"Enhanced Heat Transfer Performance in Shell and Tube Heat Exchangers: A CFD Analysis of Twisted Tape Turbulators with Nanofluid Insertion"

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Abstract - *This study presents a comprehensive computational fluid dynamics (CFD) analysis of a shell and tube heat exchanger with a novel enhancement technique - the insertion of twisted tape turbulators within the tube side - and the incorporation of Aluminum Oxide (Al_2O_3) nanoparticles in water as the base fluid. The primary objective is to investigate and compare the heat transfer rate, convective heat transfer coefficient, and pressure drop characteristics under various operating conditions. The numerical simulations were conducted using commercial CFD software, where the governing equations of mass, momentum, and energy were solved employing the finite volume method. The k-ε turbulence model was adopted to account for turbulent flow behavior inside the heat exchanger. The results obtained from the CFD simulations were validated against experimental data, ensuring the accuracy and reliability of the computational approach. Subsequently, a parametric study was performed to explore the effects of varying nanoparticle concentrations, flow velocities, and twist ratios of the tape turbulators on the heat transfer and pressure drop characteristics. The findings reveal that the incorporation of Al_2O_3 nanoparticles significantly enhances the overall heat transfer rate, with notable improvements observed at higher nanoparticle concentrations. Moreover, the convective heat transfer coefficient is found to be enhanced due to the presence of the twisted tape turbulators, demonstrating a significant impact on the overall performance of the heat exchanger. However, it is also observed that an increase in nanoparticle concentration leads to an augmented pressure drop across the heat exchanger. Therefore, a trade-off between enhanced heat transfer and increased pressure drop needs to be considered in practical applications. In conclusion, this study provides valuable insights into the use of twisted tape turbulators and SiO2 nanofluids in shell and tube heat exchangers. The results offer a fundamental understanding of the thermal and hydrodynamic behavior and can aid in optimizing the design and operational parameters to achieve an optimal balance between enhanced heat transfer performance and acceptable pressure drop levels in industrial applications.*

Key Words**: Heat Exchanger, Nanofluid, Twisted Tape Turbulator, CFD Analysis, Thermal Analysis**

1.INTRODUCTION

Heat exchangers play a pivotal role in numerous industrial processes and energy systems, facilitating efficient thermal energy transfer between two fluid streams. Over the years, researchers have explored various enhancement techniques to augment the heat transfer rate and improve the overall efficiency of these heat exchangers. Among the prominent techniques, the insertion of turbulators within the tube side and the utilization of nanofluids have shown promising results in enhancing heat transfer characteristics. In recent years, computational fluid dynamics (CFD) has emerged as a powerful tool for investigating fluid flow and heat transfer phenomena. CFD simulations provide detailed insights into complex fluid dynamics and offer a cost-effective approach to evaluate different heat exchanger configurations and operating conditions. This study focuses on conducting a comprehensive CFD analysis of a shell and tube heat exchanger, which incorporates twisted tape turbulators inside the tube and utilizes a nanofluid composed of silicon dioxide (SiO2) nanoparticles dispersed in water as the base fluid. The incorporation of twisted tape turbulators in the tube side of heat exchangers has gained popularity due to their ability to induce turbulence and enhance convective heat transfer. Twisted tapes promote the formation of secondary flow patterns, breaking the boundary layer and leading to increased heat transfer rates. Consequently, these turbulators have been widely adopted to improve the thermal performance of heat exchangers, particularly in applications involving high heat transfer requirements. In addition to the use of turbulators, nanofluids have emerged as a promising heat transfer enhancement medium. Nanofluids are colloidal suspensions of nanoparticles in a base fluid, which exhibit unique thermal properties compared to conventional fluids.

