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CFD INVESTIGATION ON THE THERMAL PERFORMANCE OF COMPACT HEAT EXCHANGERS WITH VARYING FIN GEOMETRIES USING TITANIUM DIOXIDE NANOFLUID

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ABSTRACT

This study presents a computational fluid dynamics (CFD) investigation into the thermal and hydraulic performance of a compact heat exchanger integrated with various fin geometries and titanium dioxide (TiO_2) nanofluid as the working medium. The primary objective is to analyze the influence of fin shape and nanoparticle concentration on parameters such as Nusselt number, pressure drop, and overall heat transfer coefficient. Fin configurations examined include straight fins, wavy fins, offset strip fins, and louvered fins. The CFD simulations are performed under turbulent flow conditions using the Realizable k-ε turbulence model. TiO_2 nanoparticles are added to a water-based base fluid at different volume concentrations ranging from 0.5% to 2.0%. The results show that the inclusion of nanofluid significantly enhances the convective heat transfer performance, while optimized fin geometry further improves thermal effectiveness. However, an increase in nanoparticle concentration and complex fin shapes also leads to a noticeable rise in pressure drop. This research offers insights into the optimal balance between thermal enhancement and hydraulic penalty, providing useful guidance for designing high-efficiency compact heat exchangers.

Keywords: Compact Heat Exchanger, Titanium Dioxide Nanofluid, Fin Geometry, CFD Analysis, Heat Transfer Enhancement, Nusselt Number, Pressure Drop.

1. INTRODUCTION

Heat exchangers play a vital role in a wide range of engineering applications, including automotive systems, electronics cooling, aerospace thermal control, and renewable energy devices. The continuous demand for compact and energy-efficient thermal management systems has spurred interest in enhancing the thermal performance of heat exchangers without substantially increasing their size or energy consumption. Two widely researched techniques for improving heat exchanger performance are the use of nanofluids and the incorporation of extended surface structures such as fins. Nanofluids, engineered by dispersing nanoparticles into conventional base fluids, exhibit superior thermophysical properties such as enhanced thermal conductivity, specific heat capacity, and heat transfer coefficient. Among the various types of nanoparticles, titanium dioxide (TiO_2) has gained attention due to its stability, non-toxicity, cost-effectiveness, and compatibility with water and other common base fluids. When used in compact heat exchangers, TiO_2 nanofluids can significantly improve heat transfer rates through enhanced thermal conductivity and improved convective behavior. In parallel, the geometry of fins embedded in the heat exchanger core greatly influences flow dynamics and thermal performance. Fin designs such as straight, wavy, offset strip, and louvered configurations alter the flow path and promote turbulence, thereby improving heat transfer efficiency. However, complex geometries can also increase the pressure drop, leading to higher pumping power requirements. Computational Fluid Dynamics (CFD) has emerged as a powerful tool to simulate, predict, and optimize the performance of heat exchangers. CFD allows detailed visualization of temperature and velocity fields, and enables parametric studies of design modifications without the need for extensive physical prototyping. In this research, CFD is employed to evaluate the effect of TiO_2 nanofluid and various fin geometries on the thermal and hydraulic characteristics of a compact heat exchanger under turbulent flow conditions.

C. Gnanavel et al. [1], The paper investigates heat transfer enhancement in a double pipe heat exchanger using passive techniques such as nano-fluids and twisted tape inserts with rectangular cuts on their ribs. The study focuses on the thermal performance of various nanofluids, including titanium dioxide, beryllium oxide, zinc oxide, and copper oxide, in laminar to turbulent flow conditions. The results of the numerical study are compared, and the best nanofluid for heat transfer enhancement is suggested. M.E. Nakhchi et al. [2], The paper presents numerical simulations analysing the turbulent flow and thermal performance of fluid flows inside heat exchangers with perforated louvered strip inserts, showing that the recirculation flow through the holes of the inserts improves heat transfer. The study also investigates the effects of double mounted louvered strips on the flow characteristics, finding that using double perforated louvered strips with specific slant angles can significantly enhance heat transfer. Rimah S. Al Aridi et al. [3], The paper discusses the use of trapezoidal vortex generators (VGs) in a Concentric Tube Heat Exchanger (CTHE)

