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Enhanced Heat Transfer in Double Pipe Heat Exchanger with Circular Fins Using Copper Nanofluid and Twisted Tape Inserts: A Computational Study

Chetan Kumar Korde[1],*, Pankaj Badgaiyan[2], Tanmay Awasthi[2]

Abstract

The enhancement of convective heat transfer in a double-pipe heat exchanger utilizing circular finned twisted tape inserts and helical screw-tapes with centre rods, in conjunction with copper oxide nanofluid as the heat transfer medium was studied in this project. Computational Fluid Dynamics (CFD) simulations were conducted across Reynolds numbers ranging from 500 to 5000 to analyse heat transfer characteristics. The investigation focuses on Nusselt number improvement and friction factor analysis to assess thermal performance enhancement. Results demonstrate significant augmentation in convective heat transfer efficiency with both insert types compared to plain tubes, indicating their efficacy for practical heat exchanger applications. Enhancing heat transfer surfaces increases thermal efficiency, but it can also cause higher pressure drops, potentially impacting system performance. This study explores methods to achieve an optimal balance by maximizing heat transfer while minimizing pressure losses to maintain overall efficiency. The study reveals that circular finned twisted tape inserts and helical screw-tapes with centre rods substantially increase the Nusselt number across the entire Reynolds number range studied. Specifically, the circular finned twisted tape inserts achieve notable heat transfer enhancement, particularly at higher twist ratios (TR=9.8). Meanwhile, the helical screw-tapes with centre rods exhibit favourable performance with increasing numbers of helices. These findings underscore the potential of these passive enhancement techniques to improve heat exchanger efficiency while managing pressure drop effectively.

Keywords: Heat exchangers, nanofluid, turbulence, twist tape, circular fins

INTRODUCTION

Twisted-tape inserts have emerged as a prominent method for enhancing convective heat transfer in various industrial applications, spanning thermal power plants, chemical processing, air conditioning, and refrigeration systems. By inducing swirl in the flow, these inserts disrupt the thermal boundary layer on tube surfaces, thereby augmenting heat transfer efficiency. Improved heat transfer in heat exchangers holds the potential for significant energy, material, and cost savings. Double-pipe heat exchangers (DPHEs), renowned for their suitability in high-temperature and high-pressure environments, often leverage such passive heat transfer augmentation techniques. Twisted-tape inserts offer a cost-effective means to enhance heat transfer, boasting advantages such as ease of installation, reduced fouling, and minimal pressure drop. While optimization of heat transfer surface areas has enhanced thermal efficiency, it is crucial to mitigate associated pressure drop increases.

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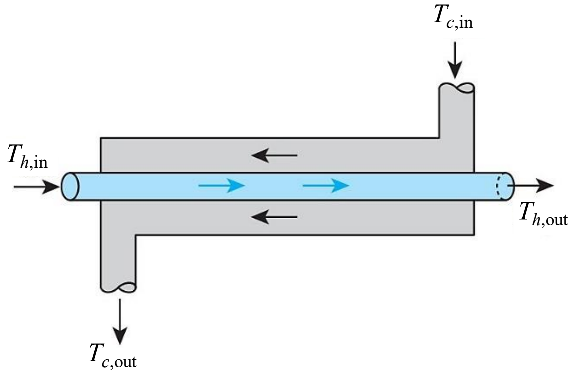

Figure 1. Double pipe heat exchanger [1].

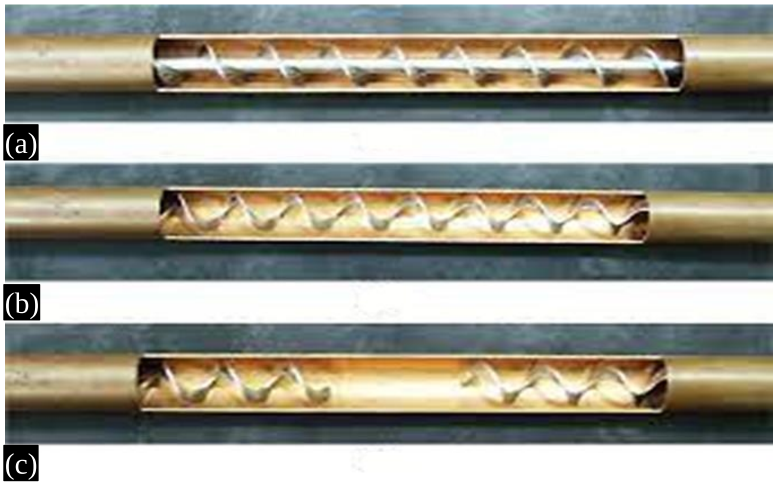

Figure 2. (a)–(c) Double pipe heat exchanger with helical tape insert [2].

Passive techniques like twisted-tape inserts offer simplicity in implementation and find extensive applications across industries, including process engineering, aerospace, and automotive sectors. Recent research has focused on refining passive methods for heat transfer enhancement, offering valuable insights for compact heat exchanger design. The overarching goal of enhancing heat transfer is to minimize the laminar sub layer, thereby facilitating more efficient heat removal or deposition on surfaces within heat exchangers.

