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Investigating the Effect of Heat Transfer Influenced by the Application of Wavy Corrugated Twisted Tape Inserts in Double Pipe Heat Exchangers

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ABSTRACT

This study investigates the heat transfer and friction factor characteristics in a heat exchanger utilizing copper wavy (corrugated) twisted tape inserts. By inducing turbulent flow within the inner tube of the heat exchanger, these inserts generated increased turbulence, thereby enhancing heat transfer and causing a rise in pressure drop. The copper twisted tapes, with various twist ratios (TR=10.7, 8.5, 7.1), measured 1 meter in length and 14 mm in width. The heat exchanger's outer tube was made of mild steel, with an outer diameter of 0.0198 m and an inner diameter of 0.0142 m, while the inner tube was constructed of copper, with an outer diameter of 0.038 m and an inner diameter of 0.032 m. The overall length of the pipe-in-pipe heat exchanger was 1.4 m. Bulk mean temperatures were recorded at different positions for various water flow rates, and new correlations for the Nusselt number and friction factor were derived from the results for the twisted tape inserts. The Reynolds number ranged from 5000 to 17000. Comparative analyses revealed that the wavy twisted tape with a twist ratio of 7.1 provided the highest heat transfer rate, showing a 172% increase in the Nusselt number and a 32.11% increase in the friction factor relative to a smooth tube.

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1. Introduction

Enhancing heat transfer within a duct can be achieved through passive methods like using different rib patterns, surfaces with indentations, and pin-like protrusions. These techniques find applications in combustion chamber linings, cooling internal turbine blades, solar air heaters, electronic cooling systems, medical equipment, and industrial heat exchangers. Currently, dimpled surfaces are favored for their ability to significantly increase heat transfer rates with minimal impact on pressure. Researchers have also explored combining these techniques to further improve heat transfer efficiency. Existing literature extensively covers how various parameters of dimples affect heat transfer. The Russian Aerodynamic Society employs dimpled surfaces not only to reduce drag but also to enhance heat transfer. They utilize configurations such as regular arrays of dimples, staggered arrays in annular passages, flow through converging and diverging ducts featuring a single hemispherical dimple, and flow through narrow ducts with spherical dimples positioned variably on opposing walls. Some studies report achieving up to 150% higher heat transfer compared to flat plates, with a relatively minor increase in pressure. Recent research indicates heat transfer improvements 2.5 times greater than that of smooth plates across various Reynolds numbers, with a pressure penalty roughly half that of ribbed turbulators. Experiments by Afanasyev *et al.,* [1] analyzed friction and heat transfer on surfaces with spherical cavities exposed to turbulent flow, using an aerodynamic test bed to study boundary layer conditions. Bunker and Donnellan [2] demonstrated that heat transfer in circular passages with dimpled surfaces can be enhanced by factors exceeding 2 when the dimple depth exceeds 0.3 and the density of the array is 0.5 or higher, resulting in friction factor multipliers between 4 and 6. This research provides initial insights into the effects of different concave arrays on heat transfer and friction in turbulent flows. Chyu *et al.,* [3] showed that both concave configurations enhance heat transfer approximately 2.5 times more than smooth surfaces for Reynolds numbers between 10,000 and 50,000, comparable to continuous ribbed turbulators. Moreover, these concave arrays lead to significantly lower pressure losses, nearly half of those caused by protruding elements. Isaev *et al.,* [4] demonstrated that altering the separation flow structure from symmetric to a single vortex significantly boosts heat transfer, increasing approximately 60% in the region of the spherical dimple and about 45% in its wake. Ligrani *et al.,* [5] presented flow structure characteristics for a channel with a dimpled surface on one wall, both with and without protrusions (matching the shapes of the dimples) on the opposite wall. Moon *et al.,* [6] showed that heat transfer enhancement and pressure penalties remain consistent across a wide range of Reynolds numbers and duct heights. Mahmood *et al.,* [7] examined mechanisms for enhancing heat transfer on plain duct surfaces with dimples on one wall, where the duct height was 50% of the dimple print diameter. Syred *et al.,* [8] studied turbulent heat transfer and hydrodynamics in concavely and convexly curved dimples with Reynolds numbers ranging from 1.3×10^5 to 3.1×10^5. Kurhade *et al.,* [9-12] discussed material selections and computational fluid dynamics (CFD) approaches for thermal cooling, while Patil *et al.,* [13] and Waware *et al.,* [14] provided critical reviews on heat transfer enhancement in heat exchangers. Rahul Khot *et al.,* [15-19] investigated laser welding parameters on the strength of TRIP steel. The present study focuses on enhancing heat transfer using wavy corrugated twisted tape inserts. Luo *et al.,* [20] utilized three methods—air bubble injection, perforated wavy strip turbulator (PWST), and Nano fluids—to enhance thermal performance in a double pipe heat exchanger. Results indicated heat transfer increases of 56% with Nano fluids, 53% with PWST, and 14.1% with bubble injection. Combining all three methods boosted heat transfer and exergy losses by 2.15 and 1.82 times, respectively, compared to a plain pipe. Kumar *et al.,* [21] presented experimental analyses on a heat exchanger tube using a newly designed perforated conical ring combined with twisted tape inserts. Aldawi [22] explored the use of twisted tapes in spiral tubes to address significant research gaps, employing a validated mathematical model to understand geometric parameters' effects on heat transfer and exergy efficiency in such configurations. Ahmad *et al.,* [23] found that corrugated geometries exhibit a performance evaluation criterion (PEC) greater than unity, surpassing smooth pipes.