for heat transfer enhancement. Computational Fluid Dynamics (CFD) analysis is conducted using ANSYS Fluent to study the effects of VGs in different locations within the CTHE.Four designs are analysed, including a with no VGs and three cases with VGs placed in different locations. Results show that VGs are effective in all locations, with the highest improvement observed in case 1, where the heat transfer ratio is enhanced by 97% and the thermal enhancement factor is increased by 210% compared to the case with no VGs. J.D. Moya-Rico et al. [4], This paper aimed to investigate how different configurations of regularly spaced twisted tape elements (TTEs) inserted into a smooth double tube heat exchanger (DTHX) influence thermo-hydraulic performance. To mimic high-viscosity food-industry fluids, a 60° brix solution of water and sugar served as the Heat Transfer Fluid (HTF). The study comprised 320 experimental tests that varied flow velocity (Reynolds number) and TTE configuration. Nine different configurations were tested, involving various TTE pitches and free-space lengths. S. Padmanabhan et al. [5], Improving the thermal efficiency of heat exchangers has a direct impact on the materials used, energy obtained, and cost savings. This enhancement is particularly valuable in applications requiring thermal transfer processes, as it can significantly increase heat efficiency and the economic viability of the design and operation. Double tube heat exchangers, with their small diameters, are well-suited for high-temperature and high-pressure applications. While they are cost-effective, they tend to have relatively high pressure drops. To address this, various techniques have been developed to achieve the required heat transfer rate while maintaining economical pumping capabilities within the heat exchanger's design parameters. Chen Heng et al. [6], In this paper, the focus is on H-type finned tube heat exchanger elements, which are known for their ability to maintain high heat transfer capacity, possess self-cleaning properties, and enable the recovery of waste heat from flue gases in boiler renovations. The research employs an experimental open high-temperature wind tunnel system to investigate the heat transfer and pressure drop characteristics of H-type finned tube banks. The study explores the impact of several parameters, including fin width, fin height, fin pitch, and air velocity, on various aspects of heat transfer and pressure drop. Specifically, the research examines fin efficiency, convective heat transfer coefficient, integrated heat transfer capacity, and pressure drop concerning these parameters. Awais Muhammad et al. [7], This paper reviews heat transfer enhancement and pressure loss reduction in compact heat exchangers using vortex generators (VGs). It explores VG type, shape, design, and attack angle effects on heat transfer and pressure loss. Longitudinal vortices generated by VGs reduce wake regions, enhance turbulence, and improve flow mixing, with effects dependent on Reynolds number. Delta winglet VGs outperform rectangular types, and downstream placement is more effective. The paper also discusses microscopic vortex formation analysis using flow visualization techniques. M. Awais et al. [8], This study used numerical analysis to explore how interrupted surfaces affect compact heat exchangers (CHXs). They found that incorporating delta winglet vortex generators (DWVGs) can enhance heat transfer and pressure drop in CHXs. The study considered various factors, including the number of vortex generator rows (N), attack angles (θ), configurations, tube arrangements (inline and staggered), and tube shapes (circular, oval, and rectangular). They determined that an attack angle of 165º (θop) provides the best heat transfer performance with moderate pressure drop (ΔP). R.P.P.D. da Silva et al. [9], The paper discusses the development of theoretical models for the thermal and hydrodynamic performance of a compact heat exchanger manufactured using the SLM process, with good agreement between the models and experimental data. The study also highlights the negligible impact of surface roughness on pressure drop and the significant influence of replacing the core material on thermal performance in the turbulent regime. One of the most popular and efficient techniques for improving heat exchangers is the use of helical inserts. This article focuses on investigating the performance of an ANSYS CFX tool for double tube heat exchangers equipped with helical inserts. Talal M. Abou Elmaaty et al. [10], The paper focuses on the research and development efforts for corrugated plate heat exchangers, which are widely used in various engineering fields and applications. It discusses the structure, thermal performance, heat transfer enhancement mechanisms, advantages, and limitations of corrugated plate heat exchangers, as well as their efficiency in both single phase and two-phase flow. It aims to conduct a comparative analysis by comparing heat exchangers with helical inserts to those without, specifically examining heat flux and temperature distribution along the pipe. This research will shed light on the effectiveness of helical inserts in enhancing heat exchanger performance. Alireza Jafari et al. [11], The paper presents experimental and numerical investigations of a brazed plate heat exchanger, highlighting the importance of considering brazing joints in the modelling process. The study also emphasizes the need for developing new correlations for Nusselt number and friction factor of brazed plate heat exchangers, based on the comparison with existing correlations. Saeed Mohebbi et al. [12], The paper presents a numerical investigation of water flow in a small-sized plate heat exchanger with a chevron type corrugation pattern, and validates the numerical modeling with experimental tests. The study examines the influence of flow regime, heat transfer, and friction on the performance of the heat exchanger, and concludes that a chevron angle of 60° and increased corrugation depth or decreased corrugation pitch result in improved performance. Ji Zhang et al. [13], The paper provides a comprehensive

