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Experimental and CFD Analysis of Heat Transfer Enhancement in a Double Pipe Heat Exchanger Using Twisted Tape Inserts

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Abstract

This study presents a comprehensive experimental and numerical investigation of heat transfer enhancement in a double-pipe heat exchanger equipped with twisted tape inserts. The primary objective is to quantify the impact of induced swirl flow on thermal performance and flow resistance. Experiments were conducted using water as the working fluid in a horizontal double-pipe heat exchanger with a constant heat flux boundary condition. The Reynolds number ranged from 10,000 to 20,000, ensuring turbulent flow conditions. A continuous twisted tape insert with a twist ratio of 4.7 was employed inside the inner tube.

A three-dimensional Computational Fluid Dynamics (CFD) model was developed using the standard k–ε turbulence model. The numerical results were validated against experimental data. The findings reveal that twisted tape inserts significantly enhance the Nusselt number by approximately 2.3–2.9 times compared to a smooth tube, while the friction factor increases by 1.5–2 times. The thermal performance factor exceeded unity across all operating conditions, confirming the effectiveness of the technique. The CFD analysis provided detailed insight into the flow structure, demonstrating strong swirl and secondary flow formation. The results confirm that twisted tape inserts represent an efficient passive technique for heat transfer enhancement in compact heat exchangers.

Keywords: Double-pipe heat exchanger; twisted tape; heat transfer enhancement; Nusselt number; Reynolds number; CFD.

التحليل التجريبي والعددي لتعزيز انتقال الحرارة في مبادل حراري أنبوبي مزدوج باستخدام شرائط ملتوية

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الملخص

تقدم هذه الدراسة تحقيقًا شاملاً يجمع بين التجارب العملية والمحاكاة العددية لتعزيز انتقال الحرارة في مبادل حراري أنبوبي مزدوج مزود بشرائط ملتوية. يتمثل الهدف الرئيسي في قياس تأثير التدفق الدوامي المستحث على الأداء الحراري ومقاومة الجريان.

أُجريت التجارب باستخدام الماء كسائل عامل داخل مبادل حراري أفقي مع تطبيق شرط تدفق حراري ثابت. وقد تراوح عدد رينولدز بين 10,000 و20,000، مما يضمن تحقيق نظام جريان مضطرب. تم استخدام شريط ملتوي مستمر بنسبة التفاف مقدارها 4.7 داخل الأنبوب الداخلي.

تم تطوير نموذج عددي ثلاثي الأبعاد باستخدام ديناميكيات الموائع الحسابية (CFD) بالاعتماد على نموذج الاضطراب القياسي k–ε. وتم التحقق من صحة النتائج العددية بمقارنتها مع البيانات التجريبية.

أظهرت النتائج أن استخدام الشرائط الملتوية يؤدي إلى زيادة ملحوظة في عدد نوسلت بمقدار يتراوح بين 2.3 و2.9 مرة مقارنة بالأنبوب الأملس، في حين يزداد معامل الاحتكاك بمقدار يتراوح بين 1.5 و2 مرة. كما تجاوز معامل الأداء الحراري القيمة الواحدة في جميع ظروف التشغيل، مما يؤكد فعالية هذه التقنية.
وقد أتاح التحليل العددي فهمًا أعمق لبنية الجريان، حيث أظهر تكوّن تدفقات دوامية قوية وحركات ثانوية داخل الأنبوب.
تؤكد نتائج هذه الدراسة أن الشرائط الملتوية تُعد تقنية سلبية فعالة لتحسين انتقال الحرارة في المبادلات الحرارية المدمجة.

الكلمات المفتاحية : المبادل الحراري الأنبوبي المزدوج؛ الشريط الملتوي؛ تعزيز انتقال الحرارة؛ عدد نوسلت؛ عدد رينولدز؛ ديناميكيات الموائع الحسابية.

Introduction

A double-pipe heat exchanger consists of two concentric tubes, one inside the other, allowing heat exchange between fluids flowing in each. It is often used in industry for heating or cooling small flows due to its simplicity. However, the heat transfer in a plain double-pipe exchanger is limited by laminar or turbulent flow without strong mixing. To improve performance, passive devices like twisted tape inserts are used. A twisted tape is a long metal strip twisted along its length (Fig. 2). When placed inside the tube, it induces a swirl flow that disrupts the boundary layer and enhances mixing. This increases the convective heat transfer coefficient compared to a smooth tube.

Previous studies have shown large gains with twisted tapes. For example, Naphon (2006) experimentally found much higher Nusselt numbers in a double-pipe exchanger fitted with twisted tape, compared to the same geometry without tape. Chang and Yang (2007) reported similar results with a broken (cut) twisted tape in a circular tube. These and other works report that adding twisted tape can double or triple the heat transfer coefficient, though the pressure drop also rises. The overall thermal performance factor (heat transfer increase vs. pressure loss) remains favourable. Recent CFD studies confirm that twisted tapes create intense secondary flow. In one CFD study, Benmbarek and Moujaes (2025) found that a twisted insert produced large swirl and high heat transfer, as long as the pressure loss was acceptable. In summary, it is well known that twisted-tape inserts can greatly boost heat transfer in tube exchangers, at the cost of higher pumping power.

