International Journal of Heat and Technology
Vol. 42, No. 5, October, 2024, pp. 1622-1632
Journal homepage: http://iieta.org/journals/ijht

Availability Prediction of a Double Pipe Heat Exchanger Using Twisted Tape and Nanofluids

Abdullah Yousef Alhussen*, Adnan M. Hussein

Kirkuk Technical Engineering College, Renewable Energy, Northern Technical University, Kirkuk 36001, Iraq

Corresponding Author Email: abdulah.yousef@ntu.edu.iq

https://doi.org/10.18280/ijht.420516

Received: 8 July 2024
Revised: 3 September 2024
Accepted: 18 September 2024
Available online: 31 October 2024

Keywords:
twisted tape (TT.), nanofluid, heat transfer, thermal performance, exergy

ABSTRACT

Heat energy conservation is essential in all aspects. Various sectors, such as HVAC (Heating, Ventilation, and Climate control), Chemical treatment, Thermoelectric plants, and Chilling units face challenges in utilizing effects, reusing heat, and preserving resources. Caloric can be recovered using a heat exchanger. Thermal exchangers necessitate substantial Monetary investment in favor of various Funds and operational costs. Therefore, it is essential to develop HE. That are more energy-intensive, costly, and resource-efficient. The approach to enhance heat transfer is nanofluid inserts with tape insertion. Through this research, we consolidated the parameters influencing the nanofluid's operation to improve the heat tray. A study has been carried out on advancing heat transmission using twisted taut.

1. INTRODUCTION

Nanotechnology is a modern technology that has garnered significant attention from academics due to its potential to enhance the physical properties of materials, particularly thermal conductivity. A group of researchers is currently focused on enhancing the heat utilization of HE. by utilizing nanotechnology. Nano and creative designs enhance surface area, enhancing heat exchange processes and reducing worldwide energy demand [1-5].

Containing nanoparticles into an ordinary heat transfer fluid and putting forward a TT. into the HE. tube is twosome of several methods that have been studied for their ability to improve heat transfer efficiency [6, 7]. Research has demonstrated that nanofluid enhances heat transmission efficiency in systems owing to its elevated Thermal transmission. Additionally, the significant mobility of nano-particles, commonly referred to as Brownian motion [8-13]. Meanwhile, by inserting objects into tubes, the efficiency of heat transmission is increased because it increases the speed of the fluid flowing in the same direction, which in turn improves the mixing of the fluid. The scientists simulated the motion and heat exchange in a nanofluid made up of CuO nanoparticles in H_2O with varying doses of solid particles from 1 vol.% to 4 vol.% within a tube [14-16]. The simulation of chaotic flow conditions at Reynolds numbers covering from 3000 to 36,000 involved using Mono-phase and bi-phase (mixing) representations.

He et al. [17] proved that using a single twisted tape is more appropriate than using two tapes from the point of view of fluid dynamics. They based this on their theoretical study of simulating the use of a nanofluid containing copper oxide particles with a variable concentration from 1% to 4%. In the turbulent flow region almost, they obtained the highest value for the coefficient of performance efficiency. With a single twisted strip and a concentration of 4%, but their study had no practical aspect.

Aghayari et al. [18] investigated the enhancement of heat transfer in a double-tube HE, utilizing twisted tape inserts and a nano-fluid comprising iron oxide and water at varying concentrations. The findings revealed a notable improvement in heat transfer efficiency. However, the study did not explore the efficacy of nanoparticles derived from alternative materials through experimental testing.

Sundar and Sharma [19] observed a notable enhancement of approximately 34% in the convective heat transfer coefficient when employing a TT. insert within the tube of a double-pipe HE., using a nano-fluid consisting of H_2O and aluminum oxide.

Others, like Hosseinnezhad et al. [20], replicated the methodology used in reference, augmenting it with an additional twisted tape insert inside the tube, resulting in a total of two twisted tape inserts. These inserts were arranged symmetrically initially and in opposition subsequently. The highest thermal performance values were achieved in the counter-swirl configuration, aimed at inducing vortices within the flow.

Nakhchi and Esfahani [21] utilized numerical analysis to examine the flow of a nanofluid consisting of copper and water through a circular duct. The study focuses on using twisted tape with the twist axis (CCTA). Simulations are performed using a three-dimensional RNG k-turbulence model for Stark tubes with 9 distinct CCTA configurations. The presence of CCTA induces a swirling motion in the fluid, resulting in enhanced fluid mixing, heat transmission, and skin friction coefficient. The heat transfer coefficient shows a significant increase when the volume fraction of nanoparticles increases up to 1.5%. Augmenting the concentration of nanoparticles in the duct amplifies the thermal efficiency.

Li et al. [22] examined entropy production and heat transmission through forced convection in the HE. containing a helical TT. and using the FVM. The nanofluid used in the study is a Blend of Al_2O_3 and H_2O. The study investigated the extent to which physical factors affect the entropy of the nano blend. Additionally, it presents a method for quantifying entropy generation. Studies indicate that the production of thermal entropy diminishes as the blockage ratio (BR) and (Re) increase, but the development of dissipative entropy increases coupled to higher height ratios.

Jafaryar et al. [23] investigated the effects of TT. inserts on pressure drop and Thermal energy trans enhancement of nanofluids consisting of H_2O. This study predicts the CuO-H_2O behavior using -3D model and illustrates entropic production contours Influenced by processes such as energy trans and rubbing between particles. The FVM, it is used to investigate the belongings of physical properties. Outcomes show that nanofluid involvement improves with lower pitch ratios, whereas secondary flow intensifies with higher Entry velocity (m/sec).

On the other hand, Ju et al. [24] examined the hydrothermal Functioning of a HE. inserted into a semi-TT. This examination was done with a three-dimensional numerical image and in a laminar flow range. The study aimed to discovery the best conditions of achieving the uppermost heat transfer level and the lowermost friction coefficient value via alum aluminium dissolved in a water-based medium.

The researchers inserted a semi-twisted strip into the tube, returning to the heat exchanger, one tape once, two tapes the second time, three tapes the third time, and four tapes the fourth time. The researchers discovered that increasing the use of TT. leads to improved heat transfer, naming the increase in the values of non-dimensional criteria (Re, F and Nu). It was noticed the same thing when they increased the nanomaterial concentration in water, obtaining a higher Nusselt number and a more significant coefficient of friction. However, the researchers did not try this in turbulent flow.

The primary objective of this study is to enhance the heat transfer performance of a double-tube heat exchanger.

A- Enhance Heat Transfer Efficiency: To improve the heat transfer process in a double-tube heat exchanger by utilizing advanced techniques and materials.
B- Minimize Energy Loss: To reduce energy wastage by optimizing the thermal performance of the system.
C- Optimize Thermal Performance: To identify the optimal positioning within the heat exchanger to achieve maximum thermal efficiency.
D- Reduce Frictional Losses: To minimize losses caused by friction, thereby improving overall system performance.

Investigate Hybrid Nanoparticles: To explore the use of hybrid nanoparticles and assess their thermal behavior in enhancing heat transfer.

2. NANOFLUIDS

Nanofluids are a mixture where nanoparticles are dispersed Embedded in a foundational fluid. It is able to enhance transmission for heat and movement of solutions in engineering applications [25-29]. Kong et al. [30] studied the nano-fluids improved convection process by dispersing nanoparticles like metallic oxides or carbon nanotubes into liquids such as water or oil. Their distinctive traits make them excellent candidates for enhancing the effectiveness and functionality of many technical systems, such as HE., Heat dissipation in electronics, and solar systems. Utilizing nanofluids' characteristics offers possibilities for improving energy efficiency and tackling thermal management issues in several engineering fields [31, 32].