A counter double twisted tape insert can also reach a Thermal Performance Factor greater than 2 (Figure 1). When flows have high Prandtl Numbers, roughness can sometimes improve heat transfer performance more than twisted tape. By disturbing the thermal boundary layer, artificial roughness produced by corrugating a surface can enhance heat transmission properties. Double pipe heat exchanger with helical tape insert is shown in Figure 2(a)–(c).

Heat Transfer Mode

Heat transfer, as its name implies, is an area of study which examines how heat and thermal energy are produced, used, exchanged, and converted among physical systems. Because it concentrates on calculating the speed at which heat can move through a medium, across an interface, or between surfaces, this is a key principle of thermal science. For the purpose of creating devices that control temperature, transform energy, and handle thermal energy, an understanding of heat transfer is essential. There are different modes of heat transfer which includes:

- Heat transfer through conduction,
- Heat transfer through convection, and
- Heat transfer through radiation.

Types of Heat Exchanger

Air Cooled Heat Exchanger

A fin tube heat exchanger, also known as an air-cooled heat exchanger (Figure 3), is a type of heavy-duty, custom-designed heat exchanger that can be used to cool a variety of process mediums directly using air. There are many applications for these heat exchangers, including power generation, chemical plants, Organic Rankine Cycle (ORC) plants, oil and gas facilities, steel plants and many more. Water can no longer be used as a secondary cooling medium, since they are specifically designed to transfer heat.

Heat Exchanger that is Cooled by Water

Water serves as the main heat conductivity of parts and industrial equipment, and water cooling uses this property to dissipate heat. This method is used by a number of sizable industrial facilities, such as hydropower generators, steam electrical energy plants, petroleum refineries, and different manufacturing units, to cool internal combustion engines in cars. This is because water has a large specific heat capacity and strong thermal conductivity, making it a great medium for thermal transport. Water cooled heat exchanger is shown in Figure 4.

Classification of Heat Exchanger

1. *Heat exchanger with direct contact:* Heat transfer and mass transfer can happen at the same time in direct contact heat exchangers because hot and cold fluids interact directly (Figure 5). Examples of direct contact heat exchangers include cooling towers, jet condensers, and direct contact feedwater heaters. These devices are efficient in transferring heat between fluids and are commonly used in various industrial processes where direct mixing is feasible and beneficial.
2. *Heat exchanger with indirect contact:* This type of heat exchanger transfers heat between two fluids through a barrier. Examples include regenerators and recuperators as shown in Figure 6.

Figure 3. Air cooled heat exchanger [3].

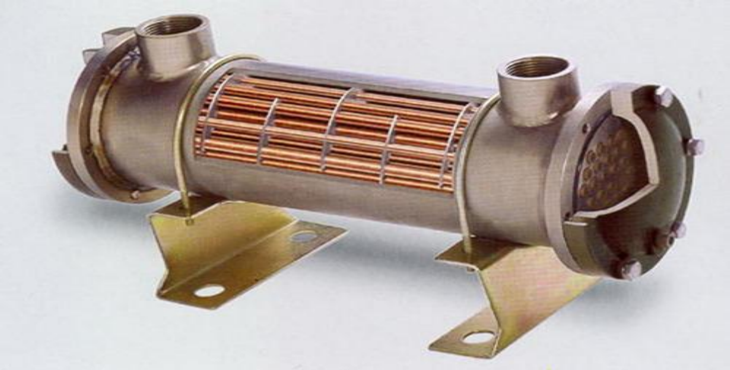

Figure 4. Water cooled heat exchanger [4].

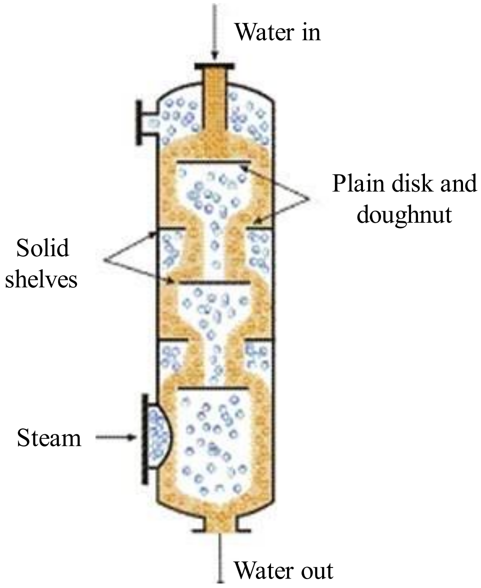

Figure 5. Direct contact heat exchanger [5].