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review of previous works on the effects of chevron corrugation geometrical parameters and heat transfer enhancement techniques in plate heat exchangers, focusing on passive surface techniques and the use of nanofluids. It aims to describe relevant studies, provide an understanding of the heat transfer mechanisms, evaluate and compare different enhancement techniques, and suggest prospective directions for future research.

The objective of this study is to systematically investigate the thermal performance, Nusselt number distribution, pressure drop, and effectiveness of a compact heat exchanger by varying fin shapes and nanoparticle concentrations. The outcomes of this work are intended to guide the design and optimization of high-performance heat exchangers with improved thermal efficiency and minimized hydraulic losses.

2. METHODOLOGY

1. A concentric shell and Tube heat exchanger is virtually designed in ANSYS and Creo Parametric version. The dimensions of the heat exchanger are as per the experimental base paper.

2. The inner tube has an inner diameter of 12mm and outer diameter of 14mm, whereas the shell is made of inner diameter of 17mm and outer diameter of 18mm respectively.

3. 2 models are being created. One with plane fins and 2nd with wavy fins.

4. The material used for both the tubes are copper with its standard properties at given temperature. The inlet temperature of cold fluid is kept at 303K and inlet temperature of hot fluid is kept at 343K. The mass flow rate of hot fluid flowing through the annuus of both the tubes is kept constant at a value of 0.05kg/s, whereas the mass flow rate of cold fluid flowing through the

annulus is varied from 0.05kg/s, 0.1kg/s, 0.15kg/s, and 0.2kg/s respectively.

5. The initial readings of this virtual model is 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.

6. 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.

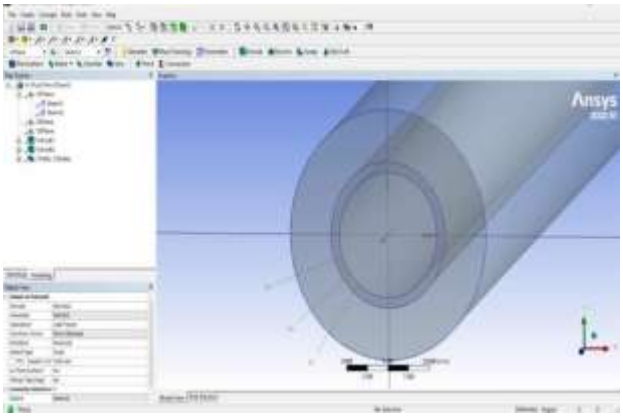

Fig 1: Showing dimension of the heat exchanger fluid according to counter flow arrangement