2. LITERATURE SURVEY

In this experimental study, the Electro-Magnetic Vibration (EMV) method utilizes a stretched string vibrating at its natural frequency within a heated tube, induced by an AC magnetic field. This novel approach generates turbulence and radial flow, boosting heat transfer rates. Analysis involving varying vibrating string turbulator (VST) diameters and exciter positions, alongside thermal performance evaluation (TEF), revealed a potential enhancement factor of up to 1.47. This underscores EMV's effectiveness in intensifying heat exchanger performance through robust radial flow generation [1]. This study introduces the Special Shape Twisted Tape Turbulator (SSTT) with a DNA-like structure to enhance heat transfer in conduits. Through segmented components, it induces swirling motion, showing a 125% improvement over plain tubes at a 2mm pitch ratio. Combining SSTT with a helical coiled wire turbulator yields a 142% increase in heat transfer but also a 960% rise in pressure drop, achieving a 20% enhancement in thermal performance to 1.31 [2]. This research employed the innovative electromagnetic vibration (EMV) technique in a double-tube heat exchanger (DTHEX) for enhanced heat transfer. Assessing factors like oscillator geometry, magnet placement, nanofluids, and fluid flow, it achieved a remarkable 277.5% improvement using CuO-water 1% nanofluid compared to a standard heat exchanger. With the potential to increase heat transfer by up to 13.3 times the energy input, this method presents a transformative opportunity in conserving materials, energy, and optimizing heat exchanger and solar system designs [3]. This paper explores renewable energy use in residential and greenhouse heating/cooling, focusing on soil air conditioning systems. Findings highlight air-driven ventilation as superior in summer, with smaller pipe diameters and longer pipelines enhancing performance. The study conducted in four Iranian cities demonstrates Rasht's system as highly effective for heating and Abadan's for cooling. Additionally, cost comparisons between soil cooling and conventional HVAC systems were examined [4]. The study investigated heat transfer and exergy losses in a double-tube heat exchanger with corrugated inner tubes. Semi-elliptical corrugations on the inner tube significantly impacted heat transfer and exergy losses, while modified corrugations, combining quarter-elliptic shapes and inclined lines, delayed flow separation, boosting heat transfer. However, heightened heat transfer led to escalated exergy losses, emphasizing the trade-offs in performance enhancement [5]. This paper delves into a numerical investigation of a three-dimensional baffled shell and tube heat exchanger, exploring the influence of physical variables like baffle numbers and baffle type changes on heat transfer and exergy using the SST turbulence model. Analyzing oil and water as hot and cold fluids, the findings reveal that increasing oil flow rates escalate heat transfer and exergy loss. Furthermore, augmenting baffles from 3 to 5 amplifies both heat transfer and exergy loss in the system [6]. The study investigates enhanced thermal performance in Shell and Helically Coiled Tube Heat Exchangers (SHCTHEXs) using an Al_2O_3-TiO_2/water hybrid nanofluid. Simulations reveal a 7.7% to 9% increase in heat transfer rates for the horizontally and vertically oriented SHCTHEXs, respectively. The best performance is seen in the horizontally oriented SHCTHEX with the hybrid nanofluid, providing superior cooling compared to other configurations, emphasizing the significant impact of nanofluid utilization on heat transfer [7]. This paper consolidates findings on enhancing thermophysical properties of nanofluids by examining key parameters like particle characteristics, base fluid, temperature, additives, and pH. It serves as a valuable resource amidst conflicting reports, aiding researchers in navigating diverse studies. Additionally, it delves into nanofluid applications, emphasizing their advantages in solar collectors and automotive heat exchangers, aiming to bridge the gap between lab-scale research and practical industrial implementation while outlining avenues for future exploration [8]. The study constructed carbon nanotubes-reinforced composite honeycomb sandwich panels via silicone molding to enhance mechanical properties. The results showcased a direct correlation between increased nanotube content and wall thickness with higher compressive and flexural strength, highlighting potential for stronger sandwich panels with tailored properties [9]. The manipulation of electrical and thermal conductivity in CNT-modified polymeric composites (CNTMPCs) hinges on various factors such as chirality, length, type, fabrication, and interface interactions. Molecular dynamics (MD) simulations highlight how chirality impacts shorter CNTs more than longer ones, with zigzag CNTs showing lower conductivity than armchair types. Additionally, MD modeling demonstrates a notable increase in thermal and electrical conductivity with longer overlap lengths, underscoring the potential for designing highly conductive CNTMPCs with specific properties, though further comprehensive studies are necessary due to the multitude of influencing factors [10]. The use of carbon nanotubes (CNTs) in silicone-molded composites for honeycomb sandwich structures enhances thermal stability and energy absorption. Increasing CNT content up to 0.075 wt.% notably raised thermal degradation temperature by 14°C and improved energy absorption by 4.6%. Innovative dispersion techniques resulted in higher thermal conductivity with lower CNT amounts compared to prior studies, offering engineers an optimal strategy for designing superior thermal properties in composite structures [11]. In this research, a novel aerodynamically designed perforated teardrop-shaped turbulator (PTST) was numerically analyzed for its impact on hydro-thermal parameters. Variations in hole geometry and area within the PTST revealed significant effects on heat transfer and pressure drop, highlighting a 1.39-fold increase in Thermal Enhancement Factor (TEF) with a 5 mm diameter circular hole. Comparatively, PTST and simple teardrop-shaped turbulator (STST) showed 298% to 310.1% higher heat transfer than a plain tube, while a correlation between TEF and perforation area was established through curve fitting

