10.50% reduction in tube side temperature and a 5.51% reduction in shell side temperature, indicating the positive effect of horizontal elliptical perforations on heat exchange efficiency. Case 6, incorporating triangular holes in baffles, stands out as the most effective configuration, with a 12.852% reduction in tube side temperature and a significant 9.40% reduction in shell side temperature, showcasing superior heat transfer characteristics. Case 7, with rhombus-shaped perforations, demonstrates good improvement, with an 11.646% reduction in tube side temperature and a 5.70% reduction in shell side temperature, suggesting that rhombus-shaped perforations positively contribute to heat exchange efficiency. Finally, Case 8, featuring vertical elliptical holes, demonstrates significant improvement, with an 11.244% reduction in tube side temperature and a 4.80% reduction in shell side temperature, further highlighting the impact of varying baffle configurations on heat transfer within the DTHE.

Comparative results for velocity

The recorded velocity readings at both the tube side outlet and shell side outlet provide crucial insights into how different baffle configurations impact fluid flow within the double-tube heat exchanger (DTHE). With consistent inlet velocities of 0.26 m/s for the tube side and 0.90 m/s for the shell side, variations in velocity profiles are observed as the fluids interact with the heat exchanger's internal components and baffles.

Table 3 Baffle Configuration Comparison in Double Pipe Heat Exchangers: Tube Side vs. Shell Side Performance

C.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

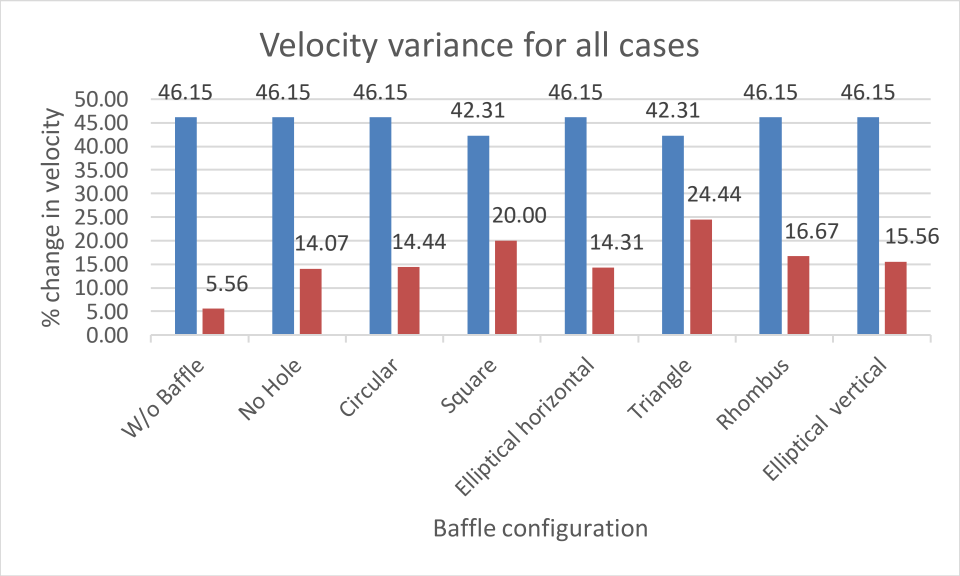


Figure 8 Comparative results for velocity

The analysis of percentage change in fluid velocity at both the tube side and shell side in the double-tube heat exchanger (DTHE) reveals the intricate interactions between counter-flowing fluids and the influence of different baffle configurations on fluid dynamics. Without baffles (Case 1), the baseline velocity shows a tube side velocity of 0.38 m/s and a shell side velocity of 0.950 m/s. When simple baffles with no holes are introduced (Case 2), there's a significant improvement, with a tube side velocity of 0.38 m/s and a shell side velocity of 1.027 m/s. Circular holes in baffles (Case 3) further increase fluid velocity, with a tube side velocity of 0.38 m/s and a shell side velocity of 1.030 m/s. Square holes (Case 4) demonstrate substantial improvement, with a tube side velocity of 0.37 m/s and a shell side velocity of 1.080 m/s. Triangular holes (Case 6) stand out as the most effective, showing a tube side velocity of 0.37 m/s and a significant shell side velocity of 1.120 m/s, demonstrating superior fluid flow characteristics. These findings underscore the impact of baffle configurations on fluid flow efficiency within the DTHE.

VI. CONCLUSION

The study systematically explored the impact of different baffle configurations on heat transfer efficiency and fluid dynamics within double pipe heat exchangers (DTHE). Through comprehensive computational fluid dynamics (CFD) analysis, it was revealed that the introduction of baffles significantly enhances heat transfer rates and alters fluid flow patterns within the DTHE. The comparative analysis demonstrated that varying baffle designs lead to distinct improvements in temperature distribution and fluid velocity profiles. Notably, configurations featuring triangular holes exhibited superior heat transfer characteristics, emphasizing the importance of geometric parameters in baffle design. These findings provide valuable insights for optimizing heat exchanger performance and contribute to the ongoing advancement of heat transfer enhancement techniques in industrial and domestic applications.

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