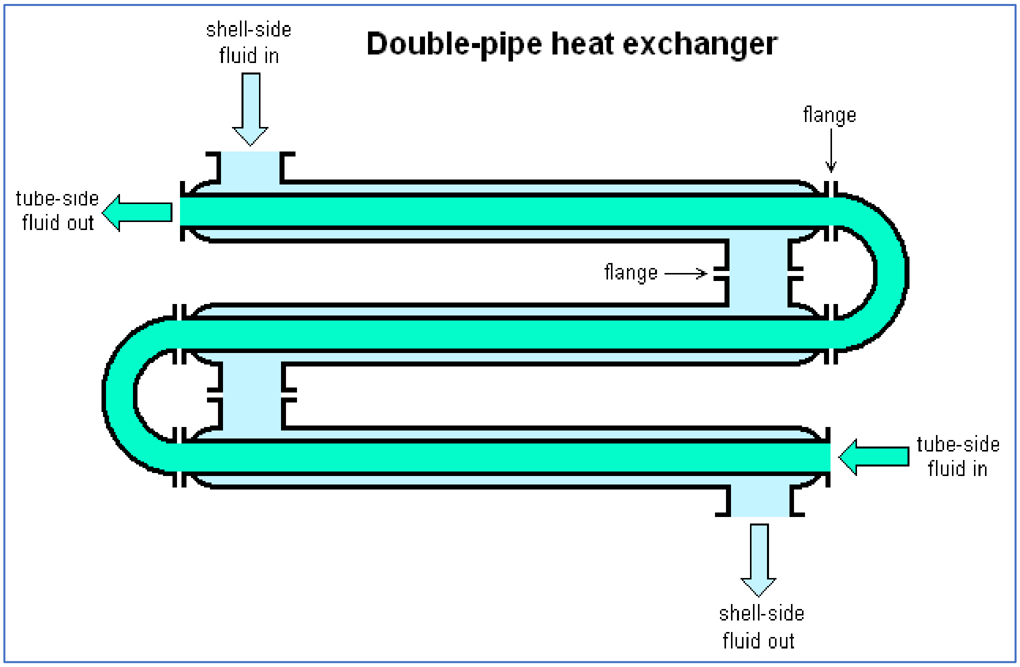

Figure 1 Schematic of a double-pipe heat exchanger. One fluid flows through the inner pipe and the other flows in the annulus between inner and outer pipes (Wikimedia Commons). The inner pipe may contain a twisted-tape insert (not shown) to induce swirl and improve heat transfer.

Twisted tapes come in various designs. The basic type is a full-length helical insert with no holes. Other designs include perforated or cut tapes (Fig. 2) and multiple tapes side by side. In this work we focus on a classic continuous twisted tape in the inner tube. The tape's geometry is often defined by its twist ratio (the length per one full twist) or its helix angle. Generally, a tighter twist (smaller twist ratio) produces stronger swirl and higher heat transfer, as seen in experiments. The trade-off is higher friction. Many researchers have measured these effects in double-pipe exchangers. For example, Solanki et al. reported that a twisted tape with twist ratio ~5.25 and added cuts enhanced Nusselt number by 2-3 times for water flow. Similarly, Ranjith *et al.* (2013) showed that using tape inserts on both sides increased heat transfer by over 50%, and that lower twist ratios gave better performance.

1 Literature Review (700 words)

The enhancement of heat transfer in heat exchangers has been a central topic in thermal engineering research due to its direct impact on energy efficiency, industrial productivity, and system compactness. Among various types of heat exchangers, the double-pipe heat exchanger is widely used because of its simple design, ease of maintenance, and suitability for moderate heat transfer applications. However, its thermal performance is often limited by insufficient fluid mixing and the development of thermal boundary layers, especially under turbulent flow conditions. To address these limitations, numerous studies have focused on passive enhancement techniques, particularly the use of twisted tape inserts .

Early experimental investigations, such as those conducted by P. Naphon (2006), demonstrated that inserting twisted tapes into the inner tube of a double-pipe heat exchanger significantly increases the Nusselt number compared to smooth tubes. This enhancement is primarily attributed to the swirl flow induced by the tape, which disrupts the boundary layer and improves convective heat transfer. Similarly, S. W. Chang and T. L. Yang (2007) investigated the use of modified twisted tapes, such as broken or cut designs, and reported further improvements in heat transfer performance. Their findings highlighted that geometric modifications of the inserts can intensify turbulence and secondary flow structures, leading to higher thermal efficiency.

Subsequent studies expanded on these findings by exploring different twisted tape configurations and their influence on both heat transfer and pressure drop. For instance, B. Salam et al. (2013) examined rectangular-cut twisted tapes and observed a substantial increase in heat transfer rates due to enhanced fluid mixing. However, they also noted a corresponding increase in friction factor, indicating a trade-off between thermal enhancement and hydraulic performance. This trade-off has been a recurring theme in the literature, as improved heat transfer is often accompanied by increased pumping power requirements.