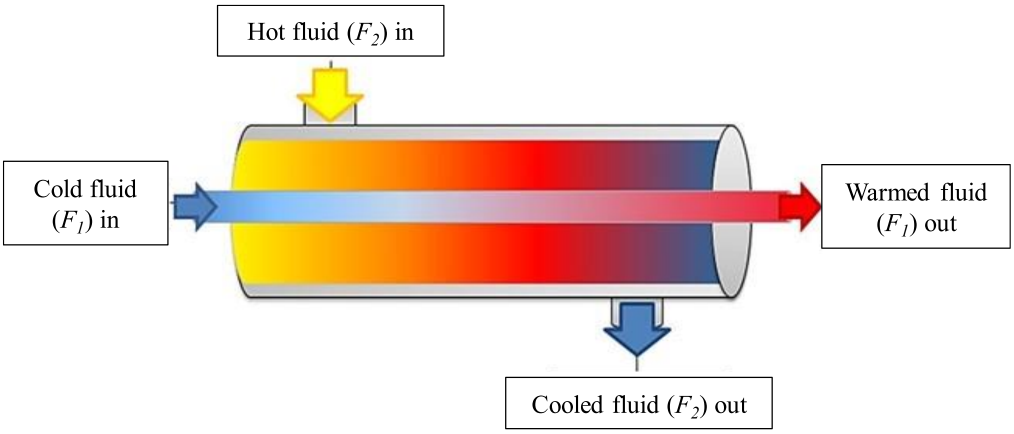

Figure 6. Indirect contact heat exchanger [6].

Flow Pattern or Arrangement-Based

1. *Heat exchanger with parallel flow:* In a parallel flow heat exchanger, both fluids move in the same direction. This configuration allows for efficient heat transfer, especially when the specific heat capacities of the fluids remain constant.
2. *Counter flow heat exchanger:* In a counter flow heat exchanger, the fluids flow in opposite directions. This arrangement maximizes the heat transfer efficiency, particularly when the specific heat capacities of the fluids remain constant.
3. *Cross flow heat exchanger:* In a cross flow heat exchanger, the direction of the fluids is perpendicular to each other. This design is commonly used when one fluid is a liquid and the other is a gas, such as in a car radiator where hot water flows horizontally while air moves vertically. Cross flow heat exchangers are known for their high efficiencies, with heat transfer dependent on the surface area covered by the flow channels. This implies that larger heat exchangers result in greater heat recovery.

LITERATURE REVIEW

In the study by Khedher *et al.*, a circular Y-shaped fin arrangement is investigated for its effectiveness in enhancing thermal response rates within a double tube heat exchanger containing paraffin phase change material (PCM) [5]. Through computational fluid dynamics (CFD) simulations, the study evaluates fluid flow, heat transfer, and phase changes, identifying an optimal fin configuration based on sensitivity analysis. Their findings demonstrate that Y-shaped fins outperform straight fins, reducing solidification time by 22% and increasing discharging rate by 26%.

Bahlekeh *et al.* utilize numerical analysis to explore the impact of fin number and size on the solidification performance of phase change material (PCM) within a double-tube container [6]. They find that longer fins with higher Reynolds numbers significantly improve solidification rates, with varying degrees of enhancement observed across different fin configurations. Increasing fin length and number drastically enhance thermal efficiency and the phase change process.

Kia *et al.* investigate heat transfer and pressure drop characteristics of Al_2O_3 and SiO_2 nanoparticles dispersed in base oil flowing through helical tubes under constant heat flux [7]. Their study analyses parameters such as flow Reynolds number, fluid temperature, nanoparticle type, and weight concentration. Results show higher heat transfer coefficients and pressure drops with nanofluids compared to the base fluid, with Al_2O_3 nanofluid exhibiting greater heat transfer enhancement than SiO_2 nanofluid.

Hamza and Aljabair enhance heat transfer in a heat exchanger tube using vortex generator inserts and hybrid nanofluid [8]. Through numerical and experimental methods, they evaluate the impact of different inserts and hybrid nanofluid compositions on heat transfer rates. Their findings demonstrate superior thermal performance with certain insert configurations and hybrid nanofluid mixtures, corroborated by both numerical simulations and experimental results.

OBJECTIVE

- The purpose of this study is to investigate the thermal characteristics of a two-pipe heat exchanger using a graphene oxide nanofluid as a medium for heat transfer [9].
- Identify the effects of twist ratio and Reynolds number on circular twisted tape insert efficiency.
- Determine how helical screw-tape inserts with central rods perform if the number of helices is changed.

METHODOLOGY

Physical Model

It focuses on improving thermohydraulic performance by causing flow disturbances. A helical screw-tape with a centre rod and a circular finned twisted tape insert are used to achieve this.