They analyzed the methods of preparing and analyzing nanofluids and their lubricating mechanisms in tribology. Difficulties in creating consistent, enduring nanofluids that are stable over time, have low clumping and do not significantly affect friction-related properties. There are two preparation procedures for nano-fluids, one-step approaches produce more stable nanofluids, while two-step procedures are adaptable for different types. Three methods enhance nanofluid stability, with the surface modification being the most successful and causing few changes to physicochemical parameters. The deposition of nanoparticles on rubbing surfaces is believed to improve tribological performance, although it needs more experimental confirmation and modelling. Thorough tribological investigations utilizing various methods are essential for comprehending interactions between nanoparticles and surfaces.

Jing et al. [33] studied effectively produced well-dispersed silicon dioxide with H_2O nanofluids with different Particle dimensions by a single step sol/gel method. Nanofluids containing particles of (5, 10, 25, 50) nanometers were verified by electron microanalysis and photon scattered methods Figure 1. This nanofluid, consisting of particles measuring 5nm and making up 2% of the volume, showed a transmittance of 97% and a thermal conductivity increase of around 20% compared to pure water. The PV/T system uses nanofluid to absorb infrared light, which helps optimize the temperature for the operation of PV cells and heat removal. Numerical simulations presented that PV/t scheme's energetic efficiency remained enhanced using nanofluid, especially at concentrations of 40 at flow velocities of 0.015 meters and 0.1 meters per second. The results indicate that best operational settings for the PV/t model employing SiO_2/water nano-fluid, improving its practical usefulness and cost-effectiveness.

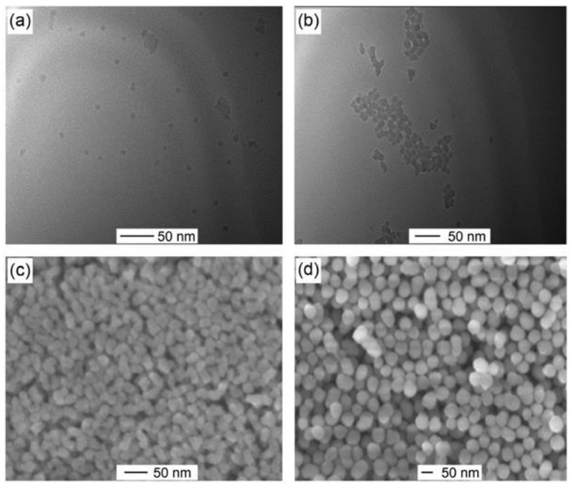

Figure 1. Images for nanofluids with volume fraction of 1.0% [33]

Chang et al. [34] used a novel way to manufacture nanofluids by utilizing a sonication-assisted subaqueous arch nano-particle formation device. The experimental results show the successful creation of evenly dispersed TiO_2 nanoparticles using these settings. The TiO_2 nanofluid has a pH of 7.5, demonstrating its electrostatic stability. The nanofluid absorbs UV light between 280 and 400 nm, with an energy band gap of 3.4 eV identified through UV-V is absorption spectrum analysis.

Zhu et al. [35] produced a CuO nano-fluid by altering an unbalanced Copper (II) hydroxide precursor into Copper (II) oxide in H_2O using sonic agitation and microwave treatment. The study investigated how these operations influence the synthesis process. The study examined the thermal-conductive of the Copper (II) oxide nano-fluid and showed that this technique could create a uniformly dispersed nanofluid with high-volume fractions. A synthesis approach was suggested, and it was noted that the CuO nanofluid produced had more thermal conductivity than those made using traditional dispersal techniques.

Dalkılıç et al. [36] studied the process of a smooth pipe with a length of 42cm. A twisted tape with four channels was inserted into it, through which Water sometimes passed and at other times a hybrid nanofluid consisting of 60% silicon dioxide and 40% graphite. The researchers used only two concentrations for this study, 0.5% and 1%, from the volume of water, which is the primary fluid used to create nanofluid. The experiment was carried out in operational conditions Re. were more significant than 3400, reaching a maximum of 11000. The researchers noticed that if the nanofluid was used, there was an improvement in the Nusselt number values whenever they increased flow rate and percentage of dissolved particles. With the nano-fluid, more length leads to more convection. As that concentration of the nanofluid grows, there is, in return, a grow in the friction coefficient and, thus, an grows in the pressure loss. However, they found an error rate in the empirical correlations of up to 10% when calculating the values of the coefficient of friction, and this percentage cannot be neglected.

Durga Prasad and Gupta [37] tested that effect of inserting a TT. into a U-tube HE. with Al_2O_3/H_2O nanofluid to see whether it may improve the fluid's heat transfer efficiency. The friction factors and heat transfer coefficients are calculated under different operating settings, such as 0.01% and 0.03% particle volume concentrations and twist ratios ranging from 5 to 20. The operation runs with Reynolds numbers between 3000 and 30,000 and flow rates between 0.0333 and 0.2667 kilograms per unit time were used to gather the data. The Nu for the entire tube, when using a nanofluid concentration of 0.03% and TT. inserts, there is a noticeable improvement in the value of more than 30% of the water. Totally, increasing concentration and using TT. generally improved non-dimension values (Re, Nu and F) and efficiency noticeably.

Mostafizur et al. [38] studied that power and work efficiency of a plate-type solar collector using four types of nano-fluid, considering that distilled water was the basis at a ratio of 1% to 4% and with a volumetric flow of 1 to 4 liters per minute. The researchers found that the nanofluid with copper oxide and water is best choice, superior to Al_2O_3 and H_2O, magnesium oxide and water, and titanium oxide and water. The researchers confirmed through the results that increasing the concentration ratio of the nano-fluid and the flow rate (kg/s) could lead to increasing the efficiency as shown in the Figure 2.

Selimefendigil et al. [39] focused on a double-tube HE. Aiming to enhance heat transfer performance by utilizing a nanofluid (SIO_2/H_2O) within the inner tube. The findings revealed a notable increase in the heat transfer coefficient, with a 16% improvement observed in the scientific simulation. However, the practical system exhibited a more substantial enhancement, ranging from 20.6% to 43.5%, depending on the flow rate and nanofluid concentration. This disparity becomes more pronounced with increasing flow rates. To mitigate this discrepancy, future studies should focus on improving the practical design. The summary of previous studies is indicated in Table 1.

Table 1. Previous studies

Author Name	Nanofluid Used	The % Volume Concentration of Nanofluid	Type of Exchanger	Development in Heat Transfer Coefficient
Mousavi Ajarostaghi et al. [11]	Aluminium oxide-H_2O, Copper(II) oxide-H_2O, Copper-H_2O, and Titanium dioxide-H_2O	(1%-5%)	Double pipe HE.	The Cu-water nanofluid has the best criterion (η=1.157) at the lowest Reynolds number (Re) 500.
Duangthongsuk and Wongwises [6]	TiO_2-water	(0.2 vol.% TiO_2)	Double pipe heat exchanger	According to the findings, nanofluid has a convective heat transfer coefficient (HTC) roughly 6%-11%,
Hussein et al. [7]	CuO-water	(0.5% to 1%)	Double pipe heat exchanger	exceeding the base fluid greatest possible total heat transfer coefficient at 1% liquid content.
Dalkılıç et al. [36]	Gr-silicon dioxide/H_2O hybrid.	(0.5%-1%)	Horizontal pipe with various quad-channel	Using Composite nano-particles increases that transfer of heat coefficient to achieve higher flow of (0.03-0.035-and 0.040) kilograms per second.
Durga Prasad and Gupta [37]	Al_2O_3/water	(0.01% to 0.03%)	U-tube heat exchanger	To the Quality achive when nanofluid was use of Al_2O_3 particles Figure 3 with Distilled water at a volume of 0.1 and 0.03% of concentrations with Re.
Bhanvase et al. [8]	(polyaniline) nanofluid	(0.1 vol.% to 0.5 vol.%)	Perpendicular spiral/wound pipe HE.	Heat transfer coefficient amplified by more than 10% when the volume content was 0. 1%.