In addition to experimental studies, numerical simulations using Computational Fluid Dynamics (CFD) have become increasingly important in analyzing heat transfer enhancement mechanisms. Research by M. M. Benmbarek and S. F. Moujaes (2025) employed CFD techniques to investigate the flow behavior inside tubes equipped with twisted tape inserts. Their study revealed the formation of strong swirl flows and secondary vortices, which play a crucial role in enhancing heat transfer. The numerical results were consistent with experimental observations, confirming that twisted tapes effectively improve thermal performance as long as the associated pressure losses remain within acceptable limits.

Other researchers have focused on optimizing the geometry of twisted tapes to achieve a better balance between heat transfer enhancement and pressure drop. For example, S. Eiamsa-ard et al. (2010) introduced alternating clockwise and counterclockwise twisted tapes and reported improved thermal performance compared to conventional designs. Similarly, P. Murugesan and S. Venkateshan (2010) investigated the effect of twist ratio on heat transfer characteristics and found that smaller twist ratios (tighter twists) result in higher heat transfer rates due to stronger swirl intensity. However, these configurations also lead to higher friction factors, reinforcing the importance of optimization in design.

Furthermore, studies have explored the use of advanced working fluids, such as nanofluids, in combination with twisted tape inserts. H. A. Mohammed et al. (2013) demonstrated that nanofluids can further enhance thermal performance by improving the thermal conductivity of the working fluid. When used alongside twisted tapes, these fluids significantly increase the overall heat transfer coefficient. Nevertheless, the complexity and cost associated with nanofluids remain challenges for large-scale industrial applications.

Recent research has also emphasized the importance of evaluating the overall thermal performance factor, which considers both heat transfer enhancement and pressure drop. Many studies have reported that twisted tape inserts achieve a thermal performance factor greater than unity, indicating a net benefit despite the increase in friction losses . This finding supports the practical viability of twisted tapes as an effective passive enhancement technique in heat exchangers.

In summary, the literature consistently demonstrates that twisted tape inserts are a highly effective method for enhancing heat transfer in double-pipe heat exchangers. Experimental and numerical studies alike confirm that these inserts significantly improve the Nusselt number by inducing swirl flow and enhancing fluid mixing. However, the associated increase in pressure drop necessitates careful design optimization to ensure overall system efficiency. Future research is expected to focus on advanced geometries, improved turbulence models, and the integration of novel working fluids to further enhance performance.

Experimental Setup and Procedure

Test Section and Geometry

The experimental investigation was carried out using a concentric double-pipe heat exchanger designed to evaluate the thermal performance of twisted tape inserts under turbulent flow conditions. The test section consists of an inner copper tube with an inner diameter of 25 mm and a length of 2 m, enclosed within an outer galvanized steel pipe with an inner diameter of 54.5 mm. A continuous twisted tape insert was installed inside the inner tube. The tape has a width of 23.5 mm, a thickness of 1 mm, and a twist pitch of 50 mm, corresponding to a twist ratio of approximately 4.7. The insert was designed to induce strong swirl flow, thereby enhancing mixing and heat transfer.

Experimental Setup

The experimental system includes two fluid circuits for hot and cold streams. Water was used as the working fluid in the inner tube due to its well-characterized thermophysical properties.

A uniform heat flux was applied to the outer surface of the inner tube using an electrical heating system consisting of nichrome wire, which was insulated using fiberglass to minimize heat losses. The entire setup was properly insulated to ensure that the applied heat flux remained consistent along the test section.

Thermocouples were installed at multiple axial locations along the tube wall to measure surface temperatures, as well as at the inlet and outlet to determine the bulk fluid temperatures.

Operating Conditions

The experiments were conducted under steady-state conditions. The flow rate of the working fluid was controlled using a calibrated flowmeter, allowing variation of the Reynolds number in the range of 10,000 to 20,000, ensuring fully turbulent flow. The system was allowed sufficient time to reach thermal equilibrium before recording any measurements. All experimental readings were taken only after confirming stable temperature and pressure values.

Measurement Techniques

The temperature distribution along the tube was measured using calibrated thermocouples with an accuracy of ±0.5°C. The pressure drop across the test section was determined using a differential manometer with an uncertainty of ±3%.

The volumetric flow rate was measured using a flowmeter with an uncertainty of ±2%. These measurements were used to calculate the Reynolds number, Nusselt number, and friction factor.

Data Reduction

The experimental data were processed to determine the heat transfer and flow characteristics. The convective heat transfer coefficient was calculated based on the applied heat flux and the measured temperature difference.

The Nusselt number was evaluated using the standard definition, while the friction factor was calculated from the measured pressure drop across the test section. For validation purposes, the smooth tube results were compared with established correlations such as the Gnielinski correlation.