[12]. This paper delves into enhancing the exergo-economic performance of compact air heat exchangers by employing passive techniques like TTI, PTTI, and DTTI with various tripartite hybrid nanofluids. Simulation results show that DTTI with THNF6 exhibits the highest overall heat transfer coefficient (26%), 2.94% exergy efficiency, 5.04% performance index, and a superior sustainability index at low Reynolds numbers, while THNF2, due to its high operating cost, is less preferred despite a PEC range of 1.42–2.35 [13]. The study enhanced conventional Shell and Helically Coiled Tube Heat Exchangers (SHCTHEXs) by integrating discs and rings as baffles, elevating thermal performance. Numerical simulations revealed a 7.1% increase in heat transfer and a 20% rise in overall heat transfer coefficient compared to the conventional design. Experimental validation closely aligned with simulations, showcasing a promising 2.4-3.5% difference, affirming the success of the modified SHCTHEX with circular baffles, achieving an overall heat transfer coefficient of 1050-1400 W/m^{2}K [14]. This study explores enhancing U-type tubular heat exchanger (THEX) efficiency by employing CuO-Al2O3/water hybrid nanofluid. Numerical simulations and experimental analyses demonstrate that this hybrid nanofluid significantly boosts overall heat transfer coefficients in THEX compared to single-component nanofluids. While fin additions elevate heat transfer, they escalate pressure drop particularly in smaller diameter THEX, highlighting the efficacy of hybrid nanofluids in augmenting thermal performance without such drawbacks [15]. This paper explores an experimental analysis of a heat exchanger tube using a newly devised perforated conical ring in combination with twisted tape inserts. It investigates diverse geometric and flow parameters, spanning Reynolds numbers from 6000 to 30000, nanoparticle volume concentrations of 0.25-1.0%, and various ratios for inlet flow diameter to inner print diameter of the ring, ring pitch, and twist ratios. Optimal thermal-hydraulic performance (1.45) was achieved at specific parameters, paving the way for empirical correlations for Nusselt number and friction factor in CuO/H2O nanofluids flow heat exchanger tubes with perforated conical rings [16].

Table 1: Properties of base fluid, nanoparticles and nanofluid

	Vol. Concentration (%)	**Thermal Conductivity (W/mK)**	**Density (kg/m3)**	**Specific heat (J/KgK)**
Al_2O_3/H_2O (Nanofluid)	1	0.6327	1026	4046
	2	0.65075	1055	3922
	3	0.66915	1085	3804
SiO_2/H_2O (Base Fluid)	-	32-36	3970-3990	760-870

3. OBJECTIVE OF PRESENT STUDY

The problem of performance of heat exchanger can be improved by either creating a turbulence in the flow regime, or by improving the quality of fluid flowing through the system. Enhancement of the heat transfer enables the size of the heat exchanger to be significantly decreased.

In the present work, passive techniques/twisted tape turbulators (TTT) producing swirl motion are used to improve the thermal performance characteristics of concentric tube heat exchangers with different nanoparticles.

Thus, the effect of fluid quality improvement is studied in double tube heat exchanger by addition of aluminum oxides nano particles (Al2O3). A comparative analysis is done by changing the concentration of nano particles in base liquid of water. The best concentration value of nanofluid will provide the optimize qualities of nanofluid which keeping the shear stress in controlled limits. A total of 4 readings are taken on different values of mass flow rates in order to verify the trend of performance. The mass flow rate of cold nanofluid is kept on 0.05, 0.1, 0.15, 0.20 kg/s respectively.

4. GEOMETRY OF THE HEAT EXCHANGER

Table 2 shows the geometry of the heat exchanger. Outside diameter of the tube is 40 mm, inside dimeter of the tube is 41 mm. outside diameter if shell is 80mm and inside diameter of shell is 82 mm

Table 2: Specifications Of Heat Exchanger

Sr.No.	Parameter	Value in mm	Value in meters
1	Outside Diameter of Aluminum tube	40 mm	0.04 m
2	Inside Diameter of Aluminum tube	41 mm	0.041 m
3	Outside Diameter of Aluminum shell	80 mm	0.08 m
4	Inside Diameter of Aluminum shell	82 mm	0.082 m
5	Effective Length of Aluminum tube	1020mm	1.02 m
6	Effective Length of Aluminum shell	1000mm	1.0 m
7	Heat Transfer Area	8.5316e+05 mm^2	0.85
8	Sweep with number of turns	4, 8, 12	-

