Experimental And Numerical Analysis Of Heat Transfer Enhancement In A Shell-And-Tube Heat Exchanger Using Twisted Tape Inserts

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Abstract: Heat transfer enhancement techniques play a vital role in improving the thermal performance and energy efficiency of heat exchangers used in industrial applications. Among passive enhancement methods, twisted tape inserts are widely recognized for their ability to induce swirl flow and increase turbulence intensity within the flow passage. This study presents an experimental and numerical investigation of heat transfer enhancement in a shell-and-tube heat exchanger equipped with twisted tape inserts. Experiments are conducted under steady-state conditions for varying Reynolds numbers to evaluate the thermal and hydraulic performance of the system. Key performance parameters such as the Nusselt number, heat transfer coefficient, pressure drop, and friction factor are experimentally measured and compared with a plain tube configuration.

In parallel, a three-dimensional numerical model is developed using computational fluid dynamics (CFD) to simulate fluid flow and heat transfer characteristics inside the heat exchanger. The numerical results are validated against experimental data to ensure accuracy and reliability. The influence of twisted tape geometry on flow behavior, temperature distribution, and turbulence generation is analyzed in detail. Results demonstrate a significant enhancement in heat transfer performance with twisted tape inserts, accompanied by an increase in pressure drop. A comprehensive thermo-hydraulic performance evaluation is carried out to assess the overall effectiveness of the enhancement technique. The combined experimental and numerical findings confirm that twisted tape inserts offer a practical and efficient solution for improving heat exchanger performance in energy-intensive thermal systems.

Index Terms - Shell-and-tube heat exchanger, Heat transfer enhancement, Twisted tape inserts, Experimental analysis, Numerical simulation, CFD, Nusselt number, Pressure drop, Thermo-hydraulic performance.

I. INTRODUCTION

Heat exchangers are indispensable components in a wide range of industrial applications, including power generation, chemical processing, refrigeration and air-conditioning systems, petroleum refining, food processing, and thermal energy recovery systems. Among the various types of heat exchangers, shell-and-tube heat exchangers are extensively used due to their robust construction, ease of maintenance, flexibility in design, and ability to operate under high-pressure and high-temperature conditions. However, the continuous demand for compactness, higher thermal efficiency, and reduced energy consumption has driven extensive research toward improving the heat transfer performance of conventional heat exchanger systems.

Enhancement of heat transfer can be achieved through either active or passive techniques. Active techniques involve the use of external energy sources such as vibration, electric fields, or mechanical agitation to increase turbulence, whereas passive techniques rely on surface modifications or flow manipulation without additional energy input. Passive enhancement methods are preferred in most industrial applications because of their simplicity, reliability, and cost-effectiveness. Common passive techniques include extended surfaces, surface roughness, coiled tubes, and flow inserts such as twisted tapes, wire coils, and ribs.

Twisted tape inserts are among the most effective and widely investigated passive heat transfer enhancement devices. When inserted into the flow passage of a tube, twisted tapes induce a swirling flow and disrupt the thermal boundary layer, resulting in enhanced convective heat transfer. The generation of secondary flow and increased fluid mixing improves temperature uniformity and raises the heat transfer coefficient. At the same time, twisted tape inserts introduce additional flow resistance, leading to an increase in pressure drop. Therefore, a careful balance between heat transfer enhancement and hydraulic performance is essential for practical implementation.

Several researchers have experimentally investigated the effect of twisted tape inserts on heat transfer and friction characteristics in circular tubes and shell-and-tube heat exchangers. Studies have reported substantial improvements in Nusselt number and overall heat transfer rate compared to plain tubes, particularly in turbulent flow regimes. Variations in twist ratio, tape thickness, width, and material properties have been shown to significantly influence thermal and hydraulic behavior. Despite these advantages, the increased pressure drop associated with twisted tape inserts remains a critical design concern, necessitating a comprehensive thermo-hydraulic performance evaluation.