Researchers are actively developing new techniques to enhance heat transfer in mechanical systems using magnetic fields, such as in internal combustion engines and vapor compression refrigerating systems. While extensive studies have explored heat transfer enhancements in double pipe heat exchangers using various techniques, the specific effects of wavy corrugated twisted tape inserts on heat transfer efficiency remain under-investigated. Existing literature often focuses on smooth twisted tapes or other turbulence-inducing inserts, leaving a significant gap in understanding how the unique geometry of wavy corrugated twisted tapes impacts heat transfer and pressure drop characteristics in turbulent flow conditions. This study aims to address this gap by systematically examining the performance of these inserts, providing new correlations and comparative analyses to fill the current void in research. The aim of this study is to investigate the heat transfer effects and friction factor characteristics of wavy corrugated twisted tape inserts in double pipe heat exchangers, to develop new correlations for Nusselt number and friction factor, and to provide a comparative analysis with smooth tube configurations under turbulent flow conditions.

2. Experimental Investigations

2.1 Experimental Set Up

Figure 1 depicted the experimental setup and various measurement instruments. It included a tube-in-tube heat exchanger with an inner tube made of copper and an outer tube made of mild steel. This material selection balances thermal efficiency, durability, cost-effectiveness, and compatibility, making it suitable for diverse industrial and commercial applications. Thermocouples were used to monitor incoming and outgoing temperatures of both hot and cold water, with four thermocouples positioned: two at each inlet and outlet. Rotameters quantified flow rates at the inlets of cold and hot water. Two centrifugal pumps circulated the water, supported by two storage tanks. An electric heater, rated at 1500 watts, heated the hot water tank. An inverted U-tube manometer measured pressure differentials across the hot fluid test section, while flow velocity through the tube was gauged using a current meter. Control valves and bypass valves were installed at the rotameter inlets. To measure air mass flow rate, an orifice meter was used in conjunction with a flow control valve. Inlet air temperature was monitored with two thermocouples, and three thermocouples were employed to measure exiting air temperatures.