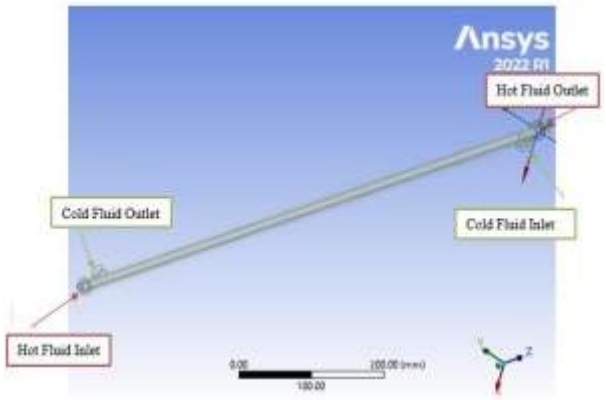

Fig 2: Geometry showing inlet and outlet of hot and cold

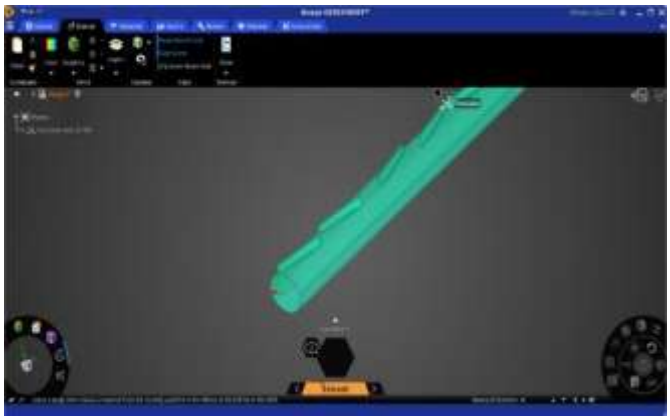

Fig 3: Geometry of plain rectangular fins all around the tube side.

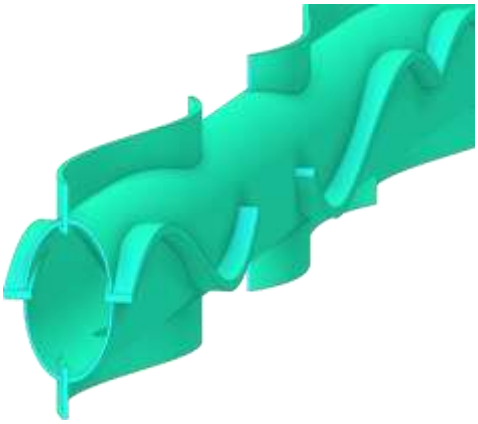

Fig 4: Wavy Fins

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3. RESULTS AND DISCUSSION

Comparison of Heat Transfer Rate

Table 1: Comparison of Heat Transfer Rate

Massflow rate of cold fluid (kg/s)	Heat Transfer Rate (Watts)			
	Water-water	Water-nano- fluid	Plain Rectangular Fins	Wavy Rectangular Fins
0.05	327	777	1785	2899
0.1	754	1340	2548	4748
0.15	1319	2826	4530	6829
0.2	2219	5016	6422	8974

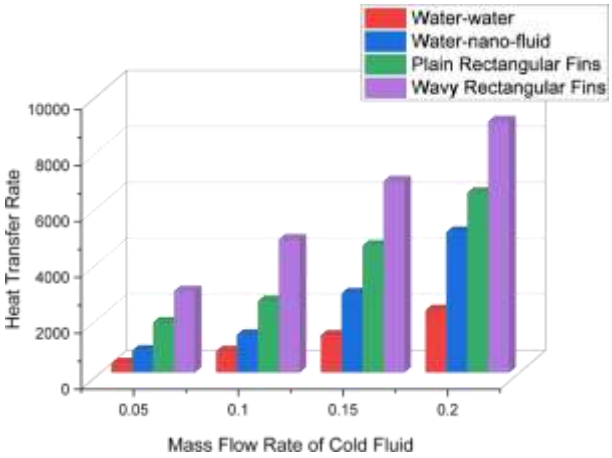

Fig 5: Comparison Graph of Heat Transfer Rate

Comparison of Overall Heat Transfer Coefficient

Table 2: Comparison of Overall HeatTransfer Coefficient

Massflow rate of cold fluid (kg/s)	Overall Heat Transfer Coefficient (Watts/metre SquareKelvin)			
	Water-water	Water-nano-fluid	Plain Rectangular Fins	Wavy Rectangular Fins
0.1	1178	1337	1572.5	1781
0.1	1357	1673	1812.8	1923
0.2	1506	1875	1975.1	2016
0.2	1725	1928	2123.7	2398