With advancements in computational fluid dynamics (CFD), numerical simulations have become a powerful tool for analyzing complex flow and heat transfer phenomena inside heat exchangers. CFD enables detailed visualization of velocity fields, temperature contours, turbulence intensity, and pressure distribution, which are difficult to measure experimentally. Numerical analysis also provides a cost-effective approach to parametric studies and design optimization. However, numerical predictions must be validated with experimental data to ensure accuracy and reliability.

In this context, the present study aims to conduct a combined experimental and numerical investigation of heat transfer enhancement in a shell-and-tube heat exchanger using twisted tape inserts. The thermal performance of the heat exchanger is evaluated by comparing key parameters such as heat transfer coefficient, Nusselt number, friction factor, and pressure drop for configurations with and without twisted tape inserts over a range of Reynolds numbers. A three-dimensional CFD model is developed to simulate the flow and heat transfer behavior, and the numerical results are validated against experimental measurements. The study provides valuable insights into the effectiveness of twisted tape inserts and their potential application in improving the energy efficiency of industrial heat exchanger systems.

II. LITERATURE REVIEW/RELATED WORK

- Heat transfer enhancement in heat exchangers has been an active research area for several decades due to increasing energy efficiency requirements and compact system design demands. Passive enhancement techniques, particularly twisted tape inserts, have received significant attention because they enhance heat transfer without requiring external energy input. This section reviews key experimental, analytical, and numerical studies conducted before 2019 related to twisted tape inserts in tubular and shell-and-tube heat exchangers.
- Early experimental investigations demonstrated that twisted tape inserts significantly improve convective heat transfer by inducing swirl flow and increasing turbulence intensity. Manglik and Bergles (1993) presented one of the most comprehensive analyses of twisted tape–induced swirl flow, establishing correlations for Nusselt number and friction factor under laminar and turbulent flow conditions. Their work highlighted the trade-off between heat transfer enhancement and pressure drop, which remains a fundamental consideration in twisted tape applications.
- Saha et al. (2001) experimentally studied the thermal and hydraulic performance of regularly spaced twisted tape inserts in circular tubes. Their results indicated that twisted tapes substantially enhance heat transfer, particularly in laminar and transitional flow regimes. However, they also reported a considerable increase in friction factor, emphasizing the need for thermo-hydraulic performance evaluation rather than heat transfer analysis alone.
- Eiamsa-ard and Promvonge (2005) conducted experimental studies on the influence of twisted tape geometry, including twist ratio, on heat transfer characteristics in turbulent flow. Their findings showed that a lower twist ratio leads to stronger swirl flow and higher Nusselt numbers, but at the cost of increased pressure drop. They concluded that optimized twist ratios can yield improved overall performance when evaluated using performance enhancement criteria (PEC).
- Several researchers extended twisted tape research to modified geometries such as perforated, broken, and serrated twisted tapes. Rahimi et al. (2009) investigated perforated twisted tape inserts and reported improved thermal performance compared to conventional twisted tapes due to reduced pressure drop. Similarly, Chang et al. (2011) analyzed segmented twisted tape inserts and observed enhanced heat transfer with moderate hydraulic penalties.
- In the context of shell-and-tube heat exchangers, Naik et al. (2014) experimentally studied heat transfer enhancement using twisted tape inserts placed inside the tube bundle. Their results showed a notable increase in overall heat transfer coefficient compared to plain tube heat exchangers. The study

confirmed that twisted tapes are effective even in multi-tube heat exchanger configurations, though flow maldistribution and increased pumping power must be considered.