- *Case 1:* A circular finned twisted tape insert with a diameter of 45 mm and a thickness of 3 mm is displayed in Figure 3. Throughout the whole length of the twisted tape, the round stainless steel fins are spaced 50 mm apart and fastened to both sides of the tape's central axis. The round fin has a diameter of 5 mm and a length of 22 mm. The ratio of twist length to tape width is known as the Twist Ratio (TR=H/D), and it is used to construct the layout. Twisted tape inserts with different pitches were used to perform the simulation by giving V-cut. Table 1 displays the specifics of circular finned twisted tape inserts. CAD model of twisting tap insert at different TR is shown in Figure 7(a)–(c).
- *Case 2:* A centre rod is included in a helical screw-tape insert that is spaced often. Its components are composed of stainless steel and include a 1 mm thick helical screw, a 39 mm diameter helical screw tape with a 40 mm pitch, and an 8 mm diameter centre rod. In order to simulate effective swirl development, the number of helices in the screw tape with V-cut was changed to 5, 7, and 9 at four places. The requirements for the helical screw-tape insert spaced regularly are shown in Table 2.

Table 1. The details of circular finned twisted tape inserts.

Pitch	Width (mm)	Twist ratio (TR)
900 mm	45	20
600 mm	45	13.3
440 mm	45	9.8

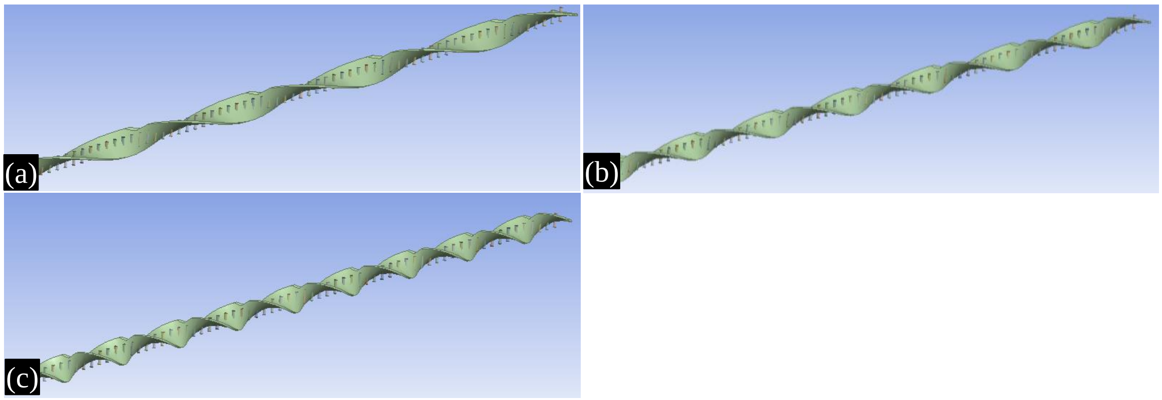

Figure 7. (a)–(c) CAD model of twisting tap insert at different TR, (a) Pitch is 900 mm, width is 45 mm, and TR is 20, (b) Pitch is 600 mm, breadth is 45 mm, and TR is 13.3, (c) TR is 9.8, Pitch is 440 mm, and Width is 45 mm.

Table 2. The specification of frequently spaced helical screw-tape insert.

No. of helices in screw	Position	Distance between two screws (mm)
5	4	560
7	4	540
9	4	460

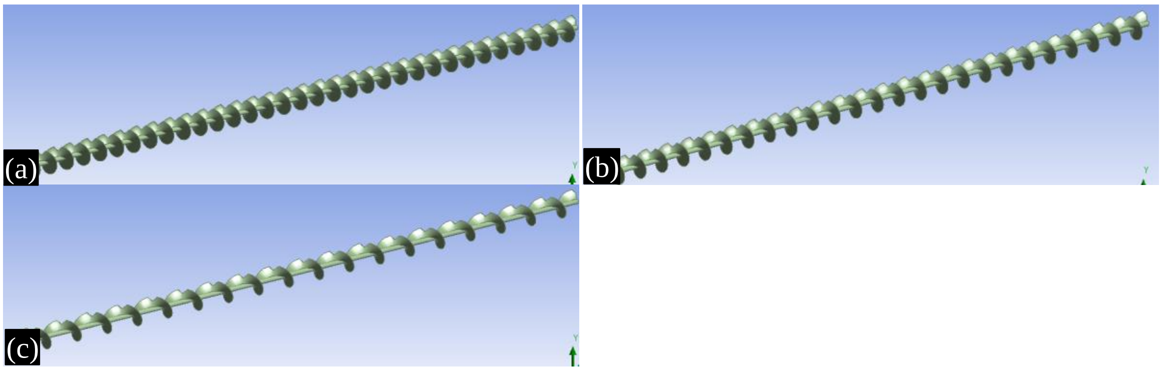

Figure 8. (a)–(c) CAD model of helical twisting tap at different helices, (a) There are five helices in a screw, spaced four times, and there are 560 mm between each screw, (b) A screw has seven helices arranged in four locations, and there are 540 mm between two screws, (c) Two screws are separated by 460 mm, and each screw has nine helices arranged in four places.

CAD model of helical twisting tap at different helices in Figure 8(a)–(c) comprises five helices evenly spaced at intervals four times, with a gap of 560 mm separating each screw. In contrast, the second type features screws with seven helices distributed across four sections along their length, positioned at a distance of 540 mm between each pair. Lastly, the third configuration entails screws spaced 460 mm apart, each adorned with nine helices arranged in four sections. Each configuration reflects a careful balance between the number of helices, their arrangement, and the spacing between screws, ensuring optimal performance and efficiency in their respective contexts [10].