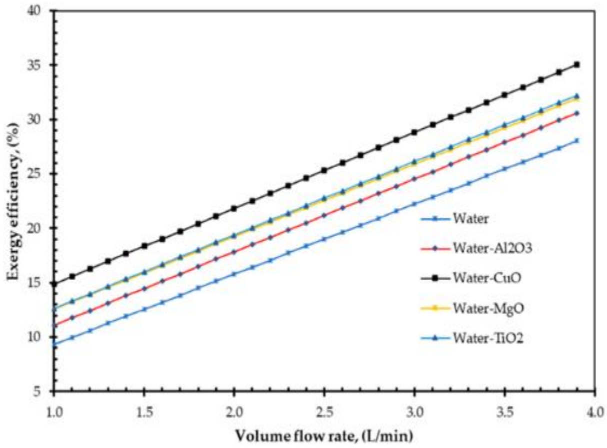

Figure 2. Effect of volume flow rate on exergy efficiency [38]

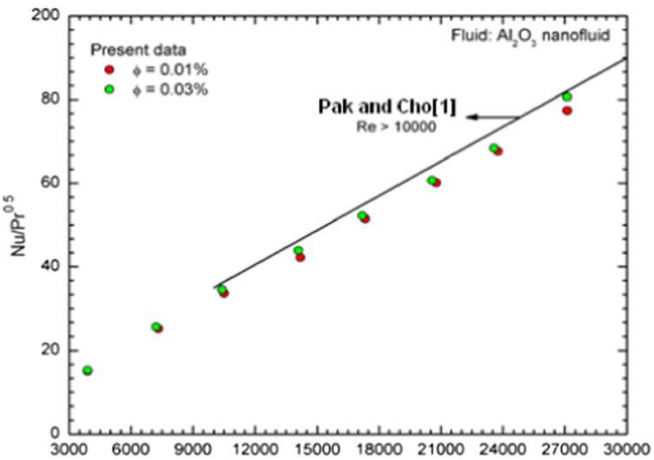

Figure 3. Nusselt number of 0.01% and 0.03% concentrations of nanofluids with Re [37]

3. TYPES OF NANOPARTICLES

Figure 4 categorizes nanoparticle fluids into metal nanofluids, ceramic nanofluids, and nanoparticles composed of carbon and polymeric nanotubes. Figure 5 illustrates the diverse forms of nanoparticles. Nanotubes, constructed from nanoparticles, possess a cylindrical shape. One hypothesis for the diverse morphologies is that heat may propagate faster over longer distances. Nanofluids require increased pumping force due to the presence of nanotubes [40].

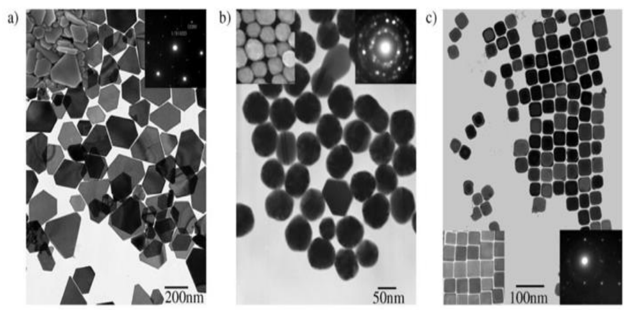

Figure 4. Shape of nanoparticles [40]

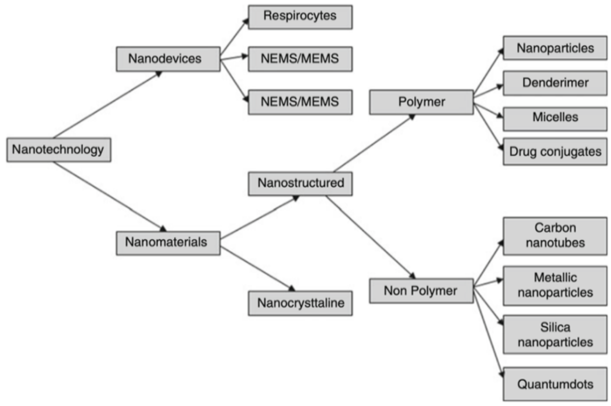

Figure 5. Type of nanofluid [40]

4. HEAT TRANSFER IMPROVEMENT BY TT.

Heat transfer augmentation methods remain frequently employed in heating systems to shrink expenses, dimensions, and mass and enhance system efficiency. By including a swirl flow device, the thermal near-wall boundary layer is disturbed, resulting in enhanced fluid mixing and consequently boosting convective heat Trans. That coiled tape within the cylinder can lead to an increased pressure drop because the enlarged interaction area amid the liquid and the TT. Scientists have created multiple variations and arrangements of twisted tapes to decrease pressure [41-43].

Nakhchi and Esfahani [44] examined the stormy properties and thermal improvement factors of Copper (II) oxide-H_2O nano-fluids in HE. Using dual V-cut TT. That tapes have a TR. (5.25), and the ratio of (b/c) varies (0-1.8). The Re fluctuates between (5000~15000), whereas the nano-particle volume fraction spans from 0% to 1.5%. They examine raging flowing using the (RNGk-ε) turbulence simulation. That study shows that creased improved tape cuts enhance fluid mixing and heat transmission by increasing turbulent kinetic energy and promoting vortex flow, resulting in a 14.5% improvement at ϕ=1.5%. Twisted tapes with a double V-cut increase the Nu by approximately 138% in comparison to plain tapes. The optimal thermal efficiency of 1.99 is attained with a porosity of 1.5% and a blockage ratio to 1.8 at a Re of 5000.

Shahsavar et al. [45] used computational methods to examine how combining TT. with nano-fluid can recover that efficiency of a double-pipe HE. An analysis compares and evaluates the impact of (Re), nanoparticle volume concentration, and (T-pitch) in performance parameters compared to a basic DPHE. Increasing Reynolds number enhances heat transmission and efficacy, raising pressure drop and pumping power. NF outperforms the base fluid unless when φ is less than or equal to 15% and Re is equal to 500. The hydrothermal performance of the nanofiltration system with a twist pitch demonstrates a fluctuating pattern of increase and decrease. The twisted DPHE demonstrates better hydrothermal performance than the plain DPHE, achieving a peak value of 2.671 Figure 6.

Abu-Hamdeh et al. [46] investigated that hydrodynamic analysis of a HE. Through utilizing cross-cut twisted tapes nanofluid consisting of single-layer carbon nano-tubes suspended on thermal oils. That simple algorithm and FVM technique are employed to evaluate heat transfer. The study concentrates on optimizing input flow and preventing flow reversal in the test area. Various geometric characteristics of twisted tapes are analyzed to optimize based on the PEC index, representing the highest performance evaluation standard. The findings indicate that TT. markedly impact thermal and fluidic properties by inducing a swirling motion, enhancing the coefficient of heat transfer, and increasing the (ΔP). That basic model it more efficient from the cross-cut model, as seen by cross-cut values continuously surpassing 1.11, showing the beneficial impacts of using turbulators. The most optimal model is case K with N=8, displaying PEC values between 1.37 and 1.93 for NF-filled systems at different Reynolds numbers. Machine learning techniques show precise prediction of output parameters in heat exchanger simulations, with maximum errors less than 1%.

Hamza and Aljabair [47] conducted a practical numerical study to expand heat transfer process through that usage of a hybrid nanofluid by different concentrations and a TT. Inserted in to a tube of round section through which that fluid passes with a fully developed turbulent flow. Heat was also applied from an external source to heat the tube from the outside. According to the results of the experiment, they found researchers found that using nanofluid improves the heat convection process compared to the values for distilled water with operating conditions same and slight increase in pressure drop. The researchers establish that (process of convection inside the pipe expansions efficiency by an expansion in concentration of hybrid nanoparticles, and that best concentration is φ=1.8%, which gives the best improvement in parameters.