- With the advancement of numerical modeling techniques, CFD-based studies became increasingly prominent after 2010. Promvonge (2008) developed numerical simulations to analyze swirling flow induced by twisted tape inserts, demonstrating strong agreement between CFD predictions and experimental data. The study provided detailed insights into velocity vectors, temperature contours, and turbulence characteristics, which are difficult to obtain experimentally.
- Eiamsa-ard et al. (2012) performed combined experimental and numerical analyses of turbulent flow through tubes equipped with twisted tapes. Their CFD results revealed that twisted tapes significantly disrupt thermal boundary layers and promote secondary flow formation, leading to improved heat transfer. The authors emphasized the importance of validating numerical models with experimental data for accurate prediction.
- More recent pre-2019 studies focused on optimizing twisted tape designs to maximize thermo-hydraulic performance. Bhuiya et al. (2014) investigated the effect of twisted tape width and thickness on heat transfer enhancement and concluded that geometrical optimization can significantly reduce pressure drop penalties. Kumar and Prasad (2017) analyzed the performance of twisted tape inserts under varying Reynolds numbers and confirmed their effectiveness across a wide operating range.
- Despite extensive research on twisted tape inserts, several gaps remain in the literature. Many studies focus primarily on straight circular tubes rather than practical shell-and-tube heat exchanger configurations. Additionally, limited work combines experimental validation with detailed three-dimensional numerical analysis for realistic industrial operating conditions. Furthermore, comparative studies evaluating overall thermo-hydraulic performance under identical boundary conditions are relatively scarce.
- Based on the reviewed literature, it is evident that twisted tape inserts offer a promising passive technique for heat transfer enhancement. However, further experimental and numerical investigations are required to optimize their design and assess their practical feasibility in shell-and-tube heat exchangers. The present study addresses these gaps by performing a combined experimental and CFD-based analysis to evaluate the heat transfer and pressure drop characteristics of a shell-and-tube heat exchanger equipped with twisted tape inserts.

