Journal of Mines, Metals and Fuels, *72(9): 1005-1012; 2024. DOI: 10.18311/jmmf/2024/45505*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

The Impact of Circular Holes in Twisted Tape Inserts on Forced Convection Heat Transfer

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Abstract

This study investigated heat transfer and friction characteristics in a forced convection system using wavy twisted tape inserts with circular holes. The inserts, with twist ratios (TR) of 8.5, 7.5, and 6.5, were placed inside a test pipe to create turbulent flow. The tapes measured 700 mm in length and 18 mm in width, while the test pipe had an outer diameter of 35 mm and an inner diameter of 30 mm, with a test section length of 700 mm. Airflow rates were adjusted to achieve different bulk mean temperatures. Experimental data were used to develop new correlations for the Nusselt number and friction factor. The Reynolds number (Re) ranged from 4,000 to 14,000. Comparisons between the wavy twisted tape inserts with varying twist ratios and pitches and a smooth tube showed that the highest heat transfer rate was achieved with a twist ratio of 6.5.

Keywords: *Heat Exchanger, Heat Transfer Rate, Nusselt Number, Reynold Number, Twist Ratio*

1.0 Introduction

In thermal systems, particularly heat exchangers, enhancing heat transfer while maintaining or minimizing pressure drop is crucial for efficiency. Heat transfer enhancement techniques have become increasingly important in various industrial applications, particularly those involving fluid flow and heat exchange processes. One effective method to augment heat transfer is the use of twisted tape inserts within pipes or ducts. These inserts create turbulence and promote fluid mixing, leading to improved heat transfer rates. The use of wavy twisted tapes, in combination with circular holes, is expected to further enhance heat transfer performance compared to

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traditional straight twisted tapes. The experimental setup consisted of a test pipe with a wavy twisted tape insert inserted into it. The tape featured varying twist ratios and circular holes, which were designed to disrupt the flow and increase turbulence. Air was forced through the pipe, and the resulting heat transfer and pressure drop were measured. Twisted tapes induce swirling flow, increasing turbulence and mixing, leading to improved heat transfer. Modifications like adding circular holes to twisted tapes have been proposed to reduce pressure drop while maintaining or enhancing heat transfer performance. Passive techniques, such as rib patterns, indented surfaces, and pin-like protrusions, can effectively increase heat transfer in ducts. These methods are widely used in combustion chambers and industrial heat exchangers. Among these, dimpled surfaces have gained popularity due to their ability to significantly boost heat transfer with minimal pressure loss. Researchers have explored various combinations of these techniques and have extensively studied the impact of different dimple parameters on heat transfer. The Russian Aerodynamic Society has utilized dimpled surfaces to reduce drag and improve heat transfer in various configurations, including regular and staggered dimple arrays, converging and diverging ducts, and narrow ducts with strategically placed dimples. These studies have demonstrated substantial heat transfer enhancements (up to 150%) compared to flat surfaces while maintaining relatively low-pressure increases. Recent research has further highlighted the effectiveness of dimpled surfaces, showing heat transfer improvements of up to 2.5 times compared to smooth surfaces across different Res, with pressure penalties significantly lower than those associated with ribbed turbulators. Previous research, such as the work of Kurhade *et al.*[1-6], Waware *et al.*[7-9] and Khot *et al.*[10-14], has explored various methods to enhance heat transfer, including material selection, CFD analysis, and the use of twisted tape inserts. Luo *et al.*[15] investigated the combined effects of air bubble injection, Perforated Wavy Strip Turbulators (PWST), and nanofluids in a double pipe heat exchanger, achieving a significant increase in heat transfer. Kumar *et al.*[16] studied the performance of a heat exchanger tube with a novel perforated conical ring and twisted tape inserts. Other researchers, such as Aldawi[17], Ahmad *et al.*[18], and Afanasyev *et al.*[19], have explored the impact of twisted tapes, corrugated geometries, and spherical cavities on heat transfer and friction. Bunker *et al.*[20] explained Heat transfer and friction factors for flows inside circular tubes with concavity surface. Chyu *et al.*[21] found that concave dimpled surfaces can significantly enhance heat transfer compared to smooth surfaces, with pressure losses significantly lower than those caused by ribbed turbulators. Isaev *et al.*[22] demonstrated that transforming the separation flow structure can further improve heat transfer. Ligrani *et al.*[23], Moon *et al.*[24], Mahmood *et al.*[25], and Syred *et al.*[26] have conducted studies on the flow structure, heat transfer, and hydrodynamics in dimpled channels. Mohadjer *et al.*[27] compared the performance of different turbulators and found that while some turbulators can improve heat transfer, others may have a negative impact. Abed *et al.*[28] investigated the use of bubble injection and magnetic turbulators to enhance heat transfer. Kumar *et al.*[29] evaluated the efficiency of a solar thermal air collector with discrete multi-arc-shaped ribs. Kurhade *et al.*[30-32] explain the performance of solar collectors and the use of biodiesel and dimethyl carbonate blends on engine performance. Waware *et al.*[33] did a review on a comprehensive evaluation of recent studies investigating nanofluids utilization in heat exchangers. Kurhade *et al.*[34-39] explained experimental studies on MQL grinding and heat transfer in electronic components revealed the influence of substrate board thermal conductivity and PCM placement on temperature regulation. Numerical and experimental investigations explored heat transfer from IC chips mounted on SMPS boards, while a comprehensive review analyzed electronic cooling technologies in harsh environments. Aerofoil design optimization through CFD simulations and wind tunnel experiments, combined with fuzzy logic techniques for predicting heat transfer enhancement using twisted tape inserts, provided insights into heat exchanger efficiency.

