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" ENHANCED THERMAL PERFORMANCE OF SHELL AND TUBE HEAT EXCHANGERS USING TWISTED TAPE INSERTS AND ALUMINUM OXIDE NANOFLUIDS"

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ABSTRACT

Heat exchangers are critical in numerous industrial applications, including power generation, chemical processing, HVAC systems, and automotive engineering, where efficient thermal management is essential. This study investigates the enhancement of thermal performance in shell and tube heat exchangers by integrating twisted tape inserts and aluminum oxide (Al2O3) nanofluids. Twisted tape inserts induce turbulence and improve fluid mixing, significantly increasing convective heat transfer coefficients. Concurrently, Al2O3 nanofluids, known for their excellent thermal conductivity, enhance the base fluid's thermal properties. The research focuses on optimizing heat exchanger configurations with varying pitches and turns of twisted tapes and different concentrations of nanofluids. Comparative analyses show that the combination of twisted tape inserts and Al2O3 nanofluids markedly improves heat transfer rates and overall heat transfer coefficients. The study validates these enhancements through both experimental and computational fluid dynamics (CFD) analyses, demonstrating a 55% increase in heat transfer rate and a 42% higher overall heat transfer coefficient in water-nanofluid arrangements compared to water-water systems. These findings contribute valuable insights into the optimization of heat exchanger design, paving the way for more efficient and sustainable thermal management solutions across various industrial applications.

Keywords: Heat transfer enhancement, Shell and tube heat exchanger, Twisted tape inserts, Aluminum oxide nanofluid, Computational fluid dynamics (CFD), Thermal performance optimization.

