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CFD-Based Evaluation of Thermal Performance and Nusselt Number Enhancement in a Heat Exchanger Using Modified Twisted Tape

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Abstract- The present work focuses on the CFD-based evaluation of thermal performance and Nusselt number enhancement in a heat exchanger using modified twisted tape inserts. Twisted tape inserts are widely used passive methods for improving heat transfer in internal flow systems. In this study, four geometries were analyzed: Plain Twisted Tape (PTT), Double-Hole Perforated Twisted Tape (DHPTT), Curved-Slot Twisted Tape (CSTT), and Multi-Hole Perforated Twisted Tape (MHPTT). A circular pipe of 44 mm outer diameter, 42 mm inner diameter, and 400 mm length was modeled with a 1 mm thick twisted tape. The total twist angle was 1800°, forming five complete rotations with an 80 mm twist pitch. The CFD model was developed in ANSYS Fluent using a polyhedral mesh of 472,350 cells. Water was used as the working fluid, while the pipe and tape were modeled as aluminum. The inlet velocity and temperature were 0.6 m/s and 293 K, and the pipe wall temperature was 365 K. The standard k-epsilon model was used for turbulent flow analysis. Results showed that MHPTT achieved the highest outlet temperature of 345.99 K, temperature rise of 52.99 K, and 18.09% change. The Nusselt number also increased with Reynolds number. Overall, MHPTT gave the best thermal performance.

Keywords- : CFD, Thermal Performance, Nusselt Number, Plain Twisted Tape, Curved-Slot Twisted Tape, Reynolds number and Polyhedral Mesh.

I. INTRODUCTION

Background of Heat Exchangers

Heat exchangers are important thermal devices used to transfer heat between two or more fluids at different temperatures. They are used where heating, cooling, evaporation, condensation, or heat recovery is required. Their main function is to transfer thermal energy from one fluid stream to another without direct mixing in most cases. Heat exchangers are widely used in power plants, HVAC systems, chemical processing units, automotive cooling systems, refrigeration units, solar thermal systems, and double-pipe heat exchange systems (Ali et al., 2026; Ahirwar et al., 2025). In power plants, heat exchangers are used in boilers, condensers, feedwater heaters, and cooling towers. In HVAC systems, they support heating and cooling control. In chemical industries, they help maintain process temperature during reactions, separation, and fluid treatment. In automobiles, radiators, intercoolers, and oil coolers remove excess heat from engines and powertrain systems.

The performance of a heat exchanger depends on heat transfer area, fluid properties, flow rate, temperature difference, wall material, and flow structure. In internal tube flow, convective heat transfer is strongly affected by the thermal boundary layer formed near the wall. This boundary layer reduces heat exchange between the heated wall and the core fluid. Therefore, stronger mixing between the wall region and central fluid improves heat transfer. The Nusselt number is commonly used to measure convective heat transfer performance. A higher Nusselt number indicates stronger convective heat transfer inside the tube. Recent CFD-based studies have also shown that twisted tape inserts can improve the temperature field and flow mixing inside heat exchanger tubes (Cabello et al., 2022; Yadav et al., 2021).

Need for Heat Transfer Enhancement

Heat transfer enhancement is needed because conventional heat exchangers often require large size to achieve high heat duty. Large heat exchangers need more material, more space, and higher installation cost. Modern thermal systems require compact size, lower weight, and better energy use. Heat transfer enhancement helps increase heat transfer rate without a large increase in heat exchanger size. This is useful in power generation, process industries, automotive cooling, solar thermal systems, and HVAC applications (Jadhao et al., 2025; Ahirwar et al., 2025).

Enhanced heat transfer also improves thermal efficiency. When heat is transferred more effectively, temperature losses are reduced, and system performance improves. In cooling systems, better heat removal prevents overheating of components. In heating systems, faster heat transfer reduces warm-up time and improves process control. In energy systems, improved heat recovery reduces fuel use and waste heat losses. Recent studies on tube inserts, turbulators, and modified flow passages confirm that passive devices can raise heat transfer by improving wall-fluid interaction and disturbing the thermal boundary layer (Mohadjer et al., 2024; Ceylan, 2026). Heat transfer enhancement also reduces material use because the same heat duty can be achieved with a smaller surface area. This supports compact design and cost saving.