This study aims to investigate the heat transfer and friction characteristics in a forced convection system using wavy twisted tape inserts with circular holes. By varying the twist ratios and airflow rates within a specified range of Reynolds numbers, the study seeks to develop new correlations for the Nusselt number and friction factor. Additionally, the study aims to identify the optimal twist ratio that maximizes heat transfer efficiency in comparison to a smooth tube.

2.0 Experimental Procedure

The experimental apparatus, as depicted in Figures 1 and 2, consisted of a blower unit connected to a test pipe. A nichrome heater was wrapped around the test section to provide heat input. Four thermocouples were embedded in the test section wall to measure its temperature, while two additional thermocouples were placed in the air stream at the inlet and outlet to monitor air temperatures. The test pipe was connected to the blower outlet, and an orifice meter was installed to measure airflow rates. A power unit supplied electricity to the heater, and the power consumption was measured using meters. It is important to note that only a portion of the total heat supplied was used to heat the air. An orifice meter and a water manometer were employed to measure airflow rates. A valve at the pipe outlet allowed for adjusting the air flow rate. Tapping with a valve was provided at the inlet of the test section to measure pressure drop. The specifications of the experimental setup and inserts are explained in Table 1 and in Table 2 respectively.

To initiate and regulate the flow rate, adjust the valve until the desired pressure difference is indicated on the manometer. Subsequently, activate the heating element of the test section using the dimmer stat and carefully fine-tune the desired heat input by monitoring the