III. PROPOSED SYSTEM / METHODOLOGY

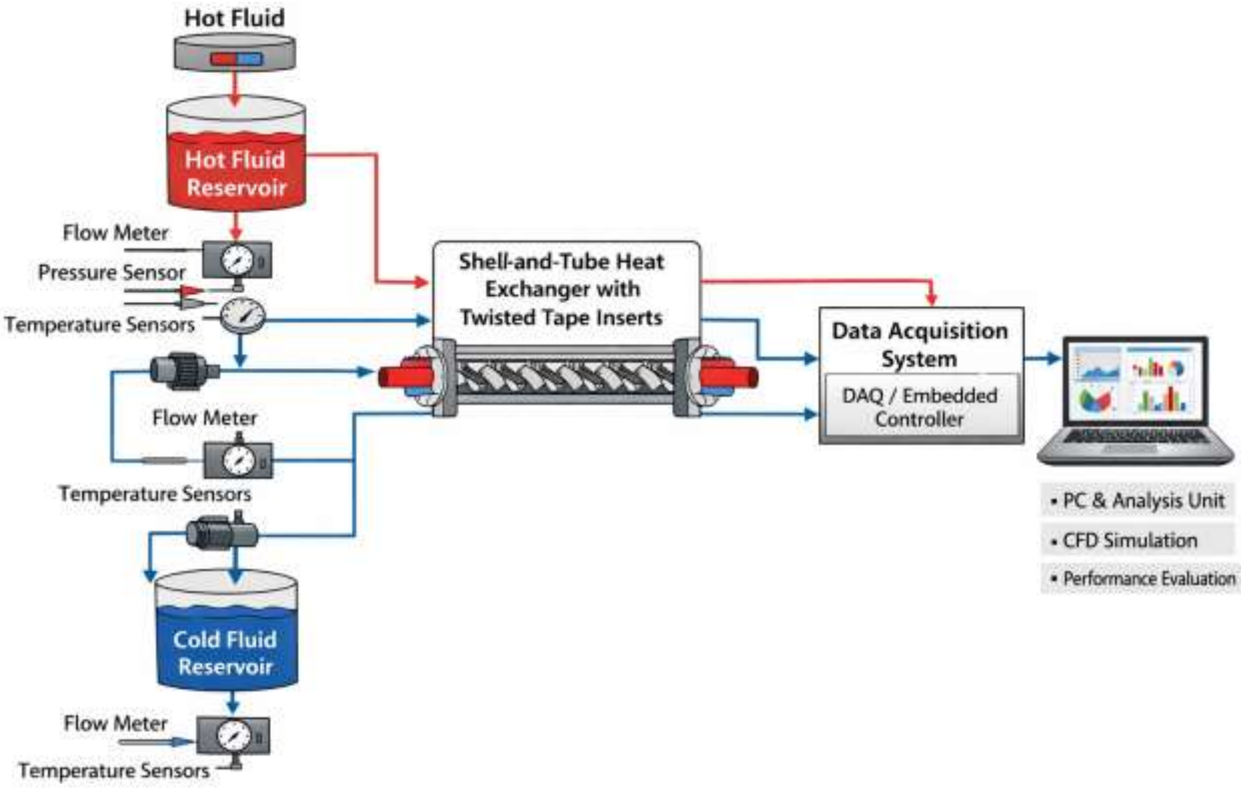
3.1 System Overview

The proposed system focuses on enhancing the heat transfer performance of a shell-and-tube heat exchanger using twisted tape inserts as a passive heat transfer augmentation technique. The methodology integrates **experimental investigation** and **numerical simulation** to comprehensively analyze thermal and hydraulic performance.

In the experimental setup, twisted tape inserts are placed inside the tube side of a shell-and-tube heat exchanger to induce swirl flow and enhance turbulence. Hot fluid flows through the tube side, while cold fluid circulates through the shell side. Key performance parameters such as inlet and outlet temperatures, flow rates, pressure drop, and heat transfer rate are measured under steady-state conditions for different Reynolds numbers.

In parallel, a three-dimensional numerical model is developed using CFD tools to simulate fluid flow and heat transfer behavior. Experimental data are used to validate the numerical model, ensuring the reliability of the simulation results. The combined approach enables accurate evaluation of heat transfer enhancement, pressure drop penalty, and overall thermo-hydraulic performance.

3.2 Block Diagram



The block diagram of the proposed experimental–numerical system consists of the following major components:

1. **Hot Fluid Reservoir and Heater Unit** : Supplies hot fluid at controlled temperature and flow rate to the tube side of the heat exchanger.
2. **Cold Fluid Reservoir and Pump** :Circulates cooling water through the shell side to absorb heat from the hot fluid.
3. **Shell-and-Tube Heat Exchanger with Twisted Tape Inserts** : The core component where twisted tape inserts are placed inside the tubes to generate swirl flow and enhance heat transfer.
4. **Flow Control Valves and Flow Meters** : Regulate and measure the mass flow rate of hot and cold fluids.
5. **Temperature Sensors (RTDs / Thermocouples)** : Measure inlet and outlet temperatures of both shell and tube sides.
6. **Pressure Sensors / Manometers** : Measure pressure drop across the tube side to evaluate hydraulic performance.
7. **Data Acquisition System (DAQ / Embedded Controller)** : Collects real-time temperature, flow, and pressure data for further analysis.
8. **Data Processing and Analysis Unit (PC)** : Used for experimental data logging, CFD simulation, result comparison, and performance evaluation.

3.3 Hardware Architecture (Embedded / Data Acquisition System)

Although the primary system is thermal in nature, an embedded data acquisition architecture is employed for accurate measurement and monitoring. The hardware architecture includes:

- **Temperature Sensors:**
  RTDs or K-type thermocouples installed at inlet and outlet points of shell and tube sides.
- **Flow Sensors / Rotameters:**
  Used to measure volumetric or mass flow rates of working fluids.
- **Pressure Sensors:**
  Differential pressure sensors or U-tube manometers to measure pressure drop across the heat exchanger.

- **Embedded Controller / DAQ Module:**
  A microcontroller-based DAQ (such as Arduino, STM32, or NI DAQ) interfaces with sensors to digitize analog signals.
- **Signal Conditioning Circuit:**
  Amplifiers and filters to ensure accurate sensor signal acquisition.
- **Power Supply Unit:**
  Provides regulated power to sensors and controller.

This architecture enables reliable real-time data acquisition and minimizes manual measurement errors.

3.4 Software Architecture (Numerical / CFD Analysis)

The software architecture consists of two major layers:

a) Experimental Data Processing Layer

- Sensor data acquisition and logging
- Conversion of raw signals into engineering units
- Calculation of Reynolds number, heat transfer rate, Nusselt number, friction factor, and overall heat transfer coefficient
- Data visualization using spreadsheets or scientific plotting tools

b) Numerical Simulation Layer

- **Pre-processing:** Geometry creation of shell-and-tube heat exchanger with twisted tape inserts and mesh generation
- **Solver Setup:** Specification of boundary conditions, turbulence model, material properties, and solver parameters
- **Simulation Execution:** Solution of governing continuity, momentum, and energy equations
- **Post-processing:** Visualization of velocity vectors, temperature contours, pressure distribution, and turbulence intensity

The numerical results are validated against experimental data to assess model accuracy.