Computational Fluid Dynamics Analysis

As information technology has advanced and mathematical approaches have become more accessible, Computational Fluid Dynamics (CFD) has emerged as an essential tool for fluid motion prediction in a variety of circumstances, thereby streamlining the designing procedure. CFD is a sophisticated technology that is used to compute the flow dynamics and heat transfer processes in order to analyse fluid flow dynamics as well as heat and mass transfer operations. The computational fluid dynamics field is the study of fluid flow and heat transport systems through computerized simulation.

- Pre-processor,
- Solver, and
- Post-processor.

Meshing of Domain

In this study, an individual regulate volume was built using a universal curve-linear coordinate grid generation technique based on body-fitted coordinates, ensuring that all related geometries were appropriately modelled and meshed. The FLUENT-equipped application ANSYS 14 was used to model and mesh each example. The development and refinement of the grid system was vital to accurately anticipate heat transfer in such complicated geometries. Because the relationship between turbulence and mean flow affects turbulent flows in addition to laminar circulation, reliability depends critically on grid density and uniformity.

There are five, seven and nine helices in a screw, they spaced four times, and there are 560 mm between each screw of five helices, 540 mm between two screws of seven helices and 460 mm between each screw of nine helices as shown in Figure 9(a)–(c) [11, 12].

CHOOSING THE PHYSICAL PROPERTIES

An essential component of building up the model is defining the physical parameters (specific heat, density, viscosity, and thermal conductivity) of fluids and solids, as shown in Table 3. In this work, heat is transferred by forcing graphene oxide nanofluid to move between and maybe even through the twisting tape, which is where the heat is conveyed [13].

RESULTS AND DISCUSSION

Model Validation

The research examined the effects of circular finned and helical twisted tape metallic inserts on heat transfer, friction factor, and thermal enhancement efficiency of a double pipe heat exchanger tube. The copper

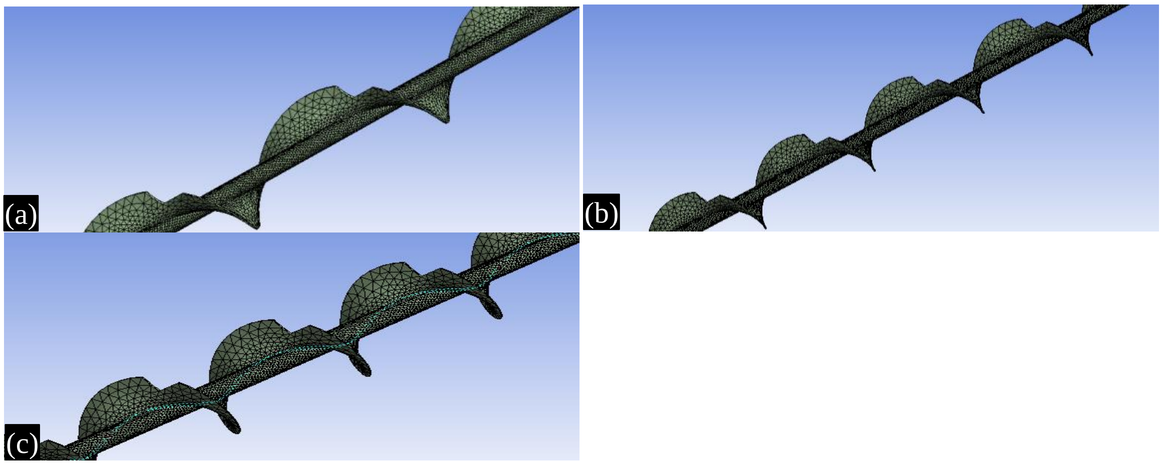

Figure 9. (a)–(c) Mesh model, (a) There are five helices in a screw, spaced four times, and there are 560 mm between each screw, (b) A screw has seven helices arranged in four locations, and there are 540 mm between two screws, (c) A screw has nine helices arranged in four locations, and there are 460 mm between each screw.

Table 3. Thermophysical properties of copper oxide nanofluid.

Temperature (°C)	Density (kg/m^3)	Viscosity (Ns/m^2×10^{-3})	Specific heat (J/kg-K)	Thermal conductivity (W/mK)
20	6500	1.432	540	18

Table 4. CFD validation results and comparison.

Reynolds number	Nusselt number from Murthy and Hedge [13]	Nusselt number from Present study
500	11.24	11.80
1000	25.61	26.89
1500	35.42	37.19
2000	40.01	42.01
2500	44.29	46.50
3000	45.61	47.89
3500	47.82	50.21
4000	50.11	52.62
4500	54.28	56.99
5000	56.71	59.55

Table 5. Effect on Nusselt Number for circular finned twisted tape inserts.