Maddah et al. [48] worked on the fluid dynamics of aluminum oxide nano-fluid in a straight double-pipe HE. with adapted TT. under chaotic flow conditions using experimental approaches, they were conducted using varied geometric sequence ratios (GPR) of turns in altered TT. and varying nano-fluid concentrations, all underneath the same operational conditions. The investigational data demonstrates that the use of RGPR and turns in conjunction with nano-fluids leads to a significant enhancement in heat transmission, ranging from 12% to 52%, as well as an increase in friction factor ranging from 5% to 28%, as compare to tubes equipped and ordinary TT. (when GPR equal one) and nanofluid. IGPR twists result in a decrease in performance. That thermal efficiency of the HE. was evaluated by utilizing nano-fluid and changed TT. to quantify that total improvement in thermal efficiency.

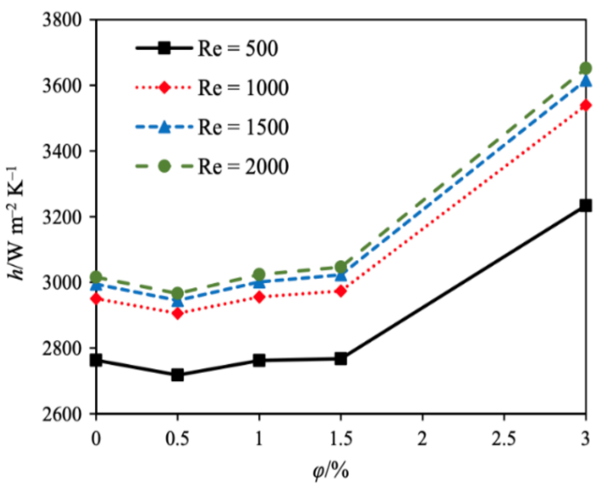

Figure 6. Volume concentration of nanoparticles (φ) with convection coefficient (h) [45]

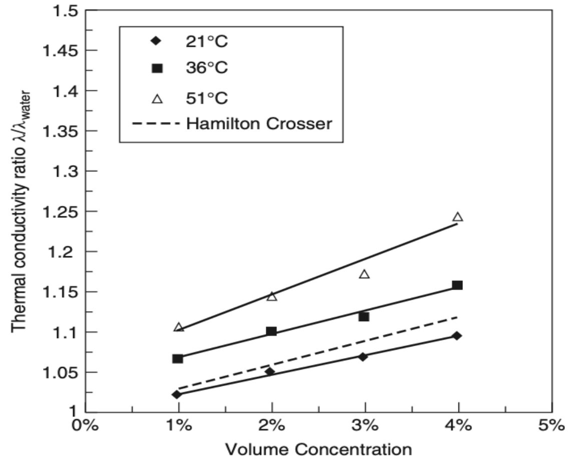

Figure 7. Temperature effects of the thermal conductivity of water- Al_2O_3 nanofluids [49]

Sundar et al. [49] worked on thermophysical characteristics of aluminium oxide nano-particles in H_2O, which are empirically measured a various volume strengths ranging from 0.2% to 0.8%. This study estimates that increase in heat transfer on copper circular pipe with constant "thermal flux" conditions. Their study examines dissimilar Re. in the turbulent region and considers a "volume fraction" of 0.02%. The effects of TT. that inserted are also investigated. It has been noted that utilizing TT. in conjunction with nanofluid in plain tubes clues more extraordinary improvement in heat transfer compared to using nano-fluid alone at same condition work. Figure 7 shows temperature effects of the thermal conductivity of water- Al_2O_3 nanofluids.

5. EXPERIMENTAL INVESTIGATION FOR NANOFLUID FLOW USING TWISTED TAPE

Nanofluids, suspensions of nanoparticles in a fluid basis, have attracted considerable attention in several industrial sectors because of their ability to improve thermal energy transfer characteristics. TT insertions are excellent on enhancing heat transfer in fluid systems [50-54]. And the twisted tape (TT.) can be manufactured in several specifications according to the required application and dimensions as Figures 8 and 9.

Twisted tapes create spinning flow patterns on that fluid, lead on improve (blending) and increase convective thermal energy transmission [55]. When nano-fluids, that have upper thermal conductivity comparison their base fluids, are used together, the possibility for additional improvement is evident [56-58].

Sundar et al. [59] and Sundar [60] examined the heat transmission and (friction-factor f) properties in an evenly heated horizontal circular tube employing magnetic Fe_3O_4 nanofluid, used or not use TT. insertions, to study turbulent convective. The study assesses improvements in heat transmission and friction factor across various particle volume concentrations (0%<u<0.6%), twist ratios (0<length/diameter<15), and flow (3000~22000) for Re value. study showed notable heat transfer(Q) and friction-factor(f) enrichments when using a (6/100) volume concentration of Iron (II, III) oxide nano-fluid in a plain circular-pipe with a TT. insert (length/diameter=5). The improvements were approximately 52% for heat transfer and (X 1.231) more for friction-factor(f) matched to H_2O flow in a plain circler pipe at similar Re.

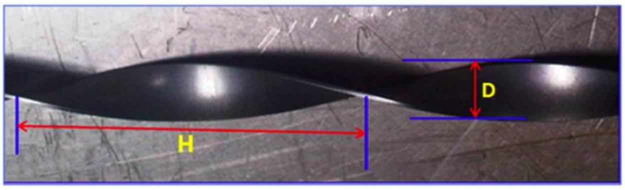

Figure 8. Twisted tape [50]

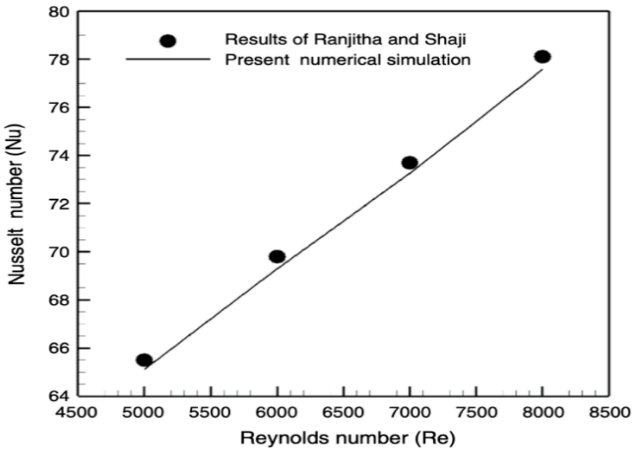

Figure 9. Validation analysis of the present numerical method [52]

Naik et al. [61] investigated the convectional thermal transfer(h) and friction-factor(f) for Copper (II) oxide nano-fluids consisting of H_2O and "propene glycol" (70:30% by volume) as they pass through a smooth tube. The study focused on cold climates where glycols are commonly employed as heat transfer fluids to prevent freezing. Nanofluids were formed by dispersing CuO nanoparticles, which have a diameter of 50 nm, The investigation is focused on Re (1000-10000). They found a substantial enhancement in heat conduction in CuO nanofluids.

Arunachalam and Edwin [62] studied convectional thermal trans and friction-factor(f) characteristics in a lined, pipe with and without cuted TT. In shape of (V) inserts, utilizing aluminium oxide with Copper/of base (H_2O) and that call (hybrid-nano-fluid). In Relatively research is being carried out on alumina nanofluid and a specific form of (Cu-alumina) hybrid nanofluid. The analysis excludes the impact of TT. and ratio of (length/diameter) on operation parameters such as (h and ΔP). Experimental data indicates a marginal convective heat transfer coefficient rises when Nano matter/base fluid (water) changed from 0.1% to 0.4%. An increase in that Nusselt number is noticed by using a copper nano-fluid volume of (1/100) mixed with (1/10) alumina nanofluid, compared to water. The slight rise in the thermal enhancement factor (η) from 1.01 to 1.05 when using V-cut twisted tapes (TT.) in nanofluids shows minimal overall benefits.

Zheng et al. [63] worked on statistical analysis of heat transfer in circular-tubes with dimpled TT. inserts using aluminium oxide/H_2O nano-fluid showed that both dimples and protrusions enhance convection, with dimples being more effective. Dimples increased the convective heat transfer coefficient by up to 25% approximately, while nanofluids improved efficiency by 59% approximately, despite a slight increase in ΔP. Smaller nano-particle sizes further boosted heat transfer with minimal resistance increase, reducing entropy generation(g) and maximum temperature.