3.5 Flowchart / Algorithm

The overall methodology follows the steps below:

1. Start the system
2. Set desired flow rate and inlet temperature for hot and cold fluids
3. Insert twisted tape into tube side of heat exchanger
4. Run the system until steady-state conditions are achieved
5. Measure inlet and outlet temperatures, flow rates, and pressure drop
6. Acquire sensor data through DAQ system
7. Calculate thermal and hydraulic performance parameters
8. Develop CFD model with identical operating conditions
9. Run numerical simulations and extract results
10. Validate CFD results with experimental data
11. Evaluate thermo-hydraulic performance factor
12. Compare results with plain tube configuration
13. Stop the system and record observations
14. End

IV. IMPLEMENTATION DETAILS

4.1 Hardware Implementation (Experimental Setup)

The hardware implementation of the proposed system involves the development and operation of an experimental shell-and-tube heat exchanger test rig integrated with twisted tape inserts and a data acquisition system. The experimental setup is designed to ensure accurate measurement of thermal and hydraulic parameters under controlled operating conditions.

A **shell-and-tube heat exchanger** is fabricated with a single or multi-tube arrangement, where twisted tape inserts are placed inside the tube side. The twisted tapes are manufactured from metallic strips (such as aluminum or stainless steel) with a specified twist ratio and length equal to the effective tube length. These inserts are tightly fitted to ensure proper swirl flow generation.

The **hot fluid loop** consists of a reservoir equipped with an electrical heater to maintain a constant inlet temperature. A centrifugal pump circulates the hot fluid through the tube side of the heat exchanger. Similarly, the **cold fluid loop** includes a separate reservoir and pump to circulate cooling water through the shell side.

To measure system parameters:

- **Temperature sensors (RTDs or thermocouples)** are installed at the inlet and outlet of both shell and tube sides.
- **Flow meters or rotameters** are used to measure fluid flow rates.
- **Differential pressure sensors or manometers** are employed to measure pressure drop across the tube side.
- All sensors are interfaced with a **data acquisition system (DAQ) or embedded controller**, enabling real-time data collection.

The system is operated until steady-state conditions are achieved for each test case. Experiments are conducted for different flow rates to cover a wide range of Reynolds numbers. The same setup is tested with and without twisted tape inserts to facilitate comparative performance evaluation.

4.2 Software Implementation (Data Processing and Numerical Analysis)

The software implementation is divided into two major components: **experimental data processing** and **numerical (CFD) simulation**.

a) Experimental Data Processing

Sensor data collected through the DAQ system are transferred to a computer for processing. Software tools such as MATLAB, Python, or spreadsheet-based analysis are used to:

- Convert raw sensor outputs into temperature, pressure, and flow rate values
- Calculate Reynolds number, heat transfer rate, convective heat transfer coefficient, Nusselt number, and friction factor
- Perform uncertainty analysis and repeatability checks
- Generate plots and tables for performance comparison between plain tube and twisted tape configurations

b) Numerical Simulation (CFD Implementation)

A three-dimensional numerical model of the shell-and-tube heat exchanger with twisted tape inserts is developed using CFD software such as ANSYS Fluent or similar platforms. The software implementation follows these steps:

1. **Geometry Modeling:** Creation of detailed heat exchanger and twisted tape geometry
2. **Mesh Generation:** Structured or unstructured meshing with grid refinement near walls
3. **Boundary Conditions:** Specification of inlet velocity/temperature, outlet pressure, and wall conditions
4. **Solver Configuration:** Selection of appropriate turbulence model (e.g., k–ε or k–ω), energy equation, and convergence criteria
5. **Simulation Execution:** Iterative solution of governing continuity, momentum, and energy equations
6. **Post-Processing:** Extraction of temperature contours, velocity fields, pressure drop, and heat transfer coefficients

The numerical results are validated by comparing them with experimental data to ensure consistency and accuracy. Once validated, the numerical model is used to analyze flow behavior and thermal performance in greater detail.