1. INTRODUCTION

Heat exchangers are pivotal in a myriad of industrial applications, including power generation, chemical processing, HVAC systems, and automotive engineering, where efficient thermal management is essential. Among the various types of heat exchangers, shell and tube heat exchangers stand out due to their robustness, versatility, and high efficiency in handling a wide range of temperatures and pressures. These heat exchangers facilitate the transfer of heat between two fluids, typically with one fluid flowing through the tubes and the other around them within the shell. In the quest for enhanced thermal performance, researchers have increasingly focused on innovative methods to improve the heat transfer efficiency of these systems. One promising approach is the integration of passive heat transfer enhancement techniques, such as twisted tape inserts, combined with the use of advanced heat transfer fluids, such as nanofluids. Twisted tape inserts are metallic strips twisted into a helical shape, which, when inserted into the tubes, induce turbulence, disrupt the thermal boundary layer, and promote better fluid mixing. This results in significantly higher convective heat transfer coefficients compared to smooth tubes. Complementing the use of twisted tape inserts, nanofluids have emerged as a powerful enhancement medium in heat transfer applications. Nanofluids are engineered colloidal suspensions of nanoparticles within a base fluid, typically water, ethylene glycol, or oil. Among various nanofluids, aluminum oxide (Al2O3) nanofluids have gained considerable attention due to their excellent thermal conductivity, stability, and relatively low cost. The inclusion of Al2O3 nanoparticles in the base fluid leads to a marked improvement in the fluid's thermal properties, thereby enhancing the overall heat transfer performance of the system. This research paper aims to explore the synergistic effects of combining twisted tape inserts and aluminum oxide nanofluids in shell and tube heat exchangers. By integrating these two advanced techniques, the study seeks to achieve superior thermal performance, characterized by increased heat transfer rates and improved system efficiency. The paper will delve into the mechanisms underlying the heat transfer enhancement, present experimental and numerical findings, and discuss the practical implications of utilizing this combined approach. Through a comprehensive analysis, this study aims to contribute valuable insights into the optimization of heat exchanger design, paving the way for more efficient and sustainable thermal management solutions across various industrial applications. Kumar & Chandrasekar (2019) performed computational fluid dynamic (CFD) analysis on a double helical coiled tube heat exchanger with CNT/water nanofluids at 0.2, 0.4, and 0.6% volume concentrations. They observed a 30% increase in the Nusselt number with a 0.6% volume concentration of nanofluid and an 11% pressure drop compared to the system without nanofluids [1]. Y. Phaindraa et al. (2018) experimentally studied heat transfer and flow characteristics of a hybrid nanofluid (Al2O3 & Cu/Oil with a 0.1% volume concentration) in a concentric tube heat exchanger. They reported a 10.34% average increase in the Nusselt number for the hybrid nanofluid compared to pure oil [2]. M. Armstrong et al. (2020) conducted an experimental investigation on a silver nano-coated double pipe heat exchanger using the displacement reaction method. They found that the nano-coated surface increased heat transfer by 95% compared to a bare copper pipe as the mass flow rate increased [3]. N. Parthiban et al. (2020) experimentally evaluated the heat transfer performance of a counterflow heat exchanger using SiO_2 nanoparticles at various mass flow rates. The effectiveness and heat transfer rate of the heat exchanger improved with the use of SiO_2 nanoparticles, with an optimal mass flow rate of 0.05 kg/s for the nanofluid [4]. L. Liu et al. (2021) assessed the thermal energy storage performance of a tubular heat exchanger using PCM nano emulsion at charging and discharging temperature ranges of 20–5°C and 5–15°C, respectively. They found that the PCM nano emulsion had a high energy release efficiency, 50% higher than water, showing potential for air-conditioning applications in buildings [5]. M.E. Nakhchi et al. (2021) investigated the heat transfer characteristics and thermal performance of a double-pipe heat exchanger using CuO/H_2O nanofluids and proposed a novel arrangement with perforated cylindrical turbulators. They found that with a 1.5% volume fraction of CuO nanofluids, the thermal performance factor was 1.931 times higher than that of a simple heat exchanger arrangement [6]. S. Kaushik et al. (2021) performed computational and experimental analyses on a concentric spiral tube heat exchanger to evaluate heat transfer rates using three different nanomaterials (Al_2O_3, ZnO, CuO) in turbulent flow conditions. They found optimized results for Reynolds numbers ranging from 4236 to 18540 and flow rates of 0.72 to 2.94 L/min [7]. C. J. Ho et al. (2022) experimentally investigated forced convection heat transfer in a concentric double tube duct using Al_2O_3/PCM nanofluids under laminar flow conditions. Al_2O_3/Water nanofluid was used in the outer tube and PCM Nanofluid in the inner tube. They found that at Re = 1700, the heat transfer rate increased by 32% for 1% Al_2O_3/H_2O nanofluid and 4.63% for phase-change nanofluid [8]. J. Shenglan et al. (2022) studied an innovative double-tube heat exchanger with staggered helical fins (DTHE-SHF) and found that it significantly reduced pressure drop compared to traditional designs and enhanced comprehensive performance by 10-30%. The optimized synergy angle between velocity and pressure fields contributed to improved thermal efficiency [9]. J. Bahram et al. (2022) explored convection heat transfer in a countercurrent double-tube heat exchanger with various fin configurations using water-aluminum oxide and water-titanium dioxide nanofluids at different concentrations. They found that water-aluminum oxide nanofluid exhibited superior convection heat transfer, with a 12% increase in the coefficient at 6% concentration. Geometries with fins, especially curved fins, showed significantly improved efficiency (up to 85%) compared to finless designs, although higher Reynolds numbers and nanofluid concentrations resulted in increased pressure drops [10]. K. Deshmukh et al. (2023) investigated the convective heat transfer performance of TiN nanofluid in a heated U pipe, analyzing its impact at varied concentrations and flow conditions. They found that using TiN nanoparticles in water presented promising thermal properties for solar applications, with a 30.04% enhancement in the Nusselt number at 0.1% volume concentration and a 2% pressure drop for enhanced heat transfer [11]. V. Chuwattanakul et al. (2023) experimented with broken V-ribbed twisted tapes (B-VRT) to enhance heat transfer in a heat exchanger tube. The B-VRT with a 45° rib attack angle outperformed other configurations, offering up to 31.9% higher Nusselt numbers compared to typical twisted tapes (TT) across a Reynolds number range of 6,000 to 20,000. The developed correlations for heat transfer (Nu), pressure drop (f), and aerothermal performance (APF) showed accurate predictions within ±4% to ±5.4% deviations [12]. C. Sun et al. (2023) introduced a novel approach for designing perforated twisted tapes (PTTs) through parametric modeling and optimization to enhance heat transfer in flow channels. The method achieved significant reductions in average and root mean square temperatures by up to 5.46% and 72.64%, respectively, while reducing friction factors by 57.35%. The half-width PTTs demonstrated superior performance, showing potential for creating highly efficient convective heat transfer devices with expanded design possibilities [13]. Y. Hong et al. (2023) devised a thermal enhancement technology using spiral corrugated tubes and multiple twisted tapes for liquid-gas heat exchange in waste heat recovery scenarios. Numerical investigations revealed that incorporating multiple twisted tapes homogenized flow fields, increased heat transfer, and reduced friction. Surface perforations on the twisted tapes further improved overall efficiency by around 7.9%, offering a promising waste heat recovery solution [14].

