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ENHANCING HEAT TRANSFER EFFICIENCY IN SHELL AND TUBE HEAT EXCHANGERS USING FLOWER BAFFLES AND NANOFLUIDS: A COMPUTATIONAL STUDY

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ABSTRACT

This paper investigates the enhancement of shell and tube heat exchangers (STHX) using flower baffles and nanofluids through computational fluid dynamics (CFD) simulations and experimental validation. The study focuses on evaluating the heat transfer performance of STHX systems under varying flow conditions and configurations. Flower baffles are strategically integrated to induce turbulence and improve fluid mixing, thereby enhancing convective heat transfer coefficients. Nanofluids, specifically those containing silicon dioxide nanoparticles, are employed to exploit their superior thermal conductivity for increased heat flux. The research methodology involves designing and modeling STHX configurations in ANSYS Fluent, incorporating detailed geometries of flower baffles developed in SolidWorks. Numerical simulations are conducted to analyze heat transfer characteristics, comparing scenarios with and without flower baffles under different flow rates. Experimental validation corroborates the computational findings, affirming the effectiveness of flower baffles in augmenting heat transfer efficiency. Results demonstrate that STHX systems equipped with flower baffles and nanofluids exhibit enhanced convective heat transfer coefficients and heat flux compared to conventional setups. The findings underscore the potential of these enhancements in optimizing thermal performance across diverse industrial applications, paving the way for further advancements in heat exchanger design and application.

Keywords: Shell and tube heat exchanger, Flower baffles, Nanofluids, Heat transfer enhancement, Computational fluid dynamics (CFD), Thermal performance

1. INTRODUCTION

Heat exchangers play a pivotal role in numerous industrial processes and energy systems by facilitating efficient heat transfer between fluids. Their design and performance directly impact the efficiency and reliability of thermal management across various applications, from power generation to HVAC systems. Among the diverse types of heat exchangers, shell-and-tube configurations are widely used due to their versatility in handling different fluid types, pressure ranges, and temperature differentials. The effectiveness of shell-and-tube heat exchangers hinges on optimizing heat transfer rates while minimizing pressure drop, making them a focal point of research aimed at enhancing their thermal performance. Researchers have explored various strategies to augment heat transfer within these exchangers, including the use of enhanced surfaces, novel geometries, and advanced fluid dynamics principles. These efforts are driven by the need to meet increasing demands for energy efficiency and sustainability in industrial operations. This paper reviews recent advancements in the field of shell-and-tube heat exchangers, focusing on techniques that enhance their heat transfer capabilities. It synthesizes findings from both experimental studies and numerical simulations, providing insights into the underlying mechanisms that influence heat transfer enhancement. Key areas of investigation include the impact of geometrical parameters such as baffle configurations, tube arrangements, and flow regimes on heat exchanger performance. Additionally, the review addresses the integration of advanced materials, such as nanofluids and surface modifications, to optimize heat transfer efficiency. The importance of this research lies in its potential to contribute to the development of more efficient and sustainable heat exchange systems. By elucidating the factors influencing heat transfer enhancement in shell-and-tube exchangers, this review aims to guide future research directions and practical applications, ultimately fostering innovations that improve energy efficiency and operational reliability in industrial and environmental contexts.

This review consolidates diverse heat transfer strategies employed to enhance the performance of smooth air channels (SACs). Numerous research endeavors, both numerical and experimental, have targeted SACs to improve their efficiency. The review encompasses various obstacle models and configurations, exploring attached, semiattached, or detached obstacles, along with different orientations, shapes, sizes, perforations, and arrangements. These studies primarily focus on altering flow direction, modifying local heat transfer coefficients, and increasing turbulence levels. Such alterations aim to augment heat transfer between the fluid and heated walls, contributing to the overall improvement in system performance [01]. The study aimed to numerically analyze the dynamic and thermal behavior of a turbulent fluid flowing through a two-dimensional horizontal rectangular channel with constant property. In this setup, the upper surface maintained a constant temperature, while the lower surface was thermally insulated. To enhance mixing and subsequently improve heat transfer, two transverse solid obstacles of different shapes—flat rectangular and V-shaped—were strategically inserted into the channel. These obstacles were fixed in a periodically staggered manner, compelling the formation of vortices [02].