Rezaei Gorjaei and Shahidian [64] combined TT. inserts and aluminium oxide nano-fluid raging flow in a curved copper tube can improve heat transmission. The investigation entailed creating a bent tube and TT. from copper, which placed in a hot water bath. A three-step technique is used to prepare water/Al_2O_3 nanofluid. The inquiry examines how (flow in cubic meter/second), nanoparticle ratio, and TT. insertion effect on parameters and non-dimensional numbers (Nu, Re, f and Q). It was observed that the use of twisted tape (TT.) in conjunction with nano-fluid resulted in a significant enhancement in the transmitted energy.

Nakhchi et al. [65] evaluated the implementation of a twisted tape with double cuts (DCTT) in the return pipe to the HE., using H_2O as the working fluid. The findings revealed an enhancement in HE performance, attributed to the cut TT. inducing internal vortices. However, unlike previous studies, the researcher did not utilize nanofluids or hybrid fluids.

Dagdevir and Ozceyhan [66] used a mixture of ethylene glycol and water as working fluids, without incorporating nanofluids. A TT. with dimples and holes was introduced, resulting in a significant increase in non-dimensional numbers (Re, Nu, f), indicating higher overall efficiency.

6. RESULTS AND DISCUSSION

6.1 Results

This study evaluated the performance enhancement of a double-pipe HE. using TT. inserts and nano-fluids. The primary findings from the experiments and simulations are summarized as follows:

(1). Heat Transfer Coefficient:

- The inclusion of twisted tape significantly increased the heat transfer coefficient. The results showed that the Nusselt number (Nu) improved by (X%) when using twisted tapes compared to a smooth tube.

- The application of nano-fluids further enhanced the heat transfer process. Specifically, a (Y%) increase in the heat transfer coefficient was observed with nanofluids compared to the base fluid.

(2). Exergy Efficiency:

- The use of nano-fluids resulted in an increase in exergy efficiency, highlighting the effectiveness of nano-fluids in reducing irreversibilities in the heat transfer process.

- The combination of TT. and nano-fluids provided the highest exergy efficiency, indicating a synergistic effect.

(3). Pressure Drop:

- The introduction of TT. caused a noticeable increase in pressure drop due to the induced turbulence and increased friction. However, this was within acceptable limits for practical applications.

- The nano-fluids slightly increased the pressure drop compared to the base fluid, but the overall benefits in heat transfer outweighed the additional pressure losses.

(4). Flow Distribution:

- The TT. inserts improved flow uniformity, which contributed to better convective heat transfer. This effect was particularly significant at higher Re., where the flow became more turbulent.

6.2 Discussion

(1). Impact of Twisted Tape (TT.) Inserts:

- The results confirm that TT. inserts are effective in enhancing the convective heat transfer in a double-pipe HE. The turbulence induced by the TT. disrupts the thermal boundary layer, leading to increased heat transfer rates. This finding is consistent with previous studies by He et al. [17], who also reported significant heat transfer improvements with twisted tape inserts.

(2). Effectiveness of Nanofluids:

- Nanofluids demonstrated superior thermal properties compared to traditional heat transfer fluids. The increased thermal conductivity of nano-fluids allowed for more efficient heat transfer, as evidenced by the higher (Nn) observed in the experiments. These results align with the findings of studies such as those by Sundar et al. [59], who reported similar enhancements in heat transfer using nanofluids.

(3). Combined Approach:

- The combination of TT. inserts and nano-fluids proved to be particularly effective. The synergy between the two techniques resulted in a significant improvement in both heat transfer and exergy efficiency. This suggests that for applications requiring high thermal performance, such as chemical processing or power generation, the combined use of TT. and nano-fluids could offer substantial benefits.

(4). Practical Considerations:

- While the enhancements in heat transfer and efficiency are clear, the increase in pressure drop must be carefully managed in practical applications. The trade-off between improved heat transfer and increased pumping power needs to be considered. However, the overall gains in thermal efficiency suggest that the benefits outweigh the drawbacks, particularly in systems where heat transfer efficiency is a priority.

(5). Future Work:

- Future research could focus on optimizing the geometry of the TT. To minimize pressure drop while maximizing heat transfer. Additionally, exploring different types of nano-fluids, including hybrid nanofluids, could provide further insights into the most effective combinations for various industrial applications.

7. STATISTICAL ANALYSIS TO VALIDATE RESULTS

The following is to outline the several statistical methodologies that used to validate our findings, which are focusing on heat transfer enhancements and friction factor analysis. The method provides a robust framework for understandings the relationships between experimental parameters and their effects on performance.

7.1 Analysis of variance (ANOVA) for nanofluid concentration and heat transfer

To test the impact of different nanofluid concentrations on heat transfer coefficient, An ANOVA test was applied to determine whether important differences exist between the groups. This analysis compares the heat transfer coefficients at different concentrations (0.01%, 0.02%, 0.03%, 0.04%, and 0.05%) across several studies [67-70]. As a result, the test revealed an increasing in heat transfer with increasing nanofluid concentration, as can be seen in Figure 10. The relationship between concentration and heat transfer is linear as shown, with higher concentrations yielding more efficient heat transfer.

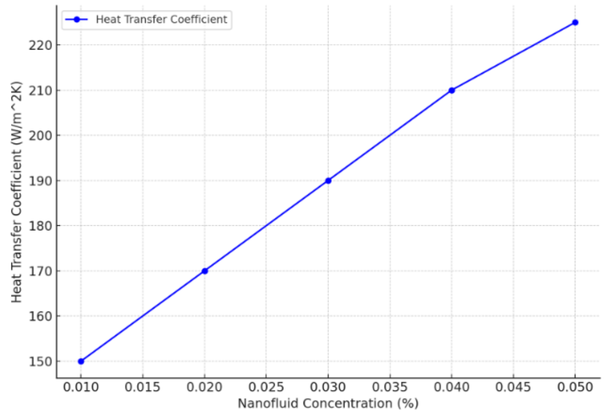

Figure 10. Heat transfer coefficient vs. nanofluid concentration

7.2 Regression analysis for friction factor and Reynolds number

To calculate the effect of the Reynolds number on the friction factor, linear regression analysis was used, drawing on data from several studies [5, 19, 71]. The regression equation will help quantify the relationships between Reynolds number and friction factor, which is important for optimizing fluid flow in heat exchangers. This analysis showed an inverse relationship between the Reynolds number and the friction factor, with the friction factor decreasing as the Reynolds number increases, as depicted in Figure 11.

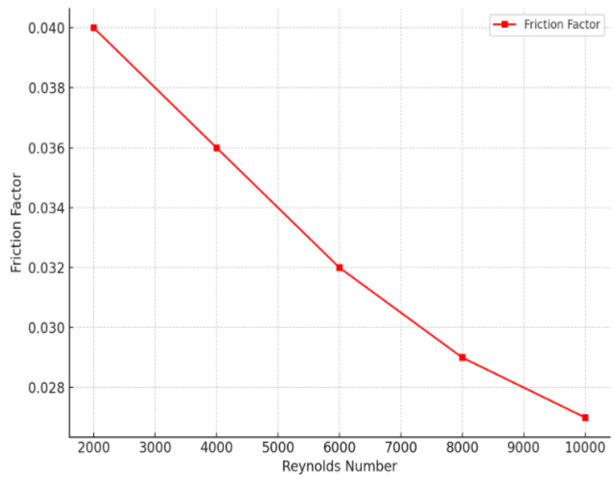

Figure 11. Friction factor vs. Reynolds number

8. CONCLUSIONS

From the above, we note that the world is heading towards using nanotechnology extensively, specifically in conserving energy, increasing thermal efficiency, and searching for the best exergy efficiency. In the field of using heat exchangers for heat transfer between two fluids, researchers have moved towards using different methods to obtain the best design that achieves the highest evaluations of thermal performance, and many used the twisted tape technique, but they were not able to try all the possibilities due to the complexity of the topic and its need for years of study and experiments.