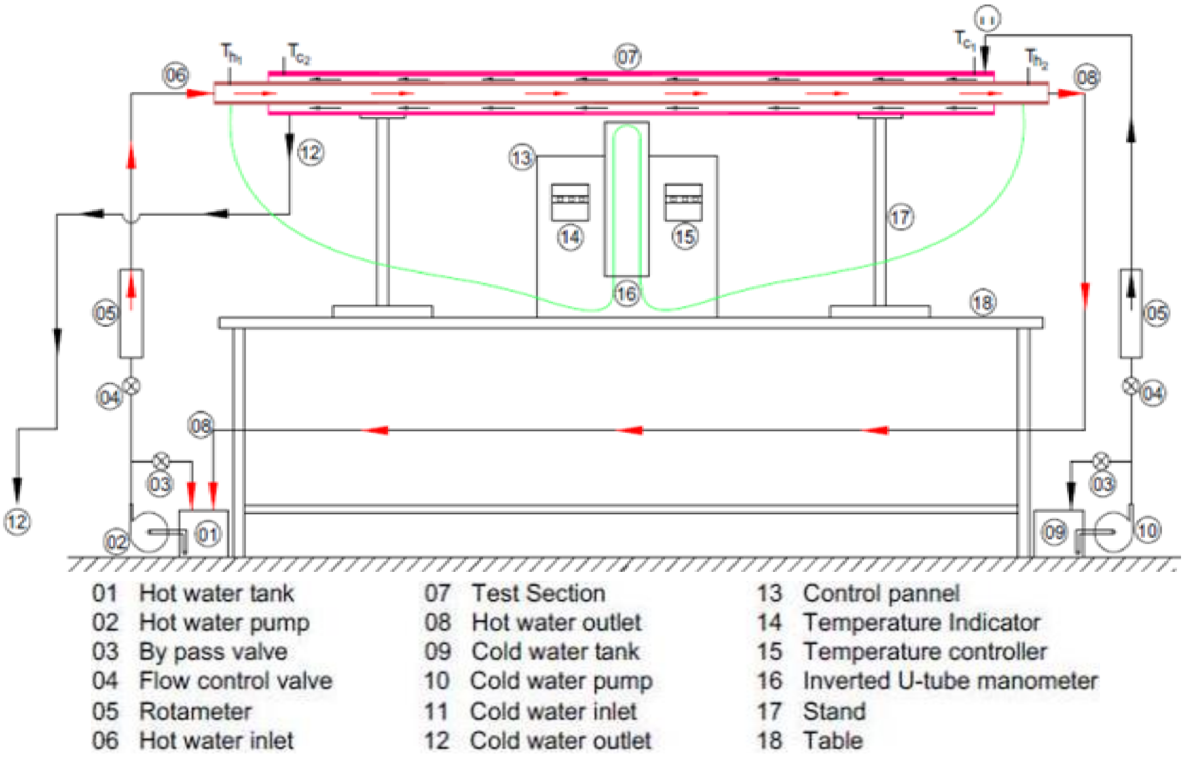

Fig. 1. Experimental set up

2.2 Procedure

In the experiment, cold water initially filled the water tank and was heated to 80°C using a water heater. Subsequently, the hot water was directed through the rotameter by opening the flow control valve, aided by the hot water pump, and then through the inner pipe of the heat exchanger. Simultaneously, cold water from the cold water tank entered the heat exchanger through another rotameter, controlled by a flow control valve and the cold water pump. The flow rate of cold water was set at 100 liters per hour (LPH) and maintained constant throughout the experiment. Similarly, the flow rate of hot water was adjusted to 300 LPH and kept constant. Once a steady state was achieved, temperatures at the inlet and outlet of both cold and hot waters were recorded, and the pressure drop across the test tube was measured for the plain tube without any inserts. Following this, the experiment was repeated using wavy twisted tapes with twist ratios (TR) of 10.7, 8.5, and 7.1, while varying the flow rates of hot water from 400 to 950 LPH. Figure 2 to Figure 5 illustrate the wavy tape inserts with twist ratios of 10.7, 8.5, and 7.1 respectively. The specifications of insert are mentioned in Table 1.