Passive Heat Transfer Enhancement Techniques

Heat transfer enhancement methods are usually classified as active, passive, and compound methods. Active methods need external energy, such as vibration, electric fields, magnetic fields, acoustic waves, or mechanical stirring. Passive methods do not need external power. They improve heat transfer by changing the flow path, surface shape, or internal geometry. Compound methods combine two or more enhancement techniques. Passive techniques are widely used because they are simple, low-cost, reliable, and easy to apply in existing heat exchanger tubes (Ahirwar et al., 2025; Jadhao et al., 2025).

Common passive methods include twisted tapes, ribs, fins, baffles, corrugated tubes, rough surfaces, wire coils, porous inserts, and extended surfaces. Ribs and rough surfaces disturb the near-wall flow. Fins increase the heat transfer area. Baffles guide the flow and increase fluid contact with the heat transfer surface. Corrugated tubes create repeated flow separation and reattachment. Inserts such as twisted tapes, helical tapes, perforated tapes, and disk-type turbulators generate swirl and secondary flow inside tubes (Waware et al., 2025; Jlidi et al., 2026). Passive methods are useful where external power input is not preferred.

Among passive techniques, twisted tape inserts have received major attention. They are easy to manufacture and can be inserted inside circular tubes without changing the outer structure of the heat exchanger. Their geometry can also be modified using holes, cuts, slots, wings, elliptical cuts, or perforations to increase fluid mixing and boundary layer disturbance (Khargotra et al., 2023; Dubey & Kumar, 2026).

Role of Twisted Tape Inserts in Heat Exchangers

Twisted tape inserts improve heat transfer by forcing the fluid to move in a helical path. In a plain tube, fluid mainly flows in the axial direction. This creates a relatively stable thermal boundary layer near the wall. When a twisted tape is inserted, the fluid rotates around the tube axis. This swirl flow improves radial mixing between the core fluid and the near-wall fluid. As a result, colder fluid moves toward the heated wall, while warmer fluid moves toward the tube center. This repeated exchange improves heat transfer rate and increases the Nusselt number (Cabello et al., 2022; Arasteh et al., 2021).

Twisted tapes also create secondary flow and disturb the thermal boundary layer. These effects increase wall-fluid interaction and reduce thermal resistance. Plain twisted tapes are effective, but modified twisted tapes can further improve thermal behavior. Perforated twisted tapes allow part of the fluid to pass through holes, creating extra mixing. Slotted and cut twisted tapes generate local vortices and flow disturbance.

Elliptical-cut, multi-hole, and helical perforated tapes improve fluid exchange near the wall and increase the strength of secondary flow (Dubey & Kumar, 2026; Waware et al., 2025). CFD analysis is useful for studying these effects because it shows velocity contours, temperature distribution, swirl pattern, and boundary layer behavior. Experimental studies provide heat transfer values, but CFD helps explain why one geometry performs better than another.

Recent CFD-based and hybrid CFD–optimization studies show that numerical analysis can effectively compare different twisted tape and turbulator geometries under controlled operating conditions (Chouhan et al., 2024; Voddepalli et al., 2025). Therefore, CFD-based evaluation is suitable for comparing modified twisted tape inserts in terms of heat transfer rate and Nusselt number.

II. LITERATURE REVIEW

Many researchers have studied heat transfer enhancement in tubes fitted with twisted tape inserts. Earlier and recent studies show that twisted tapes improve convective heat transfer by producing swirl flow and increasing fluid mixing. Yadav et al. (2021) performed three-dimensional CFD simulation and developed correlations for a circular tube fitted with twisted tape. Their study confirmed that twisted tape geometry affects Nusselt number and flow resistance. Khargotra et al. (2023) reviewed different twisted tape configurations and reported that tape geometry, twist ratio, perforation, and surface modification strongly affect the thermal performance of heat exchangers.

Plain twisted tape inserts have been widely used as a reference geometry in heat transfer studies. Cabello et al. (2022) studied heat transfer in pipes fitted with twisted tapes using CFD simulations and experimental validation. Their work showed that CFD can predict Nusselt number with good accuracy when proper turbulence models and boundary conditions are applied. Arasteh et al. (2021) studied the effect of pitch distance of rotational twisted tape and found that pitch distance affects heat transfer and fluid flow characteristics. These studies show that plain twisted tape is useful, but its performance can be improved by adding holes, cuts, perforations, or slots.