* The main results of the study reveal that the use of twisted ribbon and nano-fluids in a two-tube HE. significantly improves thermal performance and availability. Specifically, the introduction of nanofluids enhances heat transfer efficiency, while the TT. contributes to a more uniform flow distribution and increased turbulence, resulting in better overall HE.

* These results are important because they address the growing demand for more efficient thermal management systems in various industrial applications. By demonstrating the effectiveness of this combined approach, the research contributes to current knowledge on HE. optimization and provides a new perspective for improving thermal systems.

* The practical applications of these results are broad. Industries that rely on efficient HE., such as chemical processing, power generation, and HVAC systems, can benefit from adopting these technologies to improve energy efficiency and reduce operating costs. Furthermore, the study opens up new avenues for future research into the use of advanced materials and design modifications in heat exchanger technology.

REFERENCES

[1] Fuskele, V., Sarviya, R.M. (2017). Recent developments in nanoparticles synthesis, preparation and stability of nanofluids. Materials Today: Proceedings, 4(2): 4049-4060. https://doi.org/10.1016/j.matpr.2017.02.307

[2] Das, S., Bandyopadhyay, K., Ghosh, M.M. (2018). A study on thermal conductivity and stability of nanofluids containing chemically synthesized nanoparticles for advanced thermal applications. Journal of Materials Engineering and Performance, 27: 3994-4004. https://doi.org/10.1007/s11665-018-3506-4

[3] Manimaran, R., Palaniradja, K., Alagumurthi, N., Sendhilnathan, S., Hussain, J. (2014). Preparation and characterization of copper oxide nanofluid for heat transfer applications. Applied Nanoscience, 4: 163-167. https://doi.org/10.1007/s13204-012-0184-7

[4] Shariatmadar, F.S., Pakdehi, S.G. (2016). Effect of various surfactants on the stability time of kerosene-boron nanofluids. Micro & Nano Letters, 11(9): 498-502. https://doi.org/10.1049/mnl.2016.0223

[5] Ilyas, S.U., Pendyala, R., Marneni, N. (2014). Preparation, sedimentation, and agglomeration of nanofluids. Chemical Engineering & Technology, 37(12): 2011-2021. https://doi.org/10.1002/ceat.201400268

[6] Duangthongsuk, W., Wongwises, S. (2009). Heat transfer enhancement and pressure drop characteristics of TiO_2-water nanofluid in a double-tube counter flow heat exchanger. International Journal of Heat and Mass Transfer, 52(7-8): 2059-2067. https://doi.org/10.1016/j.ijheatmasstransfer.2008.10.023

[7] Hussein, A.M., Khaleell, O.S., Danook, S.H. (2022). Enhancement of double-pipe heat exchanger effectiveness by using water-CuO. NTU Journal of Engineering and Technology, 1(2): 18-22. https://doi.org/10.56286/ntujet.v1i2.59

[8] Bhanvase, B.A., Sayankar, S.D., Kapre, A., Fule, P.J., Sonawane, S.H. (2018). Experimental investigation on intensified convective heat transfer coefficient of water based PANI nanofluid in vertical helical coiled heat exchanger. Applied Thermal Engineering, 128: 134-140. https://doi.org/10.1016/j.applthermaleng.2017.09.009

[9] Delavari, V., Hashemabadi, S.H. (2014). CFD simulation of heat transfer enhancement of Al_2O_3/water and Al_2O_3/ethylene glycol nanofluids in a car radiator. Applied Thermal Engineering, 73(1): 380-390. https://doi.org/10.1016/j.applthermaleng.2014.07.061

[10] San, J.Y., Hsu, C.H., Chen, S.H. (2012). Heat transfer characteristics of a helical heat exchanger. Applied Thermal Engineering, 39: 114-120. https://doi.org/10.1016/j.applthermaleng.2012.01.048

[11] Mousavi Ajarostaghi, S.S., Shirzad, M., Rashidi, S., Li, L.K. (2020). Heat transfer performance of a nanofluid-filled tube with wall corrugations and center-cleared twisted-tape inserts. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-21. https://doi.org/10.1080/15567036.2020.1841860

[12] Sunil, A.K., Kumar, R. (2019). Efficient shell and helically coiled tube heat exchanger using carbon nanotube-water nanofluid. Songklanakarin Journal of Science & Technology, 41(4): 907-914.

[13] Karami, M., Akhavan-Behabadi, M.A., Fakoor-Pakdaman, M. (2016). Heat transfer and pressure drop characteristics of nanofluid flows inside corrugated tubes. Heat Transfer Engineering, 37(1): 106-114. https://doi.org/10.1080/01457632.2015.1042347

[14] Ghafouri, A., Salari, M. (2014). Numerical investigation of the heat transfer enhancement using various viscosity models in chamber filled with water-CuO nanofluid. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 36: 825-836. https://doi.org/10.1007/s40430-013-0091-1

[15] Jidhesh, P., Arjunan, T.V., Gunasekar, N. (2021). Thermal modeling and experimental validation of semitransparent photovoltaic-thermal hybrid collector using CuO nanofluid. Journal of Cleaner Production, 316: 128360. https://doi.org/10.1016/j.jclepro.2021.128360

[16] Nayak, R.K., Bhattacharyya, S., Pop, I. (2015). Numerical study on mixed convection and entropy generation of Cu-water nanofluid in a differentially heated skewed enclosure. International Journal of Heat and Mass Transfer, 85: 620-634. https://doi.org/10.1016/j.ijheatmasstransfer.2015.01.116

[17] He, W., Toghraie, D., Lotfipour, A., Pourfattah, F., Karimipour, A., Afrand, M. (2020). Effect of twisted-tape inserts and nanofluid on flow field and heat transfer characteristics in a tube. International Communications in Heat and Mass Transfer, 110: 104440. https://doi.org/10.1016/j.icheatmasstransfer.2019.104440

[18] Aghayari, R., Maddah, H., Pourkiaei, S.M., Ahmadi, M.H., Chen, L., Ghazvini, M. (2020). Theoretical and experimental studies of heat transfer in a double-pipe heat exchanger equipped with twisted tape and nanofluid. The European Physical Journal Plus, 135: 1-26. https://doi.org/10.1140/epjp/s13360-020-00252-8

[19] Sundar, L.S., Sharma, K.V. (2010). Turbulent heat transfer and friction factor of Al_2O_3 nanofluid in circular tube with twisted tape inserts. International Journal of Heat and Mass Transfer, 53(7-8): 1409-1416. https://doi.org/10.1016/j.ijheatmasstransfer.2009.12.016

[20] Hosseinnezhad, R., Akbari, O.A., Hassanzadeh Afrouzi, H., Biglarian, M., Koveiti, A., Toghraie, D. (2018).