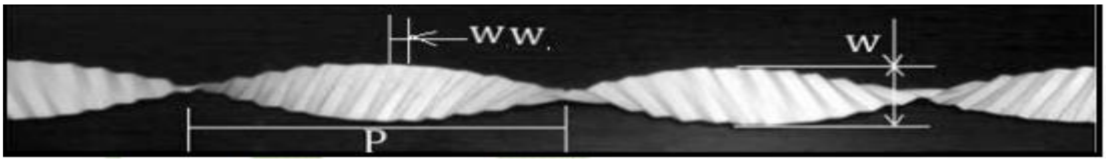

Fig. 2. Twisted tape insert

Fig. 3. Insert with TR – 10.7

Fig. 4. Insert with TR – 8.5

Fig. 5. Insert with TR – 7.1

Table 1
Inserts specifications

Sr. No.	Parameter	Material/Value
1	Material	Cu
2	Width of Insert (W)	13.5 mm
3	Twist Ratio (TR)	10.7, 8.5, 7.1
4	Insert Length	990 mm
5	Insert thickness	2.2 mm
6	Wave Width (WW)	10 mm
7	Wave Depth	10 mm

The twist ratio (TR) is calculated using the following formula

$$\text{Twist Ratio (TR)} = \frac{\text{Pitch (Length of one complete twist)}}{\text{Wifth of the tape}} \tag{1}$$

The selection of twist ratios for wavy twisted tape inserts in heat exchangers involves a trade-off between maximizing heat transfer enhancement through increased turbulence and managing associated friction losses. These ratios are typically chosen based on a combination of theoretical analysis, experimental results, and practical considerations to optimize overall heat exchanger performance.

2.3 Calculations

The bulk mean temperature T_{bh} and T_{bc} are calculated

$$T_{bh} = \frac{T_{h1}+T_{h2}}{2} \text{ and } T_{ch} = \frac{T_{c1}+T_{c2}}{2} \tag{2}$$

Hot water and cold water heat transfer rate

$$Q_h = m_h.C_{ph}.(T_{h1} - T_{h2}) \text{ and } Q_c = m_c.C_{pc}.(T_{c1} - T_{c2}) \tag{3}$$

Nusselt Number of cold water through annular space

$$Nu_o = 0.02345\ (R_{e0})^{0.8}.P_r^{0.3} \quad , Re_o = \rho\ .U_o D_h/\mu \tag{4}$$

Nusselt Number (Experimental) of hot water flowing through the tube

$$\mathrm{N_{ui}} = \frac{\mathrm{h_i.d_i}}{\mathrm{K}} \tag{5}$$

Theoretical Nusselt Number of hot water flowing through the tube

$$N_{ui} = 0.023.(R_{ei})^{0.8}.(\mathrm{Pr}\,)^{0.3} \tag{6}$$

Experimental Friction Factor

$$f = \frac{2gdih}{LU_i^2} \tag{7}$$

Theoretical Friction Factor

$$f = 0.0056\,.\,(1 + \left(50 + \left(\frac{10^6}{R_{ei}}\right)\right)^{0.33}) \tag{8}$$

3. Results and Discussion

After conducting the experimental analysis, Nusselt numbers and friction factors were calculated for both plain tubes and tubes equipped with wavy tape inserts. These results were then compared with correlations proposed by Dittus and Boelter for Nusselt number, and John Nikuradse for friction factor. Figure 6 depicts a plot showing the correlation between Nusselt number and Reynolds number for the plain tube. It was observed that there is a direct proportionality between Nusselt number and Reynolds number, indicating that Nusselt number depends on Reynolds number. Figure 7 displays the graph of friction factor versus Reynolds number for the plain tube. Here, it is evident that friction factor exhibits an inverse relationship with Reynolds number, implying that friction factor decreases as Reynolds number increases.