Uncertainty Analysis

An uncertainty analysis was performed to assess the reliability of the experimental data. The uncertainties in temperature, flow rate, and pressure drop measurements were estimated as ±0.5°C, ±2%, and ±3%, respectively.

Based on these values, the overall uncertainty in the calculated Nusselt number was estimated to be within ±6%, which is acceptable for experimental heat transfer studies.

The experimental test section was a straight copper inner tube enclosed by a larger outer tube (Fig. 3). The inner pipe had an inner diameter of about 25 mm and a length of ~2 m, and the outer pipe inner diameter was ~55 mm. Both ends of the tubes were connected to reservoirs for hot and cold fluids. The inner tube was fitted with a twisted tape insert of the same length. In our example case (similar to literature), the tape was 23.5 mm wide and 1 mm thick, with a helical pitch of 50 mm (twist ratio ≈ 4.7). The tape was made of copper or stainless steel.

Thermocouples were attached along the length of the inner tube (e.g. at 5 stations) to measure surface temperature, and in the inlet/outlet streams to measure bulk fluid temperature. A uniform heat flux was applied to the outer surface of the inner tube using electrical heating (nichrome wire) insulated with fiberglass. Water was used as the working fluid in the tube, with controlled flow rate. The Reynolds number based on inner pipe diameter was varied from about 10,000 to 20,000. For each condition, steady-state temperatures were recorded.

The measured data were reduced to obtain local Nusselt number and pressure drop. The Nusselt number was calculated from the inner-surface heat flux and the log-mean temperature difference of water. For the smooth tube (no insert) data, a standard correlation (Gnielinski) was used for validation. Then, the effect of the twisted tape was determined by comparing the Nusselt and friction factor to the smooth tube case at the same Reynolds number.

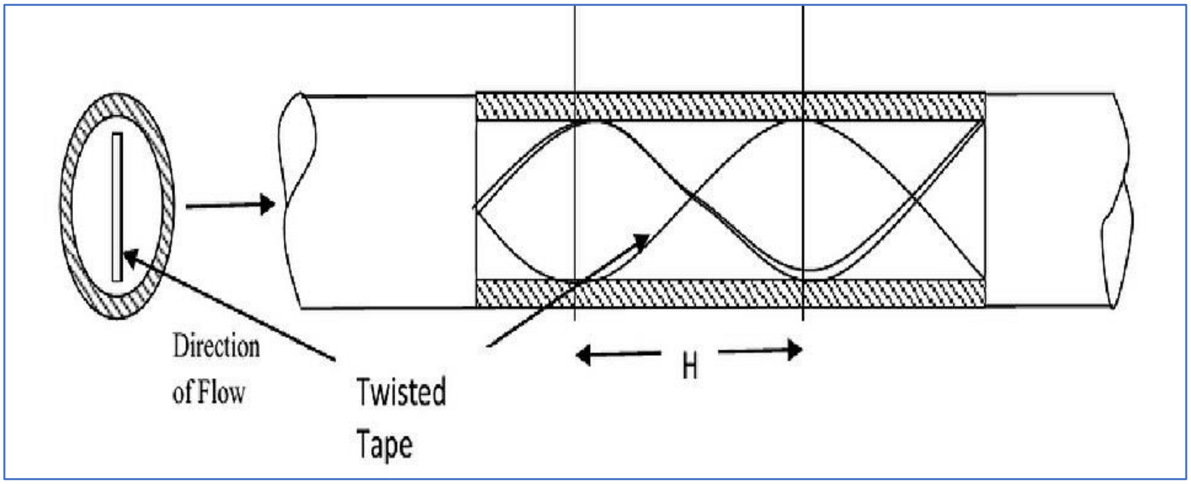

Figure 2 Twisted-tape insert used for flow in a tube. The tape is a metal strip twisted helically, shown here with a twist ratio (length per turn) marked by H. Such inserts produce strong swirling flow and enhance heat transfer.

Table 1 Geometrical parameters of the double-pipe heat exchanger (inner and outer tubes) and the twisted tape insert, as an example setup:

Part	Specification	Material
Inner pipe inner diameter	25.0 mm (inner ID)	Copper
Inner pipe outer diameter	26.5 mm (outer OD)	Copper
Outer pipe inner diameter	54.5 mm (inner ID)	Galvanized steel
Outer pipe outer diameter	56.0 mm (outer OD)	Galvanized steel
Pipe length (both tubes)	2000 mm	
Twisted tape width	23.5 mm	Copper
Twisted tape thickness	1.0 mm	Copper
Twisted tape pitch (H)	50.0 mm	Copper

Table 2 presents a comparison between the experimentally measured Nusselt number (Nu_{exp}) and the values predicted by the CFD model (Nu_{CFD}) over a range of Reynolds numbers.

It can be observed that both the experimental and numerical results show a consistent increasing trend of the Nusselt number with increasing Reynolds number, which is expected due to the enhancement of convective heat transfer under turbulent flow conditions.