Reynolds number	Water	TR=9.8	Percentage deviation	TR=13.3	Percentage deviation	TR=20	Percentage deviation
500	7.11	13.13	84.67	12.02	69.06	11.91	67.51
1000	20.21	26.23	29.79	25.12	24.29	24.01	18.80
1500	31.55	37.57	19.08	36.46	15.56	35.35	12.04
2000	37.42	43.44	16.09	42.33	13.12	41.22	10.15
2500	41.28	47.3	14.58	46.19	11.89	45.08	9.21
3000	49.41	55.43	12.18	54.32	9.94	53.21	7.69
3500	55.56	61.58	10.84	60.47	8.84	59.36	6.84
4000	58.38	64.4	10.31	63.29	8.41	62.18	6.51
4500	61.77	67.79	9.75	66.68	7.95	65.57	6.15
5000	65.81	71.83	9.15	70.72	7.46	69.61	5.77

oxide-water nanofluid in the outer tube (cold fluid) was simulated at $500 \leq Re \leq 5000$ using the following technique: hot water in the inner tube (hot fluid), subjected to a continuous heat flux, was simulated at a rate Re=2500. The heat transport results were validated by comparing them to Murthy and Hedge's results [13]. The Nusselt number, which measures the rate at which heat is transferred, indicates that the results match the prior research in a good way and fall well within the range of 5% that has already been established as shown in Table 4.

Effect on Nusselt Number for Circular Finned Twisted Tape Inserts

In this section, Nusselt Number for circular finned twisted tape inserts is compared. A circular finned twisted tape with helices spaced uniformly in distilled water and helices spaced uniformly in distilled water produces the results shown in Table 5.

Table 5 presents the impact of circular finned twisted tape inserts on the Nusselt number across a range of Reynolds numbers (500 to 5000). The Nusselt number measures convective heat transfer efficiency, with higher values indicating improved heat transfer. Table 2 shows that as Reynolds number increases, indicating a shift towards turbulent flow, the Nusselt number also increases. The inserts, identified as TR=9.8, TR=13.3, and TR=20, consistently enhance heat transfer compared to water flow alone, as indicated by the percentage deviations from the baseline Nusselt number for water. These findings underscore the effectiveness of the inserts in augmenting heat transfer rates in various flow conditions [14].

Impact of Helical Screw-tape Insert with Centre Rod on Nusselt number

The Nusselt Numbers for helical screw-tape inserts with centre rods are compared in this section. Figure 10 illustrates the effects of using circular finned twisted tape in distilled water with regularly spaced helices. Increasing the Nusselt number while reducing the twist ratio results in a greater heat transfer coefficient when the Nusselt number is increased. With a decreasing twist ratio, heat transfer

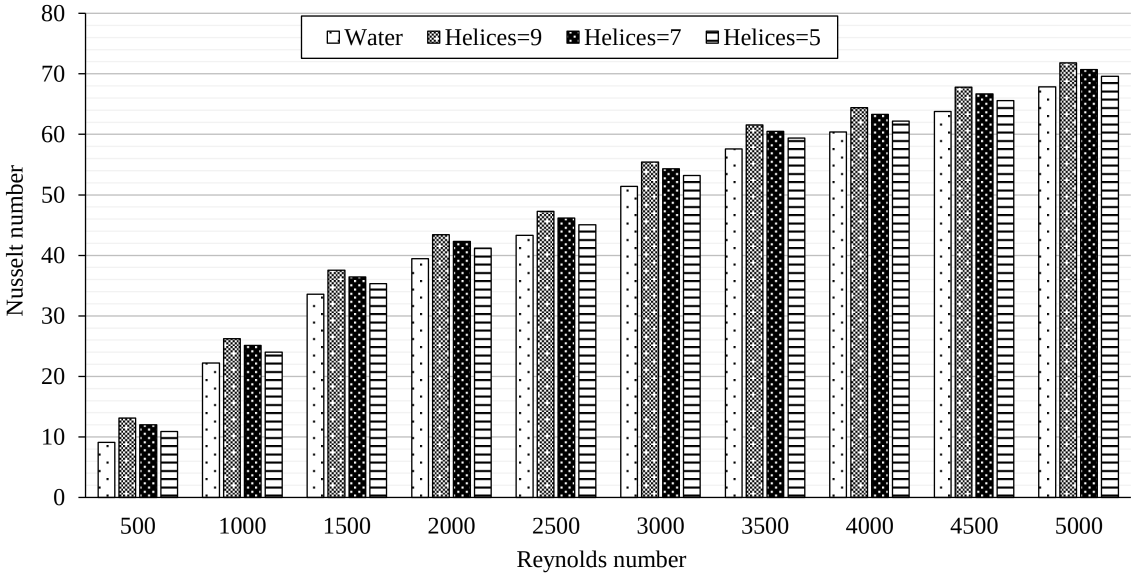

Figure 10. Effect on Nusselt Number for helical screw-tape insert with a central rod.

rate increases because the swirl effect near the tube wall is intensified, disrupting the boundary layer along the flow channel. Using circular twisted tape swirl generators at all Reynolds numbers greatly impacts the heat transfer rate due to the increase in turbulence intensity as Reynolds number increases. When comparing the Nusselt numbers of a tube with circular triple twisted tape inserts to those of a plain tube and a tube with frequent spaced helical tape inserts at similar Reynolds numbers, the tube with circular triple twisted tape inserts exhibits higher values. Heat transfer rates in heat exchangers utilizing circular finned twisted tape inserts are enhanced by the ratio of twist to helices and the number of helices. Convective heat transfer coefficients are significantly improved with these configurations due to the intensified swirl motion induced by the swirls.