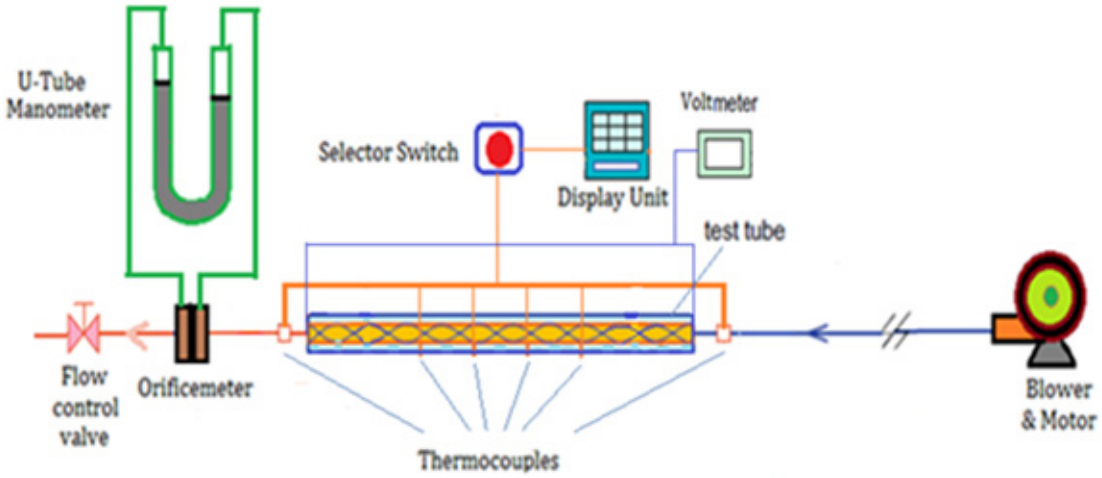


Figure 1. Experimental setup.

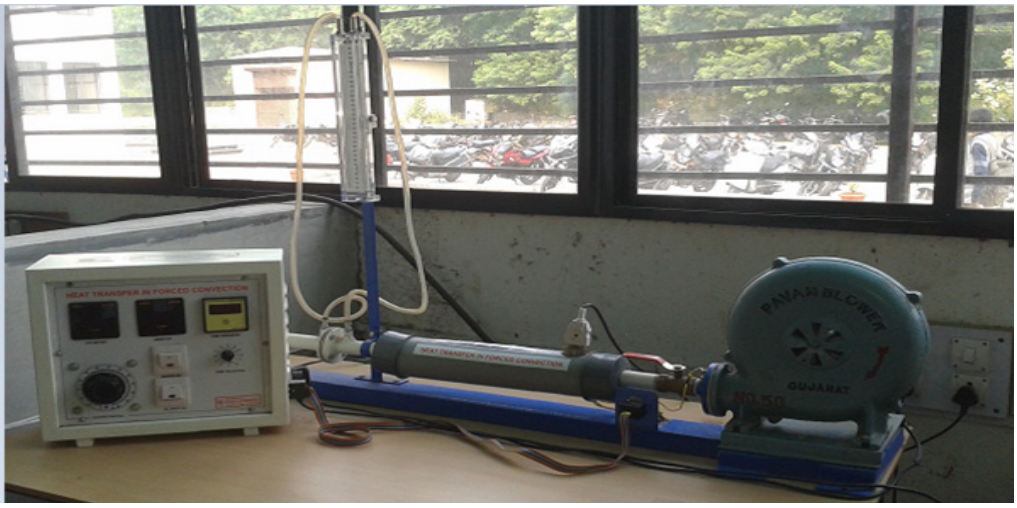


Figure 2. Actual setup.

Table 1. Specifications of the experimental setup

S. No.	Parameter		Values
1	Pipe diameter	Outer Dia. (Do)	35 mm
		Inner Dia. (Di)	30 mm
2	Length of test section (L)		700 mm
3	Blower motor		**½ H.P.**
4	Orifice Dia.(d)		14 mm
5	Dimmer-stat		0-2 amp, 0-260 VAC
6	Temperature indicator		Range 0-300˚C
7	Nichrome wire heater wound on test pipe		

voltmeter and ammeter readings. Periodically, record the temperature readings from all thermocouples at 10 min intervals until a stable state is achieved, indicating that the temperature measurements have stabilized. Once steady-state conditions are established, collect temperature readings from all six thermocouples. To evaluate the impact of twisted tape inserts with varying twist ratios, repeat this experimental procedure with inserts having twist ratios of 5.5, 6.5, and 8.5 as shown in Figure 3, Figure 4 and Figure 5. This analysis will provide valuable insights into the influence of twisted tape inserts on heat transfer performance.