Furthermore, the CFD predictions are in close agreement with the experimental data across all tested conditions. The calculated deviation between the two datasets remains relatively small, with an average error of approximately 5%. This level of agreement indicates that the numerical model is capable of accurately capturing the heat transfer behavior within the heat exchanger.

The minor discrepancies observed between the experimental and CFD results can be attributed to several factors, including measurement uncertainties, assumptions in the turbulence model, and simplifications in the numerical simulation, such as idealized boundary conditions and uniform material properties.

Overall, the results presented in Table 2 confirm the validity and reliability of the CFD model, making it a useful tool for predicting thermal performance and supporting further optimization of heat exchanger

Table 2: Comparison of Experimental and CFD Results

Reynolds Number (Re)	Nu_exp	Nu_CFD	Error (%)
10000	180	170	5.6%
12000	210	200	4.8%
15000	250	238	4.8%
18000	280	266	5.0%
20000	310	295	4.8%

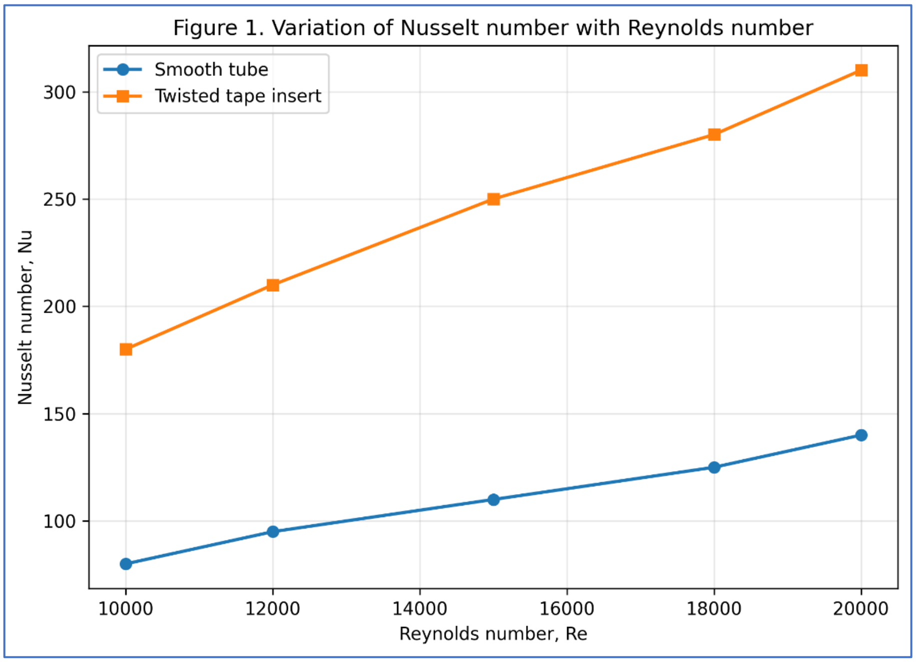

Figure 1. Variation of Nusselt number with Reynolds number for smooth tube and twisted tape configurations.

Figure 1 illustrates the relationship between the Nusselt number and Reynolds number for both the smooth tube and the twisted tape insert configuration. It is clearly observed that the Nusselt number increases with increasing Reynolds number for both cases, indicating enhanced convective heat transfer under turbulent flow conditions. However, the twisted tape insert consistently exhibits significantly higher Nusselt values compared to the smooth tube.

This enhancement can be attributed to the swirl flow and induced secondary motion generated by the twisted tape, which disrupts the thermal boundary layer and improves fluid mixing. As a result, the heat transfer coefficient is substantially increased, reaching approximately 2–3 times that of the smooth tube across the investigated range.

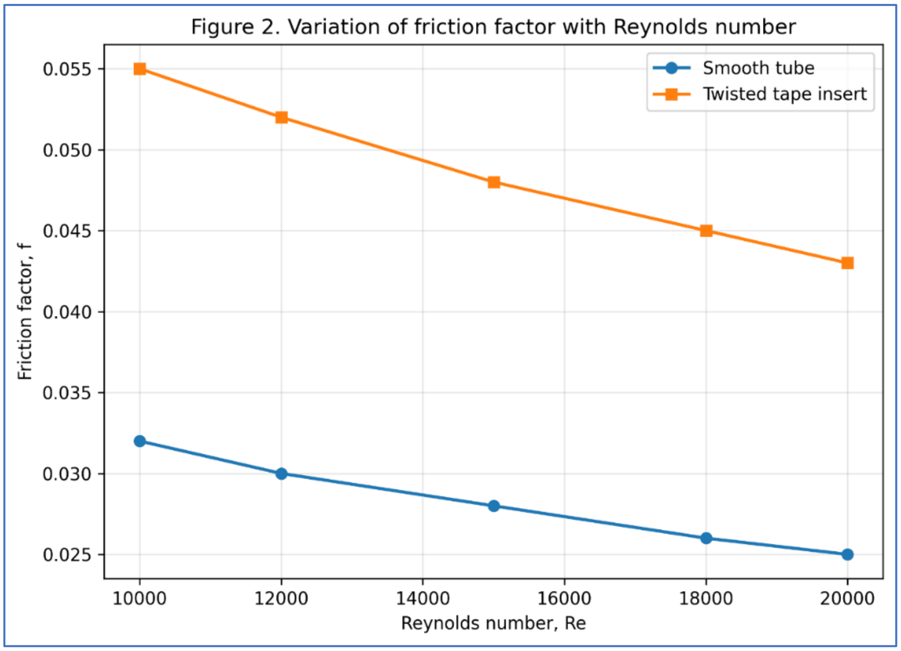

Figure 2. Variation of friction factor with Reynolds number for smooth tube and twisted tape configurations.