Perforated twisted tapes have received strong attention because holes create additional flow paths through the tape. Waware et al. (2025) experimentally investigated heat transfer improvement using perforated helical twisted tapes in a tube-in-tube heat exchanger. Their results showed that perforated tape geometry improves flow mixing and thermal performance. Rahman et al. (2023) studied porous twisted tape inserts in a double-pipe heat exchanger and showed that porous density affects velocity distribution, temperature field, and heat transfer enhancement. These studies suggest that perforation is an effective way to improve heat transfer rate because it creates local turbulence and weakens the thermal boundary layer.

Cut and slotted twisted tapes have also been studied for improving thermal behavior. Dubey and Kumar (2026) conducted CFD analysis and RSM-based optimization of a double-pipe heat exchanger fitted with elliptical-cut twisted tape inserts. Their study showed that cut geometry can improve thermal performance by increasing local flow disturbance and wall-fluid contact. Voddepalli et al. (2025) compared modified twisted tapes using the Taguchi method and CFD. Their work confirmed that geometric modification of twisted tapes changes heat transfer behavior and helps identify better insert configurations. These findings confirm that cut-based and slot-based modifications are useful for increasing convective heat transfer.

Modified turbulators and insert-based designs have also been used to intensify mixing inside heat exchanger passages. Mohadjer et al. (2024) studied nanofluid flow in tubular heat exchangers with multi-blade turbulators and showed that stronger flow disturbance affects thermo-hydraulic behavior. Ceylan (2026) examined jellyfish-inspired in-tube turbulators and found that lobe number and turbulator number influence thermo-hydraulic performance. Sah and Prasad (2026) studied perforated hollow circular ring inserts in an elliptical tube heat exchanger and reported changes in heat transfer and pressure loss. These studies support the view that internal inserts improve heat transfer by creating swirl, mixing, and repeated boundary layer disturbance.

Recent studies have focused more on CFD-based analysis, optimization, and predictive modeling. Chouhan et al. (2024) investigated heat transfer augmentation and friction factor in a twisted tape-based earth-to-air heat exchanger using CFD. Their study showed that twisted tape inserts improve thermal behavior but also affect flow resistance. Shin et al. (2026) used CFD simulation and ANN prediction for twisted oval double-pipe heat exchangers. Their work shows that CFD can be combined with prediction models for better thermal performance analysis. Yıldırım and Güven (2026) applied a hybrid CFD–RSM approach to optimize heat transfer in channels with biomimetic S-shaped turbulators. These recent studies show that CFD-based optimization has become an important method for improving insert geometry.

Review studies also show that twisted tape inserts remain important passive heat transfer devices. Ahirwar et al. (2025) reviewed active and passive heat transfer methods and highlighted twisted tape inserts as a major passive technique. Kadhim et al. (2025) reviewed typical twisted tape inserts in double-pipe heat exchangers and stated that twisted tapes are still widely used for heat transfer improvement. Jadhao et al. (2025) presented a chronological review of heat transfer enhancement using inserts in channel flows and showed that insert geometry plays a key role in thermal performance. Ali et al. (2026) reviewed twisted tape inserts, nanofluids, and twisted tubes in double-pipe heat exchangers and confirmed that combined passive methods can improve heat transfer further.

The literature shows that heat transfer rate and Nusselt number increase when the insert geometry creates stronger swirl, better radial mixing, and repeated boundary layer disturbance. Plain twisted tape improves heat transfer by forcing helical motion. Perforated twisted tape adds through-flow and jet-like mixing. Slotted and cut twisted tapes produce local separation and secondary vortices. Multi-hole and modified geometries create stronger flow interaction and improve thermal contact between the wall and fluid. However, many studies focus on one geometry or compare only limited insert designs. There is still a need for a clear CFD-based comparison of different modified twisted tape geometries under the same operating and boundary conditions.

The main research gap is that the effect of different modified twisted tape geometries on heat transfer rate and Nusselt number is not yet fully clear when all designs are compared using the same numerical model. Experimental studies provide useful data, but they do not always explain the flow and temperature behavior inside the tube.

CFD can fill this gap by showing swirl formation, wall-fluid interaction, temperature distribution, and boundary layer disturbance. Therefore, a CFD-based evaluation of modified twisted tape inserts is needed to compare plain, perforated, slotted, and multi-hole geometries in terms of heat transfer rate and Nusselt number.