Table 2. Insert specifications

S. No.	Parameter	Values
1	W (Width)	700 mm
2	T (Thickness)	**½ H.P.**
3	L (Length)	14 mm
4	D (Hole Dia)	7 mm
5	P (Pitch)	90,115,145
6	TR	6.5, 7.5, 8.5



Figure 3. Tape inserts with TR:- 6.5.



Figure 4. Tape inserts with TR:- 7.5.



Figure 5. Tape inserts with TR:- 8.5.

The Twist Ratio (TR) is calculated using the following formula:

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

3.0 Data Deduction

a. Air volume flow rate

$$Q_a = cd\ x\ A_o\ x\ \sqrt{\frac{2gHpw}{\rho_a}}$$

b. Mass flow rate

$$\dot{m}a = q_a\ \rho_a$$

c. Air velocity

$$V = \frac{q_a}{A}$$

d. Re of fluid

$$R_e = \frac{vD_i}{A}$$

e. Theoretical friction factor

$$f_{th} = (1.82\ x\ \log_{10} Re - 1.64)^{-2}$$

f. Theoretical Nusselt number

$$Nu_{th} = 0.023\ x\ Re^{0.8}\ x\ Pr^{0.4}$$

g. Experimental friction factor

$$f_{exp} = \frac{\Delta P}{\frac{L}{D_i}\ x\ \frac{\rho_a v^2}{2}}$$

h. Experimental Nusselt number

$$Nu_{exp} = \frac{hD_i}{k}$$

4.0 Result and Discussion

Following the experimental study, Nu and F were calculated for both with and without inserts. The results compared against the established correlations of Dittus-Boelter for Nusselt number and Petukhov for F. Figure 6 illustrates the relationship between Nu and Re for the plain tube. The graph demonstrates a linear correlation, indicating that as the Re rises, so does the Nu. Figure 7 presents the graph between F and Re for the ideal tube. In this case, the F exhibits an inverse relationship

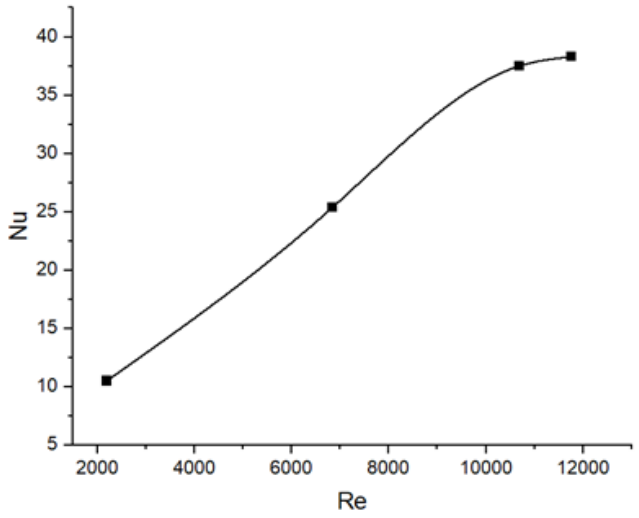


Figure 6. Re vs Nu.

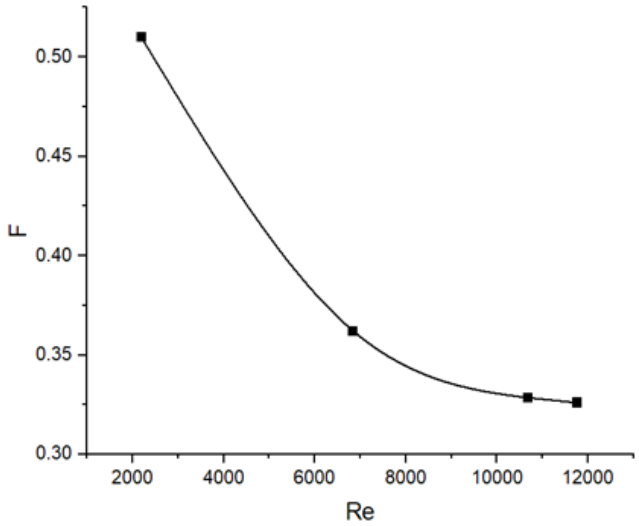


Figure 7. Re vs F.

with the Re, meaning that as the Re increases, the F decreases.