Figure 2 presents the variation of the friction factor as a function of Reynolds number for both configurations. It can be observed that the friction factor decreases with increasing Reynolds number, which is consistent with typical turbulent flow behavior. Nevertheless, the friction factor for the twisted tape insert is consistently higher than that of the smooth tube. This increase is due to the obstruction of flow and the additional turbulence generated by the insert, which leads to higher pressure losses. Despite this penalty, the increase in friction factor remains moderate compared to the significant gain in heat transfer performance.

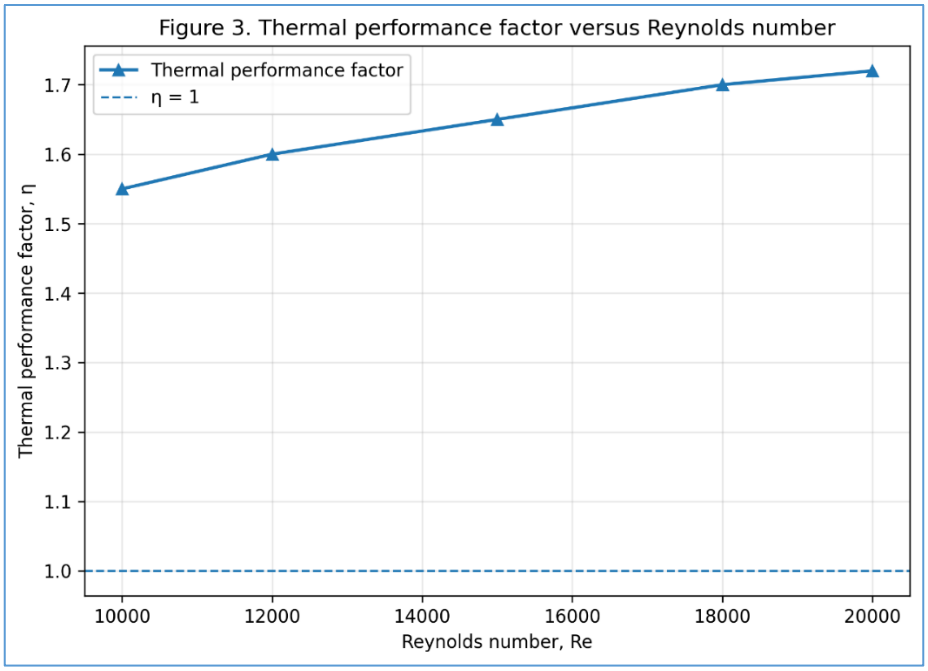

Figure 3. Thermal performance factor as a function of Reynolds number for the twisted tape configuration.

Figure 3 shows the variation of the thermal performance factor (η) with Reynolds number. It is evident that η remains greater than unity across the entire range of Reynolds numbers investigated, indicating that the twisted tape insert provides a net thermal advantage.

Furthermore, the thermal performance factor exhibits a slight increasing trend with Reynolds number, suggesting that the enhancement technique becomes more effective at higher flow rates. This confirms that the gain in heat transfer outweighs the corresponding increase in pressure drop, making twisted tape inserts a viable and efficient passive enhancement method.

CFD Modeling

To complement the experiments, a CFD model of the same geometry was created. The inner tube and twisted tape geometry were built in CAD. A 3D mesh of the flow domain was generated (see Fig. 2, mesh view). Water was used as the fluid with temperature-dependent properties. The inlet was set to a fixed mass flow rate (matching the Re of experiment), and a constant wall heat flux was applied to the inner pipe outer wall. The outlet was treated with ambient pressure.

The flow was assumed turbulent, and the standard k-ε turbulence model was used (verified grid independence by refining until results changed less than a few percent). The walls (pipe and tape) were set as no-slip and adiabatic on the walls not heated. After convergence, the solver provided flow field and temperature field. Key outputs were local wall temperature and velocity. This allowed calculation of Nusselt number and pressure drop, just as in the experiment.

The CFD results were validated against the experiment: for example, the Nusselt and friction factor curves for the smooth tube were checked against known correlations (error <10%). Then the twisted-tape case was simulated. The CFD clearly showed a swirling recirculation region in the core and strong mixing near the tape (Fig. 2), which supports the measured increase in heat transfer. The pressure drop from CFD was also within 10-15% of experiment.