III. PROBLEM STATEMENT

Heat exchangers are widely used in thermal systems, but their performance is often limited by poor fluid mixing and low convective heat transfer. Twisted tape inserts are used to improve heat transfer by creating swirl flow inside the pipe. However, the effect of modified twisted tape shapes on thermal performance and Nusselt number needs detailed analysis. Experimental testing requires time, cost, and repeated trials. Therefore, CFD analysis provides a useful method to study flow and heat transfer behavior. This study focuses on evaluating how modified twisted tape geometries improve thermal performance and Nusselt number in a heat exchanger.

IV. SIGNIFICANCE OF THE STUDY

This study is significant because it helps identify better twisted tape designs for improving heat exchanger performance. By using CFD analysis, the thermal behavior of modified twisted tape inserts can be studied clearly without expensive experimental work. The study helps explain how geometric changes affect fluid mixing, turbulence, and convective heat transfer. Improved Nusselt number values indicate better heat transfer capacity of the heat exchanger. The findings can support the design of compact and efficient heat exchangers for industrial applications. This work also provides useful guidance for selecting suitable twisted tape geometry for enhanced thermal performance.

V. RESEARCH OBJECTIVES

- To analyze the effect of modified twisted tape inserts on thermal performance in a heat exchanger using CFD analysis.
- To evaluate and compare the Nusselt number enhancement for different twisted tape geometries under varying Reynolds number conditions.

VI. METHODOLOGY

The present CFD-based work was carried out to study heat transfer and pressure drop behavior in a circular pipe fitted with different twisted tape inserts. The main aim was to compare the thermal and flow performance of different twisted tape designs under the same flow and boundary conditions. The complete method included geometry creation, design modification, geometry import, meshing, model setup, material selection, boundary condition setting, and solver setup in ANSYS Fluent.

Geometry
A circular pipe with a twisted tape insert was designed to improve heat transfer. The pipe had an outer diameter of 44 mm, inner diameter of 42 mm, and wall thickness of 1 mm. The total pipe length was 400 mm. A twisted tape of 1 mm thickness and 40 mm width was inserted along the full pipe length. The tape width was slightly smaller than the pipe inner diameter to allow smooth fitting and avoid blockage. The tape length was also 400 mm. A total twist angle of 1800° was applied, forming five complete rotations. Hence, the twist pitch was 80 mm.

VII. DESIGN OF DIFFERENT TWISTED TAPE GEOMETRIES

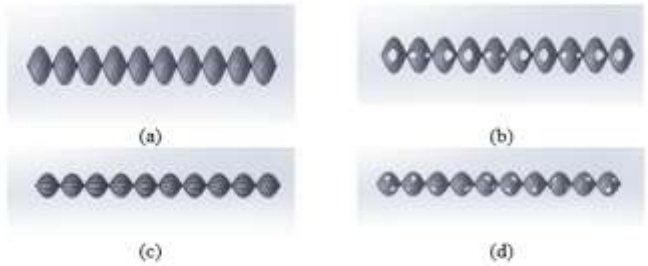


Figure 1: (a) Plain Twisted Tape (PTT), (b) Double-Hole Perforated Twisted Tape (DHPTT), (c) Curved-Slot Twisted Tape (CSTT) and (d) Multi-Hole Perforated Twisted Tape (MHPTT)

Meshing

Meshing was carried out in ANSYS Fluent Meshing using the watertight geometry workflow. The model consisted of three main regions: fluid domain, twisted tape, and pipe wall. Local face sizing was applied with a target mesh size of 4 mm and a growth rate of 1.2. The Curvature and Proximity size function was used to capture the pipe curvature and twisted tape profile accurately. A polyhedral volume mesh was generated because it provides better stability for complex internal flow with swirl. Boundary layers were added near the wall using the smooth-transition method with three layers. The final mesh contained 472,350 cells.

(a) (b)

Figure 2: (a) Cross-section view of meshing (b) side view of meshing

Model Details Used

The k-epsilon turbulence model was used for the CFD simulation. In this model, the standard k-epsilon option was selected. This model was chosen because it is suitable for turbulent flow inside pipes and gives stable results for internal flow with heat transfer. The standard wall function was used as the near-wall treatment to model the flow behavior close to the pipe wall and twisted tape surface.