Numerical study of turbulent nanofluid heat transfer in a tubular heat exchanger with twin twisted-tape inserts. Journal of Thermal Analysis and Calorimetry, 132: 741-759. https://doi.org/10.1007/s10973-017-6900-5

[21] Nakhchi, M.E., Esfahani, J.A. (2018). Cu-water nanofluid flow and heat transfer in a heat exchanger tube equipped with cross-cut twisted tape. Powder Technology, 339: 985-994. https://doi.org/10.1016/j.powtec.2018.08.087

[22] Li, Z., Sheikholeslami, M., Jafaryar, M., Shafee, A., Chamkha, A.J. (2018). Investigation of nanofluid entropy generation in a heat exchanger with helical twisted tapes. Journal of Molecular Liquids, 266: 797-805. https://doi.org/10.1016/j.molliq.2018.07.009

[23] Jafaryar, M., Sheikholeslami, M., Li, Z. (2018). CuO-water nanofluid flow and heat transfer in a heat exchanger tube with twisted tape turbulator. Powder Technology, 336: 131-143. https://doi.org/10.1016/j.powtec.2018.05.057

[24] Ju, Y., Zhu, T., Mashayekhi, R., Mohammed, H.I., Khan, A., Talebizadehsardari, P., Yaïci, W. (2021). Evaluation of multiple semi-twisted tape inserts in a heat exchanger pipe using Al_2O_3 nanofluid. Nanomaterials, 11(6): 1570. https://doi.org/10.3390/nano11061570

[25] Nazari, S., Toghraie, D. (2017). Numerical simulation of heat transfer and fluid flow of Water-CuO Nanofluid in a sinusoidal channel with a porous medium. Physica E: Low-Dimensional Systems and Nanostructures, 87: 134-140. https://doi.org/10.1016/j.physe.2016.11.035

[26] Arefmanesh, A., Aghaei, A., Ehteram, H. (2016). Mixed convection heat transfer in a CuO-water filled trapezoidal enclosure, effects of various constant and variable properties of the nanofluid. Applied Mathematical Modelling, 40(2): 815-831. https://doi.org/10.1016/j.apm.2015.10.043

[27] Pimenta, T.A., Campos, J.B.L.M. (2012). Friction losses of Newtonian and non-Newtonian fluids flowing in laminar regime in a helical coil. Experimental Thermal and Fluid Science, 36: 194-204. https://doi.org/10.1016/j.expthermflusci.2011.09.013

[28] Painuly, A., Mishra, N.K., Zainith, P. (2022). Heat transfer enhancement in a helically corrugated tube by employing w/eg based non-newtonian hybrid nanofluid under turbulent conditions. Journal of Enhanced Heat Transfer, 29(1): 1-25. https://doi.org/10.1615/JEnhHeatTransf.2021039935

[29] Nguyen, C.T., Desgranges, F., Galanis, N., Roy, G., Maré, T., Boucher, S., Mintsa, H.A. (2008). Viscosity data for Al_2O_3-water nanofluid-hysteresis: Is heat transfer enhancement using nanofluids reliable?. International Journal of Thermal Sciences, 47(2): 103-111. https://doi.org/10.1016/j.ijthermalsci.2007.01.033

[30] Kong, L., Sun, J., Bao, Y. (2017). Preparation, characterization and tribological mechanism of nanofluids. Rsc Advances, 7(21): 12599-12609. https://doi.org/10.1039/C6RA28243A

[31] Babar, H., Wu, H., Zhang, W., Shah, T.R., McCluskey, D., Zhou, C. (2024). The promise of nanofluids: A bibliometric journey through advanced heat transfer fluids in heat exchanger tubes. Advances in Colloid and Interface Science, 103112. https://doi.org/10.1016/j.cis.2024.103112

[32] Bassam, A.M., Sopian, K., Ibrahim, A., Al-Aasam, A.B., Dayer, M. (2023). Experimental analysis of photovoltaic thermal collector (PVT) with nano PCM and micro-fins tube counterclockwise twisted tape nanofluid. Case Studies in Thermal Engineering, 45: 102883. https://doi.org/10.1016/j.csite.2023.102883

[33] Jing, D., Hu, Y., Liu, M., Wei, J., Guo, L. (2015). Preparation of highly dispersed nanofluid and CFD study of its utilization in a concentrating PV/T system. Solar Energy, 112: 30-40. https://doi.org/10.1016/j.solener.2014.11.008

[34] Chang, H., Jwo, C.S., Fan, P.S., Pai, S.H. (2007). Process optimization and material properties for nanofluid manufacturing. The International Journal of Advanced Manufacturing Technology, 34: 300-306. https://doi.org/10.1007/s00170-006-0597-0

[35] Zhu, H.T., Zhang, C.Y., Tang, Y.M., Wang, J.X. (2007). Novel synthesis and thermal conductivity of CuO nanofluid. The Journal of Physical Chemistry C, 111(4): 1646-1650. https://doi.org/10.1021/jp065926t

[36] Dalkılıç, A.S., Türk, O.A., Mercan, H., Nakkaew, S., Wongwises, S. (2019). An experimental investigation on heat transfer characteristics of graphite-SiO_2/water hybrid nanofluid flow in horizontal tube with various quad-channel twisted tape inserts. International Communications in Heat and Mass Transfer, 107: 1-13. https://doi.org/10.1016/j.icheatmasstransfer.2019.05.013

[37] Durga Prasad, P.V., Gupta, A.V.S.S.K.S. (2016). Experimental investigation on enhancement of heat transfer using Al_2O_3/water nanofluid in a u-tube with twisted tape inserts. International Communications in Heat and Mass Transfer, 75: 154-161. https://doi.org/10.1016/j.icheatmasstransfer.2016.03.019

[38] Mostafizur, R.M., Rasul, M.G., Nabi, M.N. (2021). Energy and exergy analyses of a flat plate solar collector using various nanofluids: An analytical approach. Energies, 14(14): 4305. https://doi.org/10.3390/en14144305

[39] Selimefendigil, F., Şirin, C., Oztop, H.F. (2022). Numerical and experimental investigation of a double-pipe heat exchanger with SiO_2 nano-additives. Heat Transfer Research, 53(1): 1-12. https://doi.org/10.1615/HeatTransRes.2021038820

[40] Das, S.K., Choi, S.U., Yu, W., Pradeep, T. (2007). Nanofluids: Science and Technology. John Wiley & Sons. https://www.wiley.com/en-gb/Nanofluids%3A+Science+and+Technology-p-9780470180686.

[41] Liaw, K.L., Kurnia, J.C., Sasmito, A.P. (2024). Enhancing supercritical carbon dioxide heat transfer in helical tube heat exchangers with twisted tape inserts: A computational investigation. International Journal of Heat and Mass Transfer, 227: 125598. https://doi.org/10.1016/j.ijheatmasstransfer.2024.125598

[42] Wang, Y., Qi, C., Ding, Z., Tu, J., Zhao, R. (2021). Numerical simulation of flow and heat transfer characteristics of nanofluids in built-in porous twisted tape tube. Powder Technology, 392: 570-586. https://doi.org/10.1016/j.powtec.2021.07.066

[43] Qi, C., Wang, G., Yan, Y., Mei, S., Luo, T. (2018). Effect of rotating twisted tape on thermo-hydraulic performances of nanofluids in heat-exchanger systems. Energy Conversion and Management, 166: 744-757.