Effect on Friction Factor for Circular Finned Twisted Tape Inserts

Figure 11 shows the effect on friction factor for circular finned twisted tape inserts. It is observed that with increasing Reynolds number, friction factor decreases. It is also observed that when water is used in heat exchanger, friction factor is low when copper oxide is used in heat exchanger. The choice of fluid significantly influences the fluid properties (e.g., density, viscosity, thermal conductivity), which in turn affect the friction factor characteristics. As the Reynolds number increases, the flow transitions to a turbulent regime, characterized by chaotic and irregular fluid motion. Turbulence promotes greater fluid mixing and disruption of the boundary layer, reducing the frictional resistance to flow. Consequently, the friction factor decreases as turbulence intensifies with increasing Reynolds number.

Furthermore, the choice of fluid significantly influences the friction factor characteristics due to variations in fluid properties such as density, viscosity, and thermal conductivity. Water, being a relatively low-viscosity fluid, exhibits lower friction factors compared to fluids with higher viscosities such as copper oxide suspensions. The lower viscosity of water allows for smoother fluid motion and reduced energy losses due to frictional effects. Additionally, the presence of suspended particles or additives, as in the case of copper oxide, can alter the flow behaviour and increase the frictional resistance, leading to higher friction factors. The influence of fluid properties on the friction factor underscores the importance of considering the fluid characteristics in heat exchanger design and optimization studies.

Impact of a Centre Rod in a Helical Screw-Tape Insert on the Friction Factor

The friction factor of helical screw-tape inserts with centre rods is compared in this section. Figure 12 presents a comparison of the friction factors for helical screw-tape inserts with centre rods across different Reynolds numbers. It shows how the friction factor varies with varying helix numbers (9, 7, and 5)

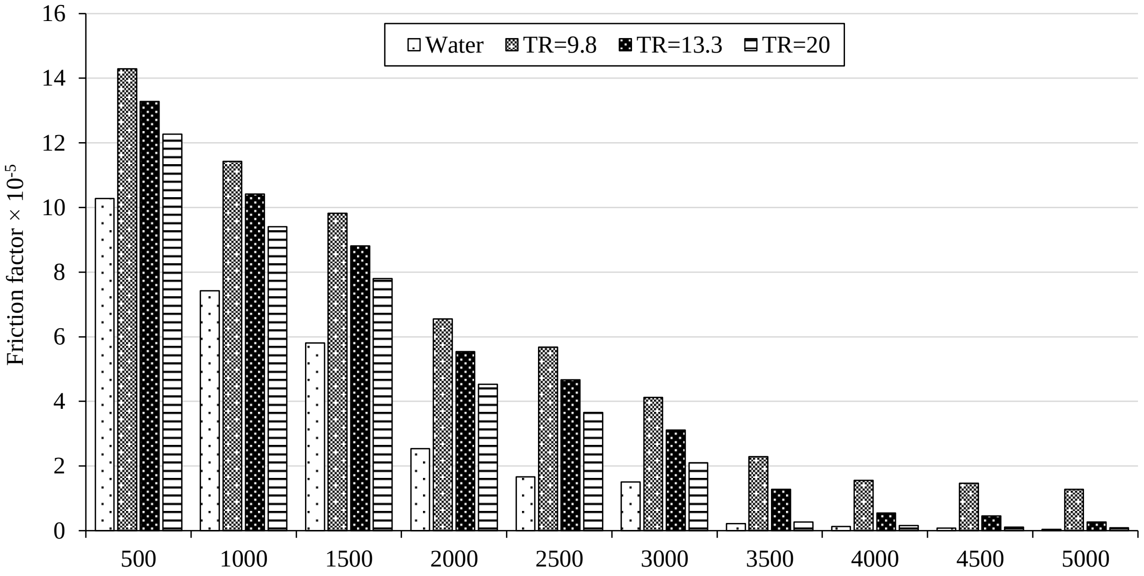

Figure 11. Effect on Friction Factor for circular finned twisted tape.