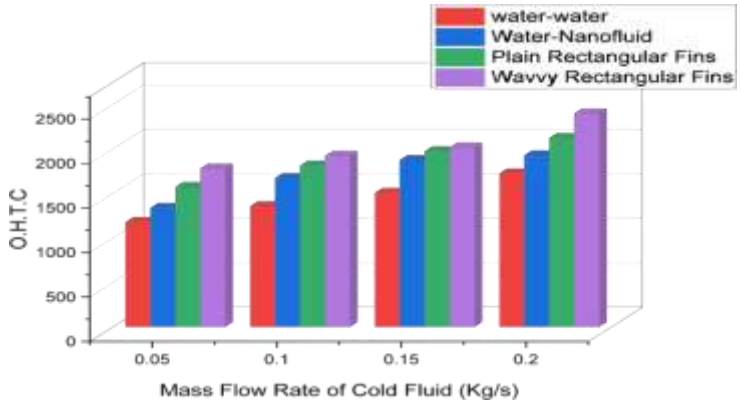

Fig 6: Comparison Graph of Overall HeatTransfer Coefficient

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Comparison of LMTD

Table 5: Comparison of LMTD

Massflow rate of cold fluid (kg/s)	LMTD			
	Water-water	Water-nano-fluid	Plain Rectangular Fins	Wavy Rectangular Fins
0.1	4.66	4.66	5.7	6.64
0.1	5.377	6.28	7.5	8.72
0.2	6.185	7.72	9.1	10.2
0.2	6.969	9.21	10	10.7

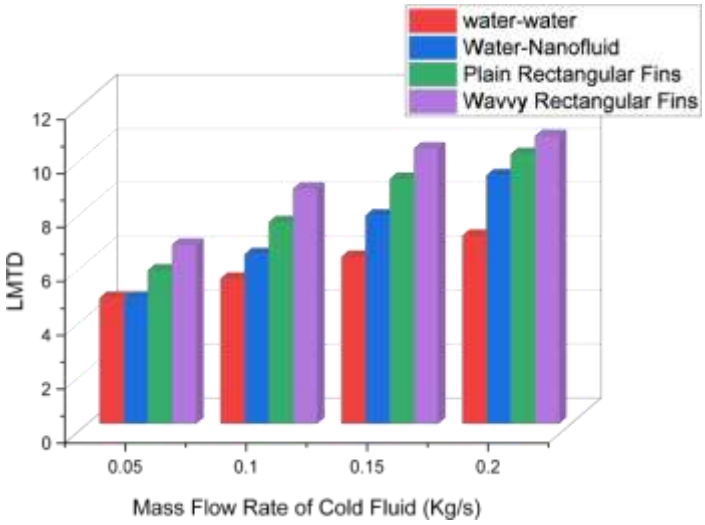

Fig 8: Comparison Graph of LMTD

4. CONCLUSION

A computational study on straight copper tube inserted in a copper shell with counter flow arrangement, straight copper tube with nanofluid of TiO2 flowing as cold liquid in place of water. The analysis is performed on a virtually modeled heat exchanger in ANSYS and Creo 2022. Tubes used for the analysis having same diameter and same length. Simulations carried out for all the tubes for same mass flow rate and the fluid used for the experiment was water and with the fins.

In this research work the properties of TiO2 nanofluid were found out and defined in software for various values of concentration factor. The performance of nanofluid is observed to be optimum at concentration factor of 0.4, which was selected to calculate the performance of heat exchanger.

In the present research work it is found out that the overall heat transfer coefficient is having a maximum value of 1724.5361 Watts/m2k for the counter flow arrangement of water-water type heat exchanger and 1927.9 W/m2K for water- nanofluid heat exchanger, which is 11 % more. And for rectangular plane fin, 2123.7 W/m2K which is 17 % more and 8974.1 W/m2K for wavy fins.

It is noted that LMTD for water-nanofluid arrangement was found to be 10.66 K which is greater than water-water arrangement by 32%.

The effectiveness of water-nanofluid arrangement was also found to be maximum with a value of0.166 which is more than that of water-water heat exchanger arrangement by 56% at a volume flow rate of 0.2kg/s of cold water.

The maximum heat transfer rate was noted to be increased by an amazing amount of 55% for a mass flow rate of 0.2kg/s water-nanofluid arrangement in comparison to the water-water arrangement which had a value of 8974.1 Watts for the same working conditions.

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