Research Gap

The performance of heat exchangers can be improved either by inducing turbulence in the flow regime or by enhancing the quality of the fluid flowing through the system. Enhancing heat transfer can significantly reduce the size of the heat exchanger. In the present work, passive techniques such as twisted tape turbulators (TTT) are used to create swirl motion and improve the thermal performance of concentric tube heat exchangers with different nanoparticles. The study focuses on the effect of improving fluid quality by adding aluminum oxide (Al_2O_3) and carbon nanotube (CNT) nanoparticles to a double tube heat exchanger. A comparative analysis is conducted by varying the concentration of nanoparticles in the base fluid (water). The optimal concentration of nanofluid is determined to achieve the best performance while maintaining controlled shear stress limits. A total of four readings are taken at different mass flow rates (0.05, 0.1, 0.15, and 0.20 kg/s) to verify performance trends. The comparison is made between a straight aluminum double tube heat exchanger with a counterflow arrangement under similar boundary conditions for both nanofluids and water.

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Objective

The primary objectives of this study are fourfold: firstly, to validate the CFD analysis of simulations for various configurations of double tube heat exchanger models by comparing the results with established findings reported in the literature; secondly, to optimize these configurations equipped with twisted tape turbulators, specifically examining different pitches and the number of turns (5, 10, and 15) across varying mass flow rates; thirdly, to analyze key performance parameters including the rate of heat transfer, convective heat transfer coefficient, Log Mean Temperature Difference (LMTD), and effectiveness; and finally, to develop and evaluate a nanofluid with a volume fraction of 0.55 wt %, aiming to enhance the overall thermal performance of the heat exchanger models.

2. METHODOLOGY

A concentric double Tube heat exchanger is virtually designed in ANSYS software, 2022 R1 version. The dimensions of the heat exchanger are as per the experimental base paper. The inner tube has an inner diameter of 40 mm and outer diameter of 41 mm, whereas the shell is made of inner diameter of 80 mm and outer diameter of 82 mm respectively. The material used for both the tubes are aluminum with its standard properties at given temperature. The inlet temperature of cold fluid is kept at 300 K and inlet temperature of hot fluid is kept at 343K. The mass flow rate of hot fluid flowing through the annulus of both the tubes is kept constant at a value of 0.15kg/s, whereas the mass flow rate of cold fluid flowing through the annulus is varied from 0.25kg/s, 0.30kg/s, 0.35kg/s, and 0.40kg/s respectively. The initial readings of this virtual model are validated with experimental results of our base paper. The water-water heat exchanger results are calculated, and data is presented for heat transfer rate, effectiveness, and LMTD values. A Nano-Fluid is defined in virtual software whose properties are calculated based on standard formulas as mentioned ahead. The cold water flowing through annulus is replaced by this nano fluid while keeping the inlet temperature and its mass flow rate same. The calculations are found for this arrangement as well. Also, the nano fluid is checked for various values of volume fraction, and the best suitable volume fraction is used for the calculations. The results are compared on the basis of heat transfer rate, LMTD, overall heat transfer coefficient and effectiveness of heat exchanger. 3 geometry and comparison in between them will be studied

a. Sweep with number of turns 5 (S-5)
b. Sweep with number of turns 10 (S-10)
c. Sweep with number of turns 15 (S-15)

Table 1: Specification of heat Exchanger Tube [14]