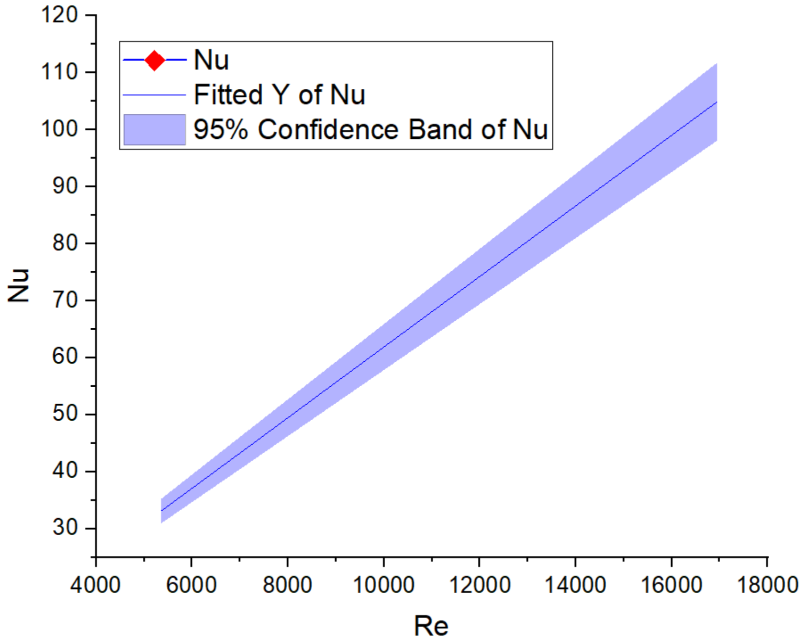

Fig. 6. Nusselt number Vs Reynolds number

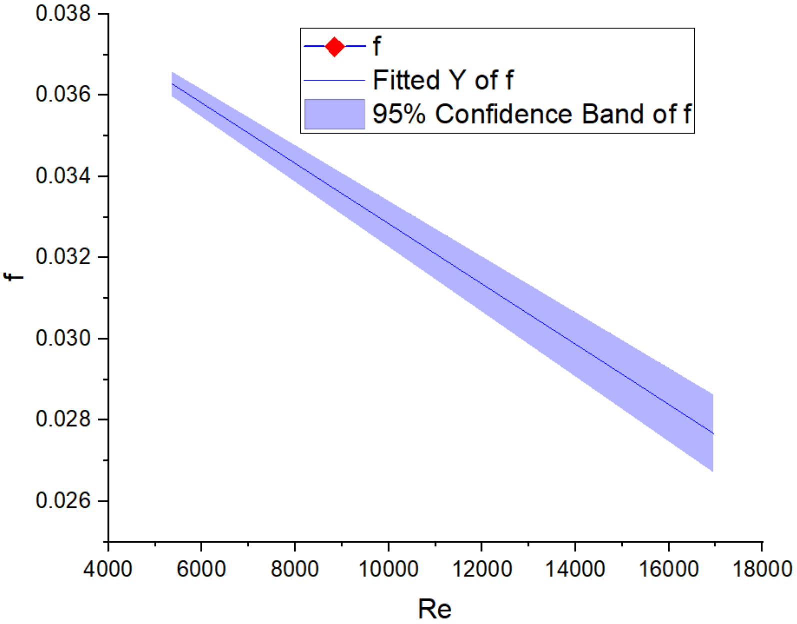

Fig. 7. Friction factor Vs Reynolds number

Figure 8 illustrates how the Nusselt number varies with Reynolds number for different twist ratios (TR=10.7, 8.5, 7.1). The results indicate that as Reynolds number increases, the Nusselt number also increases, signifying a higher heat transfer rate. Particularly noteworthy is that at a specific Reynolds number, the twisted tape with the lowest twist ratio (TR=7.1) achieves the highest Nusselt number among the tested configurations. Therefore, the highest heat transfer rate was observed with the twist ratio of 7.1.