Figure 8 illustrates the relationship between Nu and Re for TR=8.5, 7.5, and 6.5. The data reveals that as Re increases, so does the Nu, indicating enhanced heat transfer. Among the different twist ratios, the insert with the lowest twist ratio (TR=6.5) consistently exhibited higher Nus compared to the others at any given Re. This suggests that a lower twist ratio is more effective in improving heat transfer efficiency.

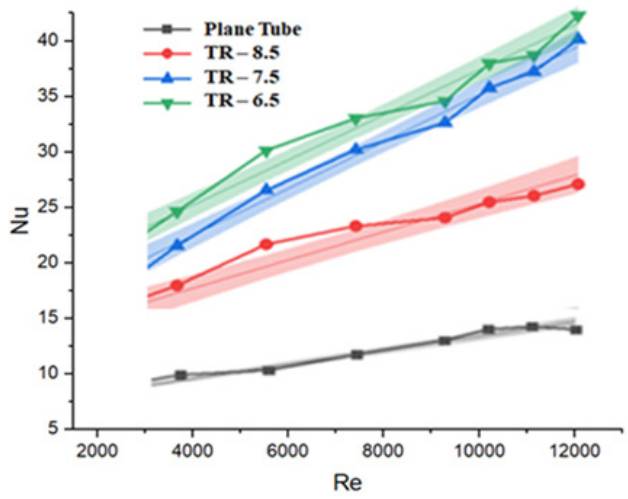


Figure 8. Re vs Nu for inserts.

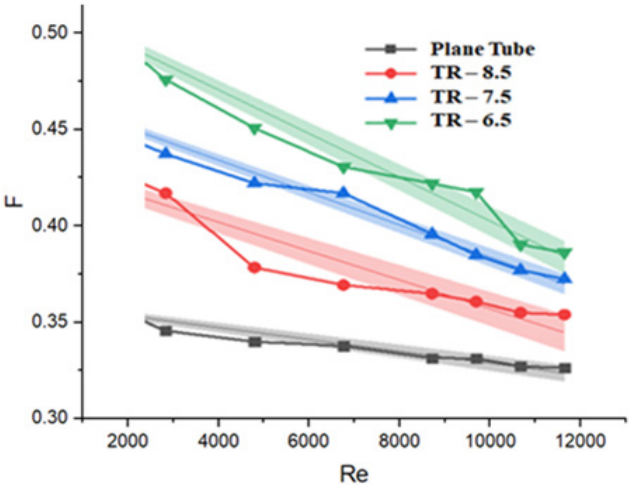


Figure 9. Re vs F for inserts.

Figure 9 illustrates how the F changes with Re. It was observed that as the twist ratio decreased, the F increased. The wavy twisted tape insert with a twist ratio of 6.5 exhibited the highest F compared to the others. The Fs for the inserts with twist ratios of 6.5, 7.5, and 8.5 were 0.535, 0.385, and 0.254 times higher than that of the plain tube, respectively.

5.0 Conclusions

This study found that the use of twisted tape inserts with varying twist ratios significantly enhanced heat transfer and slightly increased the friction factor. The inserts with lower twist ratios showed the greatest improvement in the Nusselt number, while also causing a modest rise in the friction factor.

- Nu Enhancement: The Re ranging from 4000 to 14000, the inserts with TR of 8.5, 7.5, and 6.5 increased Nus by 26.99%, 32.64%, and 34.32%, respectively.
- F Increase: The F increased by approximately 0.30%, 0.3654%, and 0.5647% for the inserts with TR of 8.5, 7.5, and 6.5, respectively.

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