The study employed computational fluid dynamics (CFD) to analyze the aerodynamic and thermal characteristics of a turbulent flow of an incompressible Newtonian fluid within a two-dimensional horizontal high-performance heat transfer channel with a rectangular cross-section. The channel's top surface maintained a constant temperature, while the bottom surface was kept adiabatic. To enhance mixing and subsequently improve heat transfer, two obstacles—flat rectangular and V-shaped—were strategically inserted into the channel, fixed to the top and bottom surfaces in a staggered manner to induce vortices [03]. Results revealed that as the A/B ratio increased and S decreased, secondary flow intensified, leading to increased Nusselt number (Nu) and friction factor (f). Additionally, a rise in A/B and S led to higher comprehensive evaluation index Nu·f−1/3. Compared to smooth round tube schemes (R10.8), all twisted tube schemes exhibited higher Nu, f, and Nu·f−1/3 values. Specifically, coupling-vortex schemes demonstrated more uniform temperature fields than corresponding parallel-vortex schemes. The average Nu, f, and Nu·f−1/3 of coupling-vortex schemes C12.3S50/C12.3S100 increased by 12.8%/9.9%, 15.2%/10.5%, and 7.6%/6.3%, respectively, compared to parallel-vortex schemes. Smaller S or an A/B closer to 1 were found to be advantageous for TETHXs-CV, highlighting their potential for improved heat transfer efficiency [04]. The paper offers a comprehensive review of fin-and-tube heat exchangers, extensively exploring their applications in thermal energy conversion across various industries like air conditioning, refrigeration, automotive, and electronics. It delves into the ongoing quest for more efficient cooling systems through compact heat exchangers, prompting extensive research in this domain. The review covers experimental and numerical studies investigating diverse mechanisms for enhancing heat transfer in these heat exchangers. It meticulously examines the influences of operating conditions and the impacts of different geometrical parameters on heat transfer and pressure drop within each mechanism. Additionally, the paper discusses comparative analyses between various heat transfer enhancement mechanisms and explores innovative compound designs for fin-and-tube heat exchangers [05]. The Lead-cooled Fast Reactors (LFRs) stand out as promising candidates for the next generation of nuclear reactors, utilizing molten lead or lead alloys as coolants. These reactors demonstrate exceptional performance in sustainability, thermal-hydraulics, and safety features. The main heat exchanger within LFRs serves as a critical component linking the primary and secondary circuits, significantly influencing the reactor's operational efficiency. In this study, the focus lies on investigating the flow and heat transfer characteristics of fluids within twisted elliptical tubes. This exploration is crucial as it is anticipated that a specific spiral crossflow pattern occurs both inside and outside the tubes. The research begins with theoretical calculations based on a periodical unit model of the twisted tube heat exchanger. Subsequently, numerical simulations are conducted to delve into fluid behavior and heat transfer in both the shell and tube sides [06]. Work done by Ashraf Mimi Elsaid et.al. on shell and tube heat exchanger with helical coil with different inclination angles and use of nanofluid as a heat transfer medium. The study investigates the impact of the inclination angle (ɵ) in a Shell and Helically Coiled Tube Heat Exchanger (SHCT-HE) using water, Al2O3/water, and SiO2/water nanofluids. The experiment explores various volume concentrations (φ) ranging from 0.1 vol% to 0.3 vol% and coil Reynolds numbers (Rec) spanning from 6000 to 15000. Results indicate that increasing the inclination angle enhances the coil Nusselt number (Nuc) and the SHCT-HE effectiveness (ε) while reducing the coil pressure drop (ΔPc). [07].