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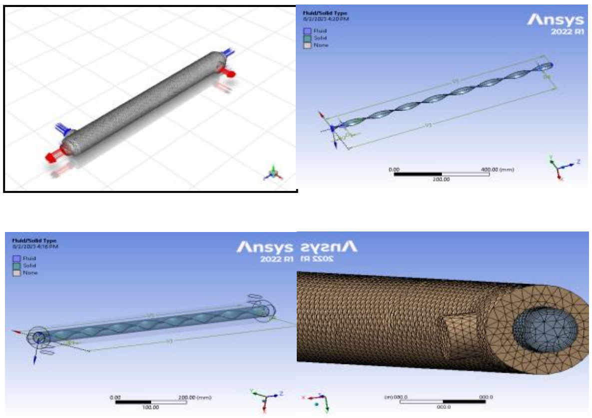

Figure 1: Geometry of Heat Exchanger with twisted tape and meshing

The dataset presents details of an aluminum tube and shell heat transfer system, featuring a tube with an outer diameter of 40 mm and an inner diameter of 41 mm, as well as a shell with an outer diameter of 80 mm and an inner diameter of 82 mm. The effective lengths of the tube and shell are 1020 mm and 1000 mm, respectively, with a heat transfer area of 853,160 mm^2. Additionally, the data mentions a parameter called "Sweep with number of turns," which is 4, 8 and 12.

5. CFD REPORT

Table 3 shows the meshing report of the geometry. It shows the element size, mesh quality, inflation information and statistics like number of nodes and elements.

Table 3: Meshing Report

Object Name	Mesh
State	Solved
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	5.e-003 m
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	No
Growth Rate	Default (1.2)
Max Size	Default (1.e-002 m)
Mesh Defeaturing	Yes
Defeature Size	Default (2.5e-005 m)
Capture Curvature	Yes
Curvature Min Size	Default (5.e-005 m)
Curvature Normal Angle	Default (18.0°)
Capture Proximity	No
Bounding Box Diagonal	1.016 m
Average Surface Area	0.11282 m^2
Minimum Edge Length	1.7279e-002 m
Quality	
Check Mesh Quality	Yes, Errors
Target Skewness	Default (0.9)
Smoothing	Medium
Mesh Metric	Skewness
Min	1.79E-03
Max	0.8814
Average	0.34647
Standard Deviation	0.22805
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Default (4.5e-005 m)
Generate Pinch on Refresh	No
Statistics	
Nodes	2364475
Elements	3916835

6. RESULT AND DISCUSSION

6.1. Heat Transfer Rate

Figure 2 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 Al2O3 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-4) Water-nanofluid with insert (No of turns-8) and Water-nanofluid with insert (No of turns-12) is 6288.7 W, 8632.7 W and 9876.17 W.

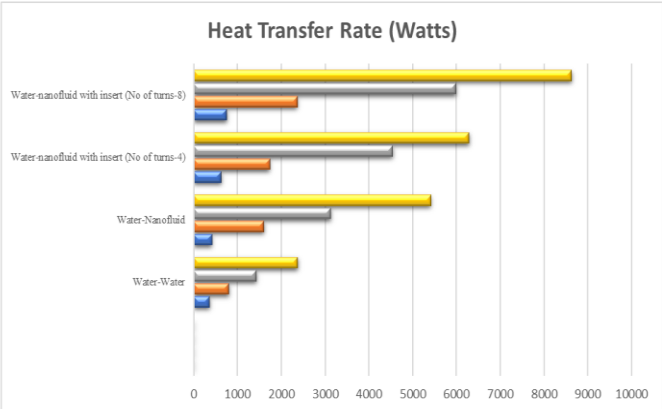

Figure 2: Rate of Heat Transfer versus mass flow rate of Hot Fluid in Counter Flow arrangement

6.2. Convective Heat Transfer Coefficient

Fig. 3 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 0.2kg/s with a value of 2245.81 (Watts/(m2-K)).