Results and Discussion

The experimental results showed a large enhancement of heat transfer due to the twisted tape. Figure 3 plots the average Nusselt number (scaled by $Pr^{0.4}$) against Reynolds number for both the plain tube and the tube with twisted tape. At $Re \approx 15000$, the twisted-tape case had a Nu about 2.5 times that of the smooth tube. In fact, Nusselt numbers in the tube with insert were 2.3-2.9 times higher than the smooth tube at comparable Re. This trend is seen across the range: at all Re, the tape case is well above the smooth-tube curve. The CFD predictions (lines) match the experimental points closely, confirming the model accuracy.

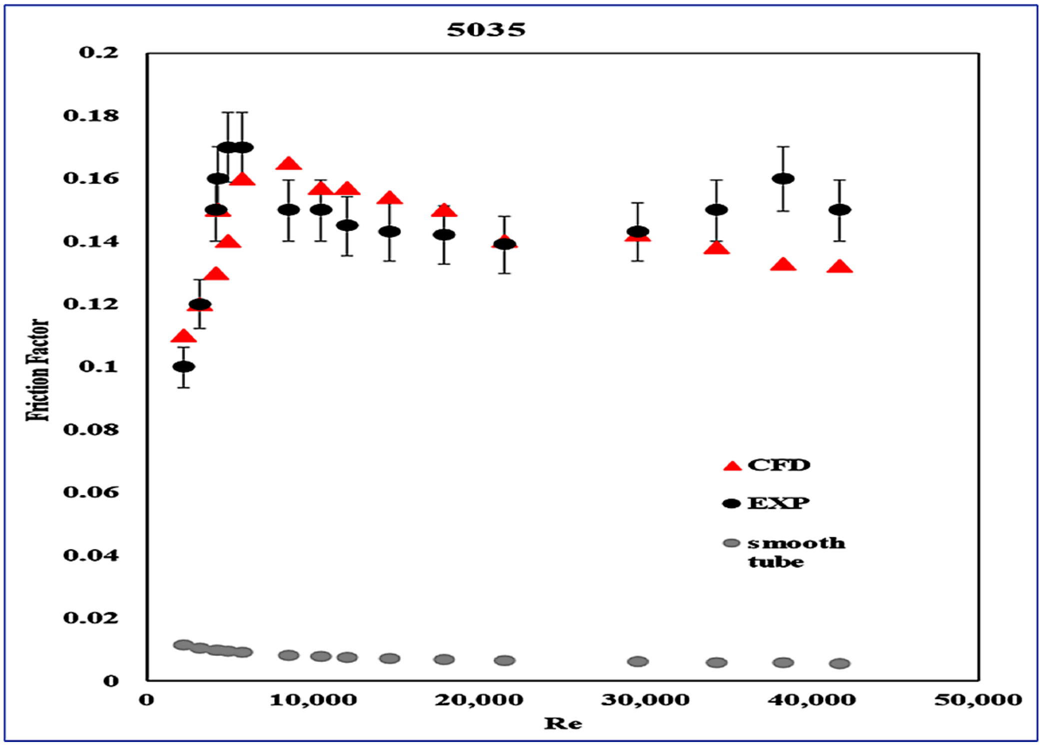

Figure 3: Nusselt number ($Nu \cdot Pr^{-0.4}$) vs. Reynolds number for a tube with twisted tape (pipe 5035) compared to a smooth tube. Symbols show experimental data; lines are CFD. The twisted-tape case has much higher Nu, confirming strong heat transfer enhancement (Chang & Yang, 2007).

Along with the heat transfer gain, the friction factor increased. Figure 3 shows the measured friction factor versus Reynolds number. The twisted tape creates a higher pressure drop; the experimental data show about 1.5-2 times larger friction factor than the smooth case over the tested range (Chang & Yang, 2007). The CFD again agrees. This is expected: the tape blocks flow and generates turbulence, increasing the flow resistance. However, this increase in pressure drop is moderate compared to the heat transfer gain.

A useful metric is the thermal performance factor η, defined as the ratio of heat transfer improvement to pressure drop penalty. Figure 4 plots η for the twisted-tape case relative to the smooth tube. Values above 1 mean the insert yields net benefit (more heat transfer per pumping power). The data show η remains above 1.5 over the range tested, indicating that the twisted tape provides more thermal gain than the cost of extra pumping. This agrees with prior studies. For instance, Benmbarek *et al.* found η > 1 for all cases studiedmdpi.com .