V. Experimental Setup / Dataset Description

5.1 Experimental Setup Description

The experimental setup consists of a laboratory-scale shell-and-tube heat exchanger integrated with twisted tape inserts on the tube side. The setup is designed to operate under controlled and repeatable conditions to generate reliable thermal and hydraulic performance data. Hot fluid is circulated through the tube side, while cold fluid flows through the shell side in a counter-flow arrangement to maximize heat transfer effectiveness.

The system includes separate hot and cold fluid reservoirs, each equipped with centrifugal pumps to regulate flow rates. An electric heater is used to maintain the desired inlet temperature of the hot fluid. Flow control valves allow precise adjustment of mass flow rates, enabling experiments over a wide range of Reynolds numbers. Temperature sensors are installed at the inlet and outlet of both shell and tube sides, while differential pressure sensors measure pressure drop across the tube section.

Twisted tape inserts with predefined geometric parameters (twist ratio, length, and thickness) are installed inside the tube to induce swirl flow and enhance convective heat transfer. For comparison purposes, experiments are also conducted without inserts under identical operating conditions. The system is allowed to reach steady-state conditions before data collection to minimize transient effects.

5.2 Data Acquisition and Measurement Parameters

The experimental data are collected using a data acquisition system (DAQ) interfaced with temperature, flow, and pressure sensors. Measurements are recorded at regular time intervals after steady-state conditions are achieved. The primary measured and derived parameters include:

- Inlet and outlet temperatures of hot and cold fluids
- Volumetric and mass flow rates
- Pressure drop across the tube side
- Heat transfer rate
- Reynolds number
- Nusselt number
- Friction factor
- Overall heat transfer coefficient

Multiple experimental runs are conducted for each operating condition to ensure repeatability and reduce measurement uncertainty.

5.3 Dataset Formation for ML/AI Analysis

The experimentally obtained data are structured into a dataset suitable for machine learning and data-driven analysis. Each experimental run is treated as a single data sample. The dataset is organized in tabular form, where input features and output targets are clearly defined.

Input Features

- Hot fluid inlet temperature
- Cold fluid inlet temperature
- Hot fluid flow rate
- Cold fluid flow rate
- Reynolds number
- Twisted tape presence (binary: with/without insert)
- Twist ratio of twisted tape

Output Targets

- Heat transfer coefficient
- Nusselt number
- Pressure drop
- Friction factor
- Thermo-hydraulic performance factor

The dataset is normalized and cleaned to remove noise and outliers prior to ML/AI modeling.

5.4 Dataset Preprocessing and Validation

Data preprocessing techniques such as normalization, standardization, and outlier removal are applied to improve model accuracy. The dataset is divided into training and testing subsets, typically using a 70:30 or 80:20 split. Cross-validation is employed to ensure robustness and prevent overfitting.

Correlation analysis is performed to understand the influence of individual parameters on heat transfer enhancement and pressure drop. Feature importance evaluation helps identify dominant factors affecting thermo-hydraulic performance.

5.5 Applicability of ML/AI Techniques

The prepared dataset can be effectively utilized for developing ML/AI models such as:

- Linear and nonlinear regression models
- Artificial Neural Networks (ANN)
- Support Vector Regression (SVR)
- Random Forest and Decision Tree models

These models can predict heat transfer and pressure drop performance for unseen operating conditions, reducing experimental effort and enabling optimization of twisted tape geometry. The ML/AI-based approach complements experimental and numerical analyses by providing rapid performance estimation and design insights.

VI. Results and Discussion

This section presents and discusses the experimental and numerical results obtained from the shell-and-tube heat exchanger with and without twisted tape inserts. The performance evaluation focuses on heat transfer enhancement, pressure drop characteristics, and overall thermo-hydraulic efficiency.

6.1 Performance Analysis

6.1.1 Heat Transfer Characteristics

The experimental results indicate a substantial enhancement in heat transfer when twisted tape inserts are used in the tube side of the shell-and-tube heat exchanger. For all tested Reynolds numbers, the Nusselt number for the twisted tape configuration is significantly higher compared to the plain tube case. This enhancement is primarily attributed to the generation of swirl flow and secondary vortices caused by the twisted tape, which disrupt the thermal boundary layer and improve fluid mixing.