The turbulent viscosity is calculated as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

Where, μ_tis turbulent viscosity, ρis fluid density, kis turbulent kinetic energy, and εis turbulent dissipation rate.
The transport equation for turbulent kinetic energy is:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon$$

The transport equation for turbulent dissipation rate is:

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

For the present simulation, the model constants were:

Material Selection and Boundary Conditions

The pipe wall and twisted tape were assigned as aluminum because both acted as solid heat-transfer regions. Water was selected as the working fluid, and the energy equation was enabled to study heat transfer. The inlet was set as a velocity inlet with 0.6 m/s velocity and 293 K temperature. Turbulence was defined using 5% intensity and a viscosity ratio of 10. The pipe wall was maintained at 365 K, while the outlet was set as a pressure outlet.

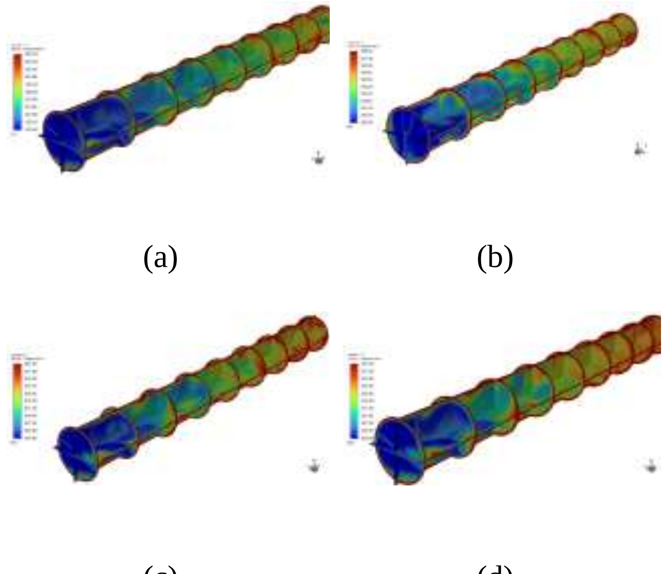
Figure 3: Inlet and Outlet of Twisted Tap

Solver Details

The solver setup used the Coupled pressure–velocity coupling scheme to improve the relation between pressure and velocity during internal pipe-flow simulation. The Rhie-Chow distance-based flux type was selected to reduce pressure–velocity errors. Gradients were calculated using the Least Squares Cell Based method for better accuracy in complex mesh regions. Pressure was solved using the Second Order scheme, while momentum and energy were solved using Second Order Upwind. Turbulent kinetic energy and dissipation rate were solved using First Order Upwind for stable convergence.

VIII. RESULTS

Thermal Performance



(a) (b)

(c) (d)

Figure 4: (a) PTT temperature contour, (b) DHPTT temperature contour, (c) CSTT temperature contour (d) MHPTT temperature contour

Table 4.1: Effect of Different Twisted Tape Geometries on Outlet Temperature and Temperature Rise

Geometry	Inlet Temperature (K)	Outlet Temperature (K)	Temperature Rise (K)	% Change
Plain Twisted Tape (PTT)	293	334.14	41.14	14.04 %
Double-Hole Perforated Twisted Tape (DHPTT)	293	339.21	46.21	15.77 %
Curved-Slot Twisted Tape (CSTT)	293	342.40	49.40	16.86 %
Multi-Hole Perforated Twisted Tape (MHPTT)	293	345.99	52.99	18.09 %

Table 4.1 shows the effect of different twisted tape geometries on outlet temperature and temperature rise in the heat exchanger. The inlet temperature was kept constant at 293 K for all cases. This helps to compare the thermal effect of each insert geometry clearly. The Plain Twisted Tape (PTT) produced an outlet temperature of 334.14 K with a temperature rise of 41.14 K. This shows the basic heat transfer improvement due to swirl flow inside the pipe.

The Double-Hole Perforated Twisted Tape (DHPTT) increased the outlet temperature to 339.21 K, with a temperature rise of 46.21 K. The Curved-Slot Twisted Tape (CSTT) showed further improvement, reaching 342.40 K with a 49.40 K rise. The highest outlet temperature was obtained for the Multi-Hole Perforated Twisted Tape (MHPTT), reaching 345.99 K with a 52.99 K rise. This indicates that MHPTT provides better mixing, stronger turbulence, and improved thermal performance.