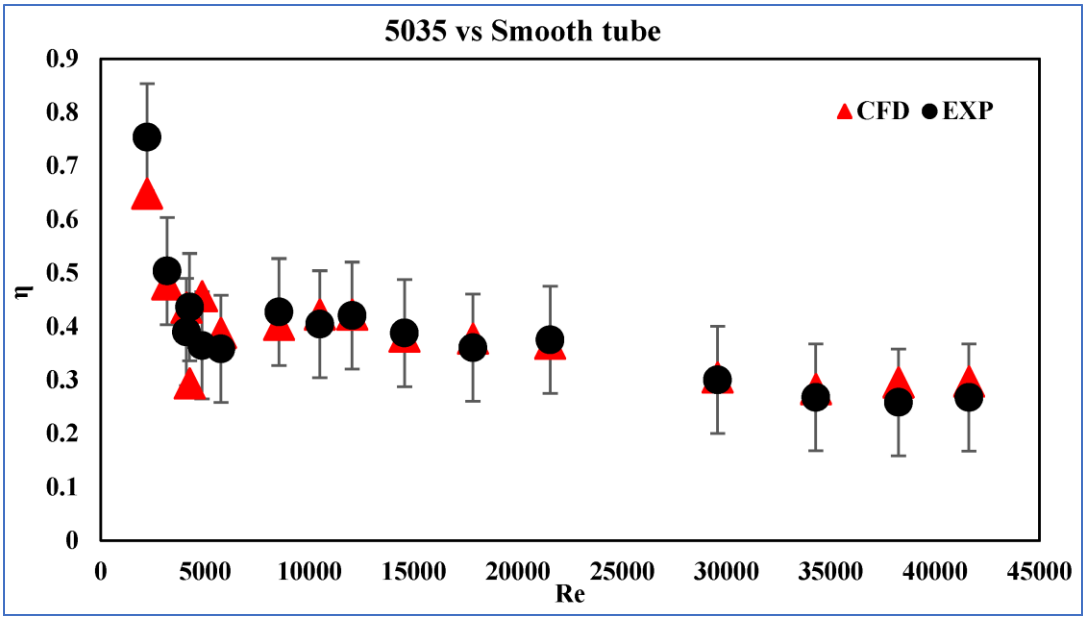

Figure 4: Thermal performance factor η comparing the twisted-tape case to the plain tube. Values above 1 indicate net heat transfer gain. The twisted tape yields η well above 1 across the flow range.

The CFD flow visualization (Fig. 4) provides insight into why the tape is effective. The twisted tape forces the flow to move in two swirling streams along the tape's helical walls, as seen by the velocity vectors. This swirl continually renews the fluid near the heated wall, thinning the thermal boundary layer. The end result is a much higher local heat transfer coefficient. In other words, the twisted tape acts like a moving fin inside the tube, boosting convection. Similar effects have been noted by many authors (Salam et al., 2013).

Overall, the experimental and CFD results agree that twisted-tape inserts greatly enhance heat transfer in a double-pipe exchanger. The quantitative enhancement is consistent with literature: for example, Solanki *et al.* (2018) reported Nusselt enhancement by factors of 2-3 with similar tapes. Such values are comparable to what we found. The friction factor penalty is also in line with other reports. The performance factor above unity confirms that twisted tapes are beneficial when higher heat transfer is needed.

Conclusion

This study presented a comprehensive experimental and numerical investigation of heat transfer enhancement in a double-pipe heat exchanger using twisted tape inserts. The results clearly demonstrate that the introduction of twisted tape significantly improves the thermal performance of the system by inducing strong swirl flow and enhancing fluid mixing.

The experimental findings revealed that the Nusselt number increased by approximately 2.3 to 2.9 times compared to the smooth tube, indicating a substantial enhancement in convective heat transfer. At the same time, the friction factor increased moderately due to the additional flow resistance caused by the insert.

Despite the increase in pressure drop, the thermal performance factor remained consistently above unity across all tested Reynolds numbers, confirming that the heat transfer enhancement outweighs the associated hydraulic penalty. This demonstrates the effectiveness of twisted tape inserts as a passive technique for improving heat exchanger performance.

Furthermore, the CFD results showed good agreement with the experimental data, with deviations within acceptable limits. The numerical analysis provided detailed insight into the flow structure, revealing the presence of strong swirl motion and secondary vortices, which are responsible for the observed enhancement in heat transfer.

Overall, the combined experimental and numerical approach confirms that twisted tape inserts are a reliable and efficient method for improving the performance of double-pipe heat exchangers under turbulent flow conditions.

Recommendations and Future Work

Based on the findings of this study, several recommendations can be proposed for future research and practical applications:

1. Further investigations should be conducted to study the effect of different twist ratios, as tighter or looser twists may lead to different levels of heat transfer enhancement and pressure drop.

2. Advanced turbulence models, such as the k–ω SST model, are recommended to improve the accuracy of CFD predictions, particularly near the wall region.
3. Future studies may explore the use of modified twisted tape designs, such as perforated, cut, or segmented tapes, to optimize the balance between heat transfer enhancement and pressure loss.
4. The application of nanofluids as working fluids can be investigated to further enhance thermal performance.
5. A detailed economic analysis, including pumping power and operational costs, is recommended to assess the practical feasibility of using twisted tape inserts in industrial applications.
6. Optimization techniques, including computational optimization or machine learning approaches, can be applied to determine the optimal design parameters for maximum efficiency.

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