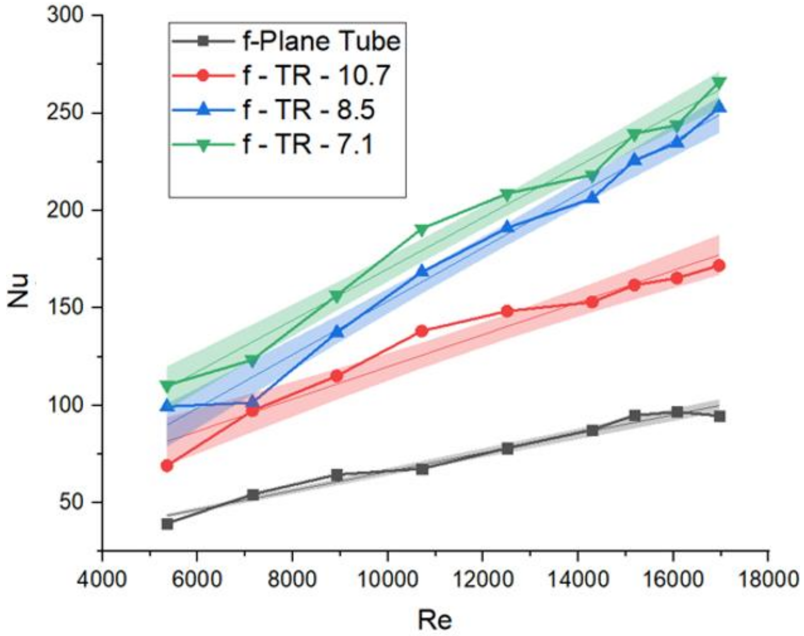

Fig. 8. Nusselt number Vs Reynolds number

Figure 9 depicts how the friction factor changes with Reynolds number. It was noted that the friction factor increased as the twist ratio decreased. Specifically, the wavy twisted tape inserts with a twist ratio of 7.1 exhibited the highest friction factor among the inserts tested. Comparatively, for twist ratios of 7.1, 8.5, and 10.7, the friction factors were 2.00, 1.47, and 0.147 times higher than that of the plain tube, respectively.

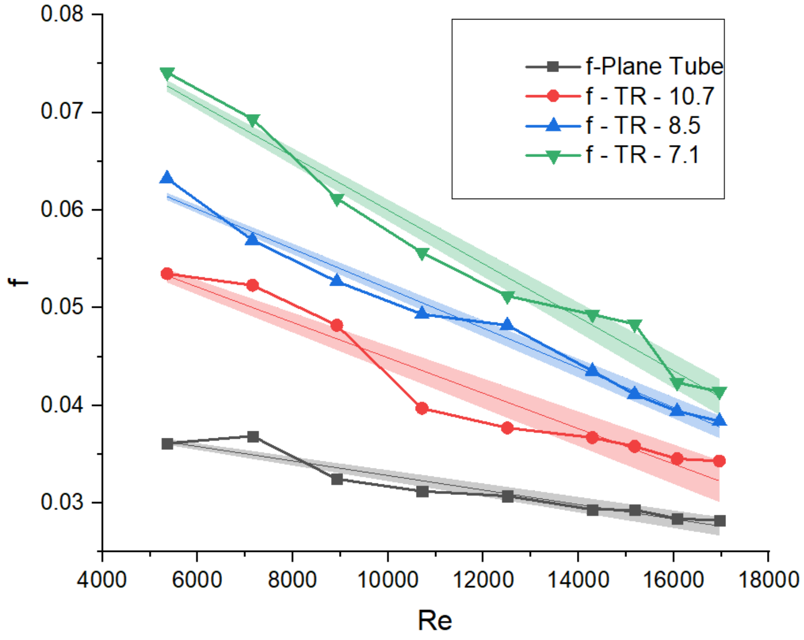

Fig. 9. Friction Factor Vs Reynolds number

4. Conclusion

The utilization of wavy (corrugated) twisted tape inserts demonstrated significant enhancements in heat transfer rates, with the twist ratio of 7.1 yielding the highest performance. Comparative analysis against a plain tube showed consistent improvements across all wavy twisted tape configurations. Increasing the twist ratio correlated with increased heat transfer and slightly elevated friction factors. Key conclusions drawn from this experimental investigation include

i. In the Reynolds number range of 5000 to 17000, the Nusselt number increased by 75.75%, 157%, and 172% for twist ratios of 10.7, 8.5, and 7.1, respectively.
ii. The friction factor rose by approximately 9.4%, 22.44%, and 32.11% with twist ratios of 10.7, 8.5, and 7.1, respectively.

Decreasing the twist ratio from 10.7 to 7.1 generally increases the turbulence and improves heat transfer rates in the heat exchanger. This is attributed to the enhanced convective heat transfer resulting from increased fluid mixing and disturbance caused by the wavy corrugated twisted tape inserts.

These findings underscore the effectiveness of wavy twisted tape inserts in enhancing heat transfer efficiency in double pipe heat exchangers, offering insights into optimizing their performance under various flow conditions.

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