https://doi.org/10.1016/j.enconman.2018.04.086
[44] Nakhchi, M.E., Esfahani, J.A. (2021). Numerical investigation of turbulent CuO-water nanofluid inside heat exchanger enhanced with double V-cut twisted tapes. Journal of Thermal Analysis and Calorimetry, 145: 2535-2545. https://doi.org/10.1007/s10973-020-09788-4
[45] Shahsavar, A., Bakhshizadeh, M.A., Arici, M., Afrand, M., Rostami, S. (2021). Numerical study of the possibility of improving the hydrothermal performance of an elliptical double-pipe heat exchanger through the simultaneous use of twisted tubes and non-Newtonian nanofluid. Journal of Thermal Analysis and Calorimetry, 143(3): 2825-2840. https://doi.org/10.1007/s10973-020-10201-3
[46] Abu-Hamdeh, N.H., Almitani, K.H., Gari, A.A., Alimoradi, A., Ahmadian, A., Baleanu, D. (2021). Hydrodynamic analysis of a heat exchanger with crosscut twisted tapes and filled with thermal oil-based SWCNT nanofluid: Applying ANN for prediction of objective parameters. Journal of Thermal Analysis and Calorimetry, 145: 2163-2176. https://doi.org/10.1007/s10973-020-10521-4
[47] Hamza, N.F., Aljabair, S. (2023). Numerical and experimental investigation of heat transfer enhancement by hybrid nanofluid and twisted tape. Engineering and Technology Journal, 41(1): 69-85. https://doi.org/10.30684/etj.2022.131909.1069
[48] Maddah, H., Alizadeh, M., Ghasemi, N., Alwi, S.R.W. (2014). Experimental study of Al_2O_3/water nanofluid turbulent heat transfer enhancement in the horizontal double pipes fitted with modified twisted tapes. International Journal of Heat and Mass Transfer, 78: 1042-1054. https://doi.org/10.1016/j.ijheatmasstransfer.2014.07.059
[49] Sundar, L.S., Sharma, K.V., Ramanathan, S. (2007). Experimental investigation of heat transfer enhancements with Al_2O_3 nanofluid and twisted tape insert in a circular tube. International Journal of Nanotechnology and Applications, 1(2): 21-28. http://www.ripublication.com/ijna.htm.
[50] Kumar, N.R., Bhramara, P., Kirubeil, A., Sundar, L.S., Singh, M.K., Sousa, A.C. (2018). Effect of twisted tape inserts on heat transfer, friction factor of Fe_3O_4 nanofluids flow in a double pipe U-bend heat exchanger. International Communications in Heat and Mass Transfer, 95: 53-62. https://doi.org/10.1016/j.icheatmasstransfer.2018.03.020
[51] Qi, C., Liu, M., Tang, J. (2019). Influence of triangle tube structure with twisted tape on the thermo-hydraulic performance of nanofluids in heat-exchange system based on thermal and exergy efficiency. Energy Conversion and Management, 192: 243-268. https://doi.org/10.1016/j.enconman.2019.04.047
[52] Noorbakhsh, M., Ajarostaghi, S.S.M., Zaboli, M., Kiani, B. (2022). Thermal analysis of nanofluids flow in a double pipe heat exchanger with twisted tapes insert in both sides. Journal of Thermal Analysis and Calorimetry, 147(5): 3965-3976. https://doi.org/10.1007/s10973-021-10738-x
[53] Ghazanfari, V., Taheri, A., Amini, Y., Mansourzade, F. (2024). Enhancing heat transfer in a heat exchanger: CFD study of twisted tube and nanofluid (Al_2O_3, Cu, CuO, and TiO_2) effects. Case Studies in Thermal Engineering, 53: 103864. https://doi.org/10.1016/j.csite.2023.103864
[54] Bahiraei, M., Mazaheri, N., Hassanzamani, S.M. (2019). Efficacy of a new graphene–platinum nanofluid in tubes fitted with single and twin twisted tapes regarding counter and co-swirling flows for efficient use of energy. International Journal of Mechanical Sciences, 150: 290-303. https://doi.org/10.1016/j.ijmecsci.2018.10.036
[55] Chaurasiya, P.K., Heeraman, J., Singh, S.K., Verma, T.N., Dwivedi, G., Shukla, A.K. (2024). Exploring the combined influence of primary and secondary vortex flows on heat transfer enhancement and friction factor in a dimpled configuration twisted tape with double pipe heat exchanger using SiO_2 nano fluid. International Journal of Thermofluids, 22: 100684. https://doi.org/10.1016/j.ijft.2024.100684
[56] Azhari, A.A., Milyani, A.H., Abu-Hamdeh, N.H., Hussin, A.M. (2023). Thermal improvement of heat exchanger with involve of swirl flow device utilizing nanomaterial. Case Studies in Thermal Engineering, 44: 102793. https://doi.org/10.1016/j.csite.2023.102793
[57] Bantan, R.A., Abu-Hamdeh, N.H., AlQemlas, T., Abd Elmotaleb, A.M.A. (2023). Heat transfer improvement of hybrid nanofluid with use of twisted tapes within a heat exchanger. Alexandria Engineering Journal, 70: 673-684. https://doi.org/10.1016/j.aej.2023.03.016
[58] Dhumal, G.S., Havaldar, S.N. (2023). Enhancing heat transfer performance in a double tube heat exchanger: Experimental study with twisted and helical tapes. Case Studies in Thermal Engineering, 51: 103613. https://doi.org/10.1016/j.csite.2023.103613
[59] Sundar, L.S., Kumar, N.R., Naik, M.T., Sharma, K.V. (2012). Effect of full length twisted tape inserts on heat transfer and friction factor enhancement with Fe_3O_4 magnetic nanofluid inside a plain tube: An experimental study. International Journal of Heat and Mass Transfer, 55(11-12): 2761-2768. https://doi.org/10.1016/j.ijheatmasstransfer.2012.02.040
[60] Sundar, L.S. (2023). Heat transfer, friction factor and exergy efficiency analysis of nanodiamond- Fe_3O_4/water hybrid nanofluids in a tube with twisted tape inserts. Ain Shams Engineering Journal, 14(9): 102068. https://doi.org/10.1016/j.asej.2022.102068
[61] Naik, M.T., Janardana, G.R., Sundar, L.S. (2013). Experimental investigation of heat transfer and friction factor with water-propylene glycol based CuO nanofluid in a tube with twisted tape inserts. International Communications in Heat and Mass Transfer, 46: 13-21. https://doi.org/10.1016/j.icheatmasstransfer.2013.05.007
[62] Arunachalam, U., Edwin, M. (2018). Experimental studies on laminar flow heat transfer in nanofluids flowing through a straight circular tube with and without V-cut twisted tape insert. Heat and Mass Transfer, 54(3): 673-683. https://doi.org/10.1007/s00231-017-2162-9
[63] Zheng, L., Xie, Y., Zhang, D. (2017). Numerical investigation on heat transfer performance and flow characteristics in circular tubes with dimpled twisted tapes using Al_2O_3-water nanofluid. International Journal of Heat and Mass Transfer, 111: 962-981. https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.062
[64] Rezaei Gorjaei, A., Shahidian, A. (2019). Heat transfer enhancement in a curved tube by using twisted tape insert and turbulent nanofluid flow: An experimental study.

Journal of Thermal Analysis and Calorimetry, 137: 1059-1068. https://doi.org/10.1007/s10973-019-08013-1

[65] Nakhchi, M.E., Hatami, M., Rahmati, M. (2020). Experimental investigation of heat transfer enhancement of a heat exchanger tube equipped with double-cut twisted tapes. Applied Thermal Engineering, 180: 115863. https://doi.org/10.1016/j.applthermaleng.2020.115863

[66] Dagdevir, T., Ozceyhan, V. (2021). An experimental study on heat transfer enhancement and flow characteristics of a tube with plain, perforated and dimpled twisted tape inserts. International Journal of Thermal Sciences, 159: 106564. https://doi.org/10.1016/j.ijthermalsci.2020.106564

[67] Sharma, S., Kumar, A., Maithani, R. (2022). Influence of twisted tape with collective protruded rib parameters of thermal-hydraulic performance of Al_2O_3-H_2O nanofluid flow in heat exchanger tube. Materials Today: Proceedings, 50: 1129-1133. https://doi.org/10.1016/j.matpr.2021.08.021

[68] Bhatia, S., Bhatia, S. (2016). Nanoparticles types, classification, characterization, fabrication methods and drug delivery applications. Natural Polymer Drug Delivery Systems: Nanoparticles, Plants, and Algae, pp. 33-93. https://doi.org/10.1007/978-3-319-41129-3_2

[69] Paul, G., Chopkar, M., Manna, I., Das, P.K. (2010). Techniques for measuring the thermal conductivity of nanofluids: A review. Renewable and Sustainable Energy Reviews, 14(7): 1913-1924. https://doi.org/10.1016/j.rser.2010.03.017

[70] Xu, R., Wang, D., Zhang, J., Li, Y. (2006). Shape-dependent catalytic activity of silver nanoparticles for the oxidation of styrene. Chemistry-An Asian Journal, 1(6): 888-893. https://doi.org/10.1002/asia.200600260

[71] Abdollahi, S.A., Alizadeh, A.A., Zarinfar, M., Pasha, P. (2023). Investigating heat transfer and fluid flow betwixt parallel surfaces under the influence of hybrid nanofluid suction and injection with numerical analytical technique. Alexandria Engineering Journal, 70: 423-439. https://doi.org/10.1016/j.aej.2023.02.040