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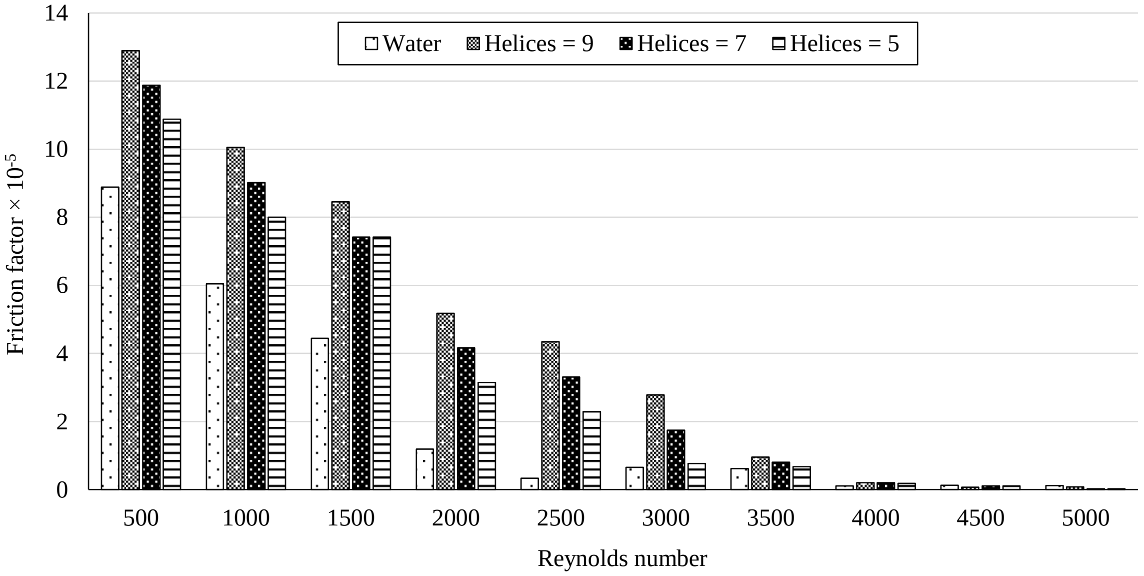

Figure 12. Impact of a centre rod in a helical screw-tape insert on the friction factor.

for water flow at Reynolds numbers ranging from 500 to 5000. As Reynolds number increases, the friction factor generally decreases, indicating reduced resistance to flow. The data illustrates that configurations with fewer helices tend to have lower friction factors, suggesting potentially higher flow efficiency compared to configurations with more helices.

Improvement in Results

Table 6 presents a comparative analysis of Reynolds numbers and corresponding values from two different studies: the present study and a study conducted by Murthy and Hegde [13]. Each row represents a specific Reynolds number, while each column pair corresponds to a Reynolds number within the study conditions (TR=20, TR=13.3, TR=9.8). The values within each cell denote some measurement or characteristic related to water flow, such as velocity or pressure drop. By comparing the results between the present study and Murthy and Hegde's study, one can discern any discrepancies or similarities in the observed values under various Reynolds number conditions. This comparison aids in understanding the consistency and reliability of the experimental findings across different research endeavours.

Table 6. Improvement in Nusselt Number when compared results with Murthy and Hegde [13].

Reynolds number	**Water**	**Present study**	**Murthy and Hegde [13]**	**Present study**	**Murthy and Hegde [13]**	**Present study**	**Murthy and Hegde [13]**
		TR=20	***TR=20***	***TR=13.3***	***TR=13.3***	***TR=9.8***	***TR=9.8***
500	7.11	11.91	10.11	12.02	9.13	13.13	7.89
1000	20.21	24.01	23.21	25.12	22.10	26.23	20.99
1500	31.55	35.35	34.55	36.46	33.44	37.57	32.33
2000	37.42	41.22	40.42	42.33	39.31	43.44	38.2
2500	41.28	45.08	44.28	46.19	43.17	47.3	42.06
3000	49.41	53.21	52.41	54.32	51.3	55.43	50.19
3500	55.56	59.36	58.56	60.47	57.45	61.58	56.34
4000	58.38	62.18	61.38	63.29	60.27	64.4	59.16
4500	61.77	65.57	58.77	66.68	57.66	67.79	57.55
5000	65.81	69.61	80.81	70.72	67.7	71.83	65.59

CONCLUSION

In conclusion, the investigation into convective heat transfer enhancement using circular finned twisted tape inserts and helical screw-tapes with centre rods in a double-pipe heat exchanger reveals promising results. The study employed Computational Fluid Dynamics (CFD) simulations to evaluate the thermal performance across Reynolds numbers ranging from 500 to 5000, focusing on Nusselt number improvement and friction factor analysis. The use of circular finned twisted tape inserts demonstrated significant increases in the Nusselt number compared to plain tubes, particularly evident at higher twist ratios (TR=9.8). This enhancement signifies improved convective heat transfer efficiency, which is crucial for enhancing the thermal performance of heat exchangers. The findings indicate that these inserts effectively disrupt the thermal boundary layer, promoting heat transfer rates through increased turbulence without excessively compromising pressure drop. Similarly, the helical screw-tapes with centre rods exhibited favourable performance, especially with configurations featuring more helices. This variation in design parameters allowed for tailored optimization of heat transfer characteristics, demonstrating versatility in adapting to different flow conditions and operational requirements.

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