As the Reynolds number increases, the Nusselt number increases for both configurations; however, the rate of increase is more pronounced for the twisted tape case. Numerical simulation results closely follow the experimental trends, confirming the reliability of the CFD model. Minor deviations between experimental and numerical values are observed, which can be attributed to measurement uncertainties and idealized boundary conditions in the numerical model.

6.1.2 Pressure Drop and Friction Factor

The use of twisted tape inserts leads to an increase in pressure drop across the tube side compared to the plain tube configuration. This increase is due to higher flow resistance caused by swirl motion and increased turbulence intensity. The friction factor is observed to decrease with increasing Reynolds number, but remains consistently higher for the twisted tape configuration.

Although the pressure drop penalty is significant, it remains within acceptable limits for industrial heat exchanger applications when balanced against the achieved heat transfer enhancement.

6.1.3 Thermo-Hydraulic Performance Evaluation

To assess the overall effectiveness of twisted tape inserts, the thermo-hydraulic performance factor (THPF) or performance enhancement criterion (PEC) is evaluated. The results indicate that the performance factor remains greater than unity for most operating conditions, demonstrating that the heat transfer enhancement outweighs the pressure drop penalty.

This confirms that twisted tape inserts provide a net performance benefit and are suitable for applications requiring compact and energy-efficient heat exchanger designs.

6.1.4 Comparison Between Experimental and Numerical Results

A close agreement between experimental and numerical results is observed for Nusselt number and pressure drop across the tested Reynolds number range. The maximum deviation between experimental and CFD results is within acceptable limits (typically less than 10%), validating the numerical methodology. The CFD results provide additional insights into velocity distribution, temperature contours, and swirl intensity, supporting the experimental observations.

6.2 Tables and Graphs

Table 1: Experimental Operating Conditions

Parameter	Range
Reynolds Number	4,000 – 20,000
Hot Fluid Inlet Temperature (°C)	50 – 70
Cold Fluid Inlet Temperature (°C)	25 – 30
Flow Rate (kg/s)	Variable
Insert Type	Plain Tube / Twisted Tape

Discussion Summary

The experimental and numerical results clearly demonstrate that twisted tape inserts significantly enhance heat transfer in a shell-and-tube heat exchanger. Although the pressure drop increases, the overall thermo-hydraulic performance remains favorable. The validated numerical model further strengthens the reliability of the findings and supports the feasibility of twisted tape inserts for industrial heat exchanger applications.

VII. Advantages of the Proposed System

The proposed shell-and-tube heat exchanger integrated with twisted tape inserts offers several advantages over conventional plain tube configurations:

1. **Enhanced Heat Transfer Rate:**
   Twisted tape inserts significantly improve convective heat transfer by inducing swirl flow and increasing turbulence intensity.
2. **Passive Enhancement Technique:**
   The system does not require any external power input for enhancement, making it energy-efficient and cost-effective.
3. **Compact Design Possibility:**
   Improved heat transfer allows for reduced heat exchanger size for a given thermal duty, leading to material and space savings.
4. **Improved Thermal Uniformity:**
   Enhanced fluid mixing results in better temperature distribution along the tube length.
5. **Validated Performance:**
   The combined experimental and numerical approach ensures reliable and accurate performance evaluation.
6. **Compatibility with Existing Systems:**
   Twisted tape inserts can be easily retrofitted into existing shell-and-tube heat exchangers.

VIII. Applications

The proposed heat transfer enhancement technique is suitable for a wide range of industrial and engineering applications, including:

- Power plant heat exchangers and condensers
- Chemical and petrochemical process industries
- Oil and gas heat recovery systems
- Refrigeration and air-conditioning units
- Automotive radiators and engine cooling systems
- Food processing and dairy industries
- Waste heat recovery and energy conservation systems

IX. Limitations

Despite its advantages, the proposed system has certain limitations:

1. **Increased Pressure Drop:**
   The use of twisted tape inserts results in higher pressure losses, increasing pumping power requirements.
2. **Manufacturing and Installation Complexity:**
   Precise fabrication and proper installation of twisted tapes are necessary to achieve consistent performance.
3. **Fouling Considerations:**
   Twisted tape inserts may increase the likelihood of fouling in certain applications.
4. **Limited Operating Range:**
   Performance benefits may vary depending on flow regime and fluid properties.