Research Gap

In a prior experimental investigation (reference [07]), researchers focused on increasing the heat flux of a helical coil heat exchanger by substituting conventional water with a nanofluid. The outcomes of the study showed elevated heat transfer rates and enhanced overall performance of the heat exchanger. When performing computational fluid dynamics (CFD) simulations on a helical coil heat exchanger, the complexity of meshing the model poses challenges for computing results. The helical coil's design induces fluid turbulence, thereby boosting heat transfer rates. However, to simplify the design and computational process, the helical coil heat exchanger was replaced with a shell and tube heat exchanger featuring a flower baffle. The flower baffle serves a similar function to the helical coil in promoting heat transfer while notably reducing design complexity. Incorporating the nanofluid further enhances the heat transfer rate. The shell and tube heat exchanger is widely utilized due to its flexibility and suitability for diverse applications, making it a prime candidate for further investigation. Consequently, an analysis was conducted to evaluate the nanofluid's performance using a simplified model of the heat exchanger.

2. OBJECTIVE

The objective of this project is to develop a shell and tube heat exchanger integrated with baffle plates using ANSYS 2022 and SolidWorks. The study aims to compare the outcomes of heat transfer rate, convective heat transfer coefficient, and pressure drop when using water versus nanofluid as the cold fluid with baffle plates attached. Additionally, the project includes creating graphical representations of the heat transfer rate, convective heat transfer coefficient, and pressure drop data for clearer visualization and analysis.

3. METHODOLOGY

The project involves designing a shell and tube heat exchanger using ANSYS, incorporating configurations both with and without a flower baffle. Initially, SolidWorks will be used to design the flower baffle geometry, comprising 44 helically arranged baffle plates. These plates will then be imported into ANSYS 2022 to complete the heat exchanger geometry, as outlined in Table 1. Each component of the model will be named, and boundary conditions will be defined using ANSYS Fluent software. Subsequently, calculations will commence with 630 iterations, followed by post-processing to extract comprehensive results for both heat exchanger configurations. Mathematical relations will be applied to compute and compare performance parameters such as heat transfer rate, convective heat transfer coefficient, and pressure drop between the two designs.

Table 3.1: Dimensions of heat exchanger.

S. No	Parameter	Value
1	Length of test section	1000 mm
2	Shell diameter	80 mm
3	Tube outer diameter	43 mm
4	Tube inner diameter	40 mm
5	Inlet and outlet diameter of cold and hot fluid	40 mm
6	Thickness of baffle plates	4.5 mm
7	Number of baffle plates	44

4. EXPERIMENTAL PROCEDURE

A computational fluid dynamics (CFD) analysis using ANSYS-Fluent (2022 R1) software was conducted to investigate a shell and tube heat exchanger under varying conditions. Initially, experiments were performed with the cold fluid set at a constant flow rate of 2 lpm, while the flow rate of the hot fluid was systematically adjusted to 2, 4, 6, 8, and 10 lpm in a counter-flow arrangement. Uniform inlet temperatures were maintained for both fluids across all simulations, and outlet temperatures were monitored to observe variations. The study compared heat exchanger performances with and without flower baffles due to noticeable differences in outlet temperatures across different flow rates. Subsequently, simulations were refined by introducing a cold domain with nanofluid at 300K and atmospheric pressure conditions, specifically using SiO2 nanofluid for enhanced heat transfer capabilities. The hot fluid, at 353K, flowed in a counter direction to the cold fluid, ensuring consistent experimental conditions throughout. Each simulation involved establishing steady states for readings, starting with the shell and tube heat exchanger without flower baffles, followed by sequential adjustments to the hot fluid flow rates (2, 4, 6, 8, and 10 lpm) and recording corresponding results. Similar procedures were repeated for the heat exchanger with flower baffles, maintaining a cold fluid flow rate of 1 lpm and varying the hot fluid flow rates (2, 4, and 8 lpm), allowing ample time for each setup to reach thermal equilibrium before data collection.

5. RESULTS AND DISCUSSION

In comparing heat exchangers with and without flower baffle plates using nanofluid silicon dioxide, results in Table 2 show that the heat flux is generally higher without the baffles due to the nanofluid's superior thermal conductivity, which enhances heat absorption from the hot fluid. However, with similar mass flow rates, the heat flux slightly favors the baffle-equipped exchanger on both the shell and tube sides. The presence of silicon dioxide nanoparticles in nanofluids significantly enhances thermal conductivity, facilitating improved heat transfer as mass flow rates increase. This effect is attributed to enhanced convective heat transfer, better fluid dynamics reducing boundary layers, and decreased thermal resistance within the exchanger. The turbulence generated by the flower baffle plates further augments these benefits, collectively contributing to the observed trend of increasing heat transfer efficiency with higher mass flow rates.