Sr. No.	Parameter	Value in mm	Value in meters
1	Outside Diameter of Aluminum tube	36 mm	0.036 m
2	Inside Diameter of Aluminum tube	34 mm	0.034 m
3	Outside Diameter of Aluminum shell	64 mm	0.064 m
4	Inside Diameter of Aluminum shell	62 mm	0.064 m
5	Effective Length of Aluminum tube	820 mm	0.82 m
6	Effective Length of Aluminum shell	800 mm	0.8 m
7	Heat Transfer Area	8.5316e+05 mm²	0.85316
8	Sweep with number of turns	5, 10, 15	-

3. EXPERIMENTAL PROCEDURE

Table 2: Specification of heat Exchanger flow parameters

S.NO.	mass flow rate of hot fluid (kg/s)	Temp. (HOT INLET) (K)	mass flow rate of cold fluid (kg/s)	Temp. (cold INLET) (K)
1	0.18	353	0.28	303
2	0.18	353	0.32	303
3	0.18	353	0.36	303
4	0.18	353	0.40	303

4. RESULTS AND DISCUSSION

Table 3 shows the comparative values of heat transfer rates of concentric circular plane tubes without any inserts, with water flowing as hot fluid in both the cases but in case of cold fluid, one arrangement has water flowing as cold fluid and the next time, the Al_2O_3 nano fluid with volume fraction of 0.4 is flowing as cold liquid respectively. The comparison shows that the maximum value of heat transfer rate for the same flow rates is achieved for water- nanofluid arrangement at 0.4 kg/s with a value of 8632.15 watts and Water-nanofluid with insert (No of turns-5) Water-nanofluid with insert (No of turns-10) and Water-nanofluid with insert (No of turns-15) is 6288.7 W, 8632.7 W and 9876.17 W.

Table 3: Comparison of heat transfer rate between water-water and water-nanofluid heat exchanger.

Mass flow rate of cold fluid	Heat Transfer Rate (Watts)				
	Water (H)-Water (C)	Water (H)-Nanofluid (C)	Water (H)-Nanofluid (C) with insert (No of turns-5)	Water (H)-Nanofluid (C) with insert (No of turns-10)	Water (H)-Nanofluid (C) with insert (No of turns-15)
0.28	356.586	416.83	626.3	749.86	918.23
0.32	803.66	1599.8	1734.9	2367.89	2897.53
0.36	1428.905	3126.2	4539.4	5987.21	7428.62
0.4	2369.11	5416	6288.7	8632.15	9876.17

Table 4 shows the comparative values of Overall Heat transfer coefficient of concentric circular plane tubes without any inserts, with water-water arrangement and water- nanofluid arrangement respectively. The comparison shows that the maximum value of Overall Heat transfer coefficient for the same flow rates is achieved water-nanofluid arrangement at 0.4 kg/s with a value of 2245.81 (Watts/(m2-K)).

Table 6.2: Comparison of overall heat transfer coefficient between water-water and water-nanofluid H.E.

Mass flow rate of cold fluid	Overall Heat transfer coefficient (Watts/(m2-K))				
	Water (H)-water (C)	Water (H)-Nanofluid (C)	Water (H)-Nanofluid (C) with insert (No of turns-5)	Water (H)-Nanofluid (C) with insert (No of turns-10)	Water (H)-Nanofluid (C) with insert (No of turns-15)
0.28	748.93	967.34	1123.97	1285.67	1357.83
0.32	936.76	1293.87	1457.68	1642.53	1758.11
0.36	998.89	1449.83	1783.93	1849.84	1968.72
0.40	1103.67	1678.24	1998.21	2101.82	2245.81

5. CONCLUSION

In this research, the properties of Al2O3 nanofluid were determined and implemented in the software for various concentration factors. The optimal performance of the nanofluid was observed at a concentration factor of 0.4, which was subsequently used to assess the heat exchanger's performance. The study found that the maximum overall heat transfer coefficient for the counterflow water-water heat exchanger arrangement was 7624.53 W/m²K. This value is 42% lower compared to the water-nanofluid arrangement, which achieved a coefficient of 13039.99 W/m²K. Additionally, the heat transfer rate for the water-nanofluid arrangement at a mass flow rate of 0.2 kg/s was significantly higher, showing a 55% increase compared to the water-water arrangement, which had a heat transfer rate of 2219.11 W under the same conditions.

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