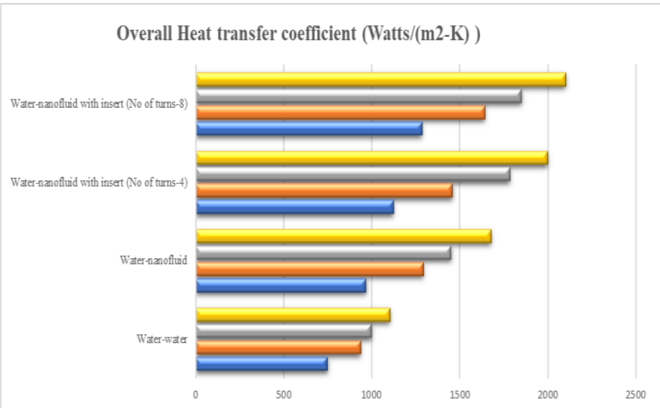

Figure 3: Overall Heat transfer coefficient versus mass flow rate of Cold Fluid in Counter Flow arrangement

6.3. LMTD

Fig 4 shows the comparative values of LMTD of concentric circular plane tubes without any inserts, with water-water and water-nanofluid arrangement respectively. The comparison shows that the maximum value of LMTD for the same flow rates is achieved for water-nanofluid arrangement, and it was at its maximum on 0.2kg/s with a value of 9.21088. This growth is due to the fact that temperature difference at the inlet and exit increases. Since LMTD is directly proportional to change in temperature at inlet and exit. Thus, it also shows increase w.r.t the mass flow rate.

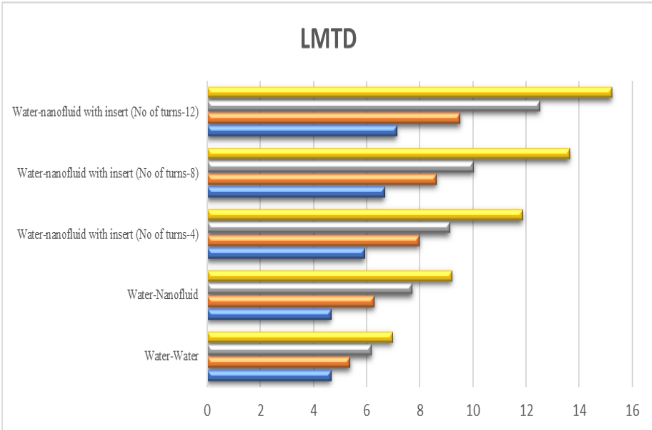

Fig. 4: LMTD versus mass flow rate of cold Fluid in Counter Flow arrangement

6.4. Effectiveness

Figure 5 shows the comparison of heat transfer rates among water as a hot fluid and cold fluid, hot fluid as a water and cold fluid as a nanofluid with different number of turns of the insert like 4 turns, 8 turns and 12 turns. From the graph, it can clearly be seen that as the thermal properties of the fluid increases, rate of heat transfer increases due to high thermal properties of nanofluid in comparison with water. But as we put a insert of twisted tape turbulator, it provides turbulence in the fluid. Turbulence increases the convective heat transfer coefficient of the fluid. And we know that convective heat transfer coefficient of turbulent flow is greater than the laminar.

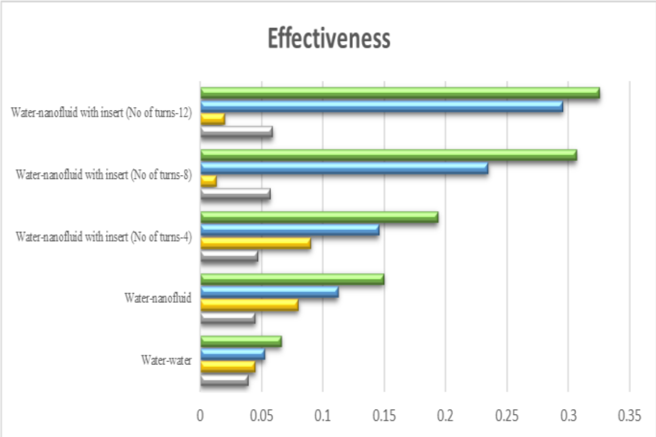

Fig. 5: Effectiveness versus mass flow rate of Hot Fluid in Counter Flow arrangement

7. CONCLUSION

1) In this research work the properties of Al2O3 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.

2) In the present research work it is found out that the overall heat transfer coefficient is having a maximum value of 7624.53 Watts/m2k for the counter flow arrangement of water-water type heat exchanger which is 42% less than the value we obtained for water-nanofluid arrangement, which has a value of 13039.99 Watts/m2K.

3) It is noted that LMTD for water-nanofluid arrangement was found to be 9.21 K which is greater than water-water arrangement by 24%.

4) The effectiveness of water-nanofluid arrangement was also found to be maximum with a value of 0.149 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.

5) 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 2219.11 Watts for the same working conditions.

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