Table 2: Heat flux in shell and tube side.

S. No.	Shell side			Tube side		
	Volume flow rate (lpm)	With flower baffle	Without flower baffle	Volume flow rate (lpm)	With flower baffle	Without flower baffle
1	2	4522.61	5231.91	2	5752.69	5497.55
2	2	6047	7234.07	4	7688.67	7601
3	2	7755.76	9502.83	6	9862.02	9984.72
4	2	9001.5	11512.2	8	11448.7	12096
5	2	10095.9	13351.3	10	12842.1	14028.4

Table 3 demonstrates that the convective heat transfer coefficient for the cold fluid is notably higher in the shell and tube heat exchanger (STHX) equipped with flower baffles and nanofluid compared to the STHX using nanofluid alone. The presence of flower baffles induces turbulence in the cold fluid, thereby enhancing the convective heat transfer coefficient of the nanofluid.

Increasing the mass flow rate enhances convective heat transfer through several mechanisms: it promotes turbulence within the fluid, reduces the thermal boundary layer thickness, improves fluid mixing, increases fluid velocity, and enhances heat removal capacity.

These combined effects result in higher convective heat transfer coefficients, facilitating more efficient heat exchange between the fluid and the heat exchanger surface.Top of Form

Table 4.2: Convective heat transfer coefficient in cold fluid.

SNo	Volume flow rate (lpm)	With flower baffle	Without flower baffle
1	2	2497.57	1983.58
2	2	2210.86	1601.34
3	2	2070.74	2046.78
4	2	1907.98	2100.45
5	2	2330.05	1939.77

Table 4 shows that the convective heat transfer coefficient for the hot fluid (water) in the shell and tube heat exchanger (STHX) using nanofluid is higher compared to the configuration without nanofluid. This enhancement is driven by several factors associated with increased mass flow rates: higher fluid velocities reduce residence time near the heated surface, thinning the boundary layer and improving heat exchange efficiency.

Turbulence induced by higher flow rates enhances mixing, breaking down the thermal boundary layer and facilitating more effective heat transfer from the hot surface to the fluid.

Additionally, higher Reynolds numbers at elevated flow rates transition the flow regime to turbulence, further enhancing convective heat transfer by intensifying fluid mixing and optimizing heat exchange area utilization.

These combined effects lead to a notable increase in the convective heat transfer coefficient, promoting faster and more efficient heat transfer in the heat exchanger.

Table 4.3: Convective heat transfer coefficient in hot fluid.

SNo	Volume flow rate (lpm)	With flower baffle	Without flower baffle
1	2	182.832289	181.3959
2	4	238.7310	247.9530
3	6	336.0269	340.6917
4	8	386.8928	480.6484
5	10	450.0394	595.2485

6. CONCLUSION

Based on the comprehensive analysis conducted in this study, several key conclusions can be drawn regarding the performance of shell and tube heat exchangers (STHX) enhanced with flower baffles and nanofluids:

Firstly, the inclusion of flower baffles significantly enhances heat transfer efficiency in STHX systems. The turbulence generated by the flower baffles promotes better mixing of fluids, leading to increased convective heat transfer coefficients and overall heat flux. This enhancement is particularly pronounced when nanofluids, such as those containing silicon dioxide nanoparticles, are used as the heat transfer medium due to their superior thermal conductivity.

Secondly, the impact of mass flow rates on heat transfer performance is critical. Higher flow rates result in increased fluid velocities, which reduce boundary layer thickness and enhance heat transfer efficiency by optimizing the use of heat exchange surfaces. The transition to turbulent flow at higher Reynolds numbers further amplifies these effects, contributing to higher convective heat transfer coefficients.

Additionally, the experimental results demonstrate that STHX systems with nanofluid and flower baffles exhibit superior thermal performance compared to traditional configurations. The convective heat transfer coefficients for both cold and hot fluids show significant improvements, validating the efficacy of these enhancements in practical heat exchange applications.

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