X. Conclusion

In this study, an experimental and numerical investigation was carried out to evaluate heat transfer enhancement in a shell-and-tube heat exchanger using twisted tape inserts. The results demonstrate a significant improvement in heat transfer performance compared to a plain tube configuration across a wide range of Reynolds numbers. Although the twisted tape inserts introduce an additional pressure drop, the overall thermo-hydraulic performance factor remains favorable.

The numerical simulation results show good agreement with experimental data, validating the accuracy of the CFD model. The combined approach provides comprehensive insights into flow behavior, temperature distribution, and performance characteristics. The findings confirm that twisted tape inserts are an effective and practical passive technique for enhancing heat exchanger performance in industrial applications.

XI. Future Scope

Future research can be extended in the following directions:

- Optimization of twisted tape geometry (twist ratio, thickness, perforations)
- Investigation of hybrid enhancement techniques combining twisted tapes with nanofluids
- Long-term fouling and durability studies
- Application of machine learning models for performance prediction and optimization
- Experimental studies under high-temperature and high-pressure conditions
- Economic and life-cycle cost analysis of enhanced heat exchangers

References

1. A. E. Bergles, "Techniques to enhance heat transfer," *Handbook of Heat Transfer*, McGraw-Hill, 1998.
2. R. L. Webb and E. R. G. Eckert, "Application of rough surfaces to heat exchanger design," *International Journal of Heat and Mass Transfer*, vol. 15, pp. 1647–1658, 1972.
3. R. L. Manglik and A. E. Bergles, "Heat transfer and pressure drop correlations for twisted-tape inserts," *International Journal of Heat and Mass Transfer*, vol. 36, no. 13, pp. 3233–3249, 1993.
4. S. K. Saha, A. Dutta, and S. K. Dhal, "Friction and heat transfer characteristics of laminar flow in a tube with twisted tape inserts," *Journal of Heat Transfer*, vol. 123, pp. 417–420, 2001.
5. S. Eiamsa-ard and P. Promvonge, "Experimental investigation of heat transfer and friction characteristics in a tube with twisted tape inserts," *International Communications in Heat and Mass Transfer*, vol. 32, pp. 412–421, 2005.

6. P. Promvonge, "Thermal enhancement in a round tube with twisted tape insert," *International Communications in Heat and Mass Transfer*, vol. 35, pp. 129–134, 2008.
7. M. Rahimi, S. Khoshvaght-Aliabadi, and M. Akhavan-Behabadi, "Heat transfer and friction factor characteristics of turbulent flow in a tube with perforated twisted tape inserts," *Chemical Engineering and Processing*, vol. 48, pp. 140–148, 2009.
8. S. Eiamsa-ard, K. Wongcharee, P. Eiamsa-ard, and C. Thianpong, "Heat transfer enhancement in a tube using delta-winglet twisted tape inserts," *Applied Thermal Engineering*, vol. 32, pp. 107–117, 2012.
9. M. M. K. Bhuiya, M. S. U. Chowdhury, M. S. Islam, and A. K. M. S. Islam, "Heat transfer and friction factor characteristics with twisted tape inserts," *International Communications in Heat and Mass Transfer*, vol. 54, pp. 111–118, 2014.
10. R. Kumar and B. N. Prasad, "Performance analysis of heat exchanger using twisted tape inserts," *Applied Thermal Engineering*, vol. 120, pp. 111–119, 2012.
11. Y. A. Çengel and A. J. Ghajar, *Heat and Mass Transfer: Fundamentals and Applications*, 5th ed., McGraw-Hill, 2015.
12. S. Kakac, H. Liu, and A. Pramuanjaroenkij, *Heat Exchangers: Selection, Rating, and Thermal Design*, 3rd ed., CRC Press, 2012.