Nusselt Number

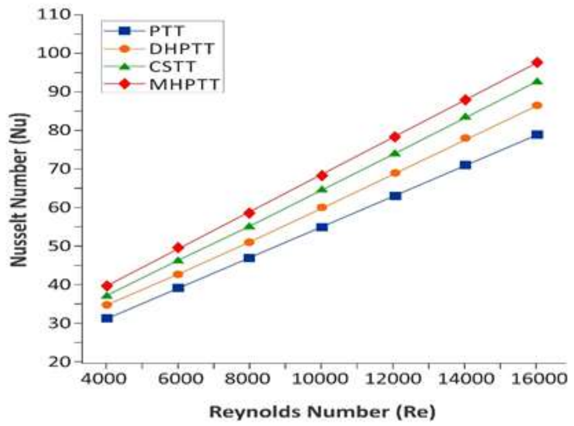


Figure 4: Nusselt Number vs Reynolds Number

Figure 4: shows the variation of Nusselt number with Reynolds number for different twisted tape geometries. For all cases, the Nusselt number increases as Reynolds number rises from 4000 to 16000. This indicates that higher flow velocity improves

turbulence and heat transfer inside the heat exchanger. Among all designs, the Multi-Hole Perforated Twisted Tape (MHPTT) gives the highest Nusselt number at every Reynolds number. It is followed by Curved-Slot Twisted Tape (CSTT), Double-Hole Perforated Twisted Tape (DHPTT), and Plain Twisted Tape (PTT). The result shows that holes and slots improve fluid mixing and thermal performance compared with plain twisted tape.

IX. CONCLUSION

The present study concludes that modified twisted tape inserts improve both thermal performance and Nusselt number in a heat exchanger. The CFD results show that geometric changes in twisted tape inserts increase outlet temperature and temperature rise under the same inlet temperature of 293 K. The Plain Twisted Tape (PTT) produced an outlet temperature of 334.14 K with a temperature rise of 41.14 K and 14.04% change. The Double-Hole Perforated Twisted Tape (DHPTT) improved the outlet temperature to 339.21 K with a 46.21 K rise and 15.77% change. The Curved-Slot Twisted Tape (CSTT) showed better performance with an outlet temperature of 342.40 K, a 49.40 K rise, and 16.86% change. The highest thermal performance was obtained for the Multi-Hole Perforated Twisted Tape (MHPTT), which reached 345.99 K outlet temperature, 52.99 K temperature rise, and 18.09% change. The Nusselt number also increased with Reynolds number from 4000 to 16000 for all geometries. MHPTT showed the highest Nusselt number, followed by CSTT, DHPTT, and PTT. Overall, MHPTT was the most effective design for heat transfer enhancement.

REFERENCES

1. Afsharpanah, F., Sheshpoli, A. Z., Pakzad, K., & Ajarostaghi, S. S. M. (2021). Numerical investigation of non-uniform heat transfer enhancement in parabolic trough solar collectors using dual modified twisted-tape inserts. Journal of Thermal Engineering, 7(1), 133–147.
2. Ahirwar, B. K., Sharma, A., & Kumar, R. (2025). A comprehensive review on heat transfer enhancement in heat exchangers using active and passive techniques. Renewable and Sustainable Energy Reviews.
3. Ali, H. H. M., Abbas, A. H., & Noor, M. M. (2026). Heat transfer augmentation in double-pipe heat exchangers using twisted tape inserts, nanofluids and twisted tubes: A review. International Journal of Heat and Technology, 44(2), 821–834.
4. Arasteh, H., Rahbari, A., Mashayekhi, R., Keshmiri, A., Mahani, R. B., & Talebizadehsardari, P. (2021). Effect of pitch distance of rotational twisted tape on the heat transfer and fluid flow characteristics. International Journal of Thermal Sciences, 170, 106966.
5. Cabello, R., Llopis, R., Sánchez, D., Catalán-Gil, J., & Nebot-Andrés, L. (2022). Heat transfer in pipes with twisted tapes: CFD simulations and experimental validation. Computers & Chemical Engineering, 165, 107930.
6. Ceylan, M. (2026). Experimental thermo-hydraulic performance of jellyfish-inspired in-tube turbulators: Effects of lobe number and turbulator number. International Journal of Thermal Sciences, 226, 110867.
7. Chouhan, S., Kumar, A., & Dhiman, P. (2024). Investigation of heat transfer augmentation and friction factor in twisted tape-based earth-to-air-heat exchanger: A CFD-based analysis. International Journal of Ambient Energy, 45(1), 2277311.
8. Dubey, N., & Kumar, A. (2026). CFD analysis and RSM-based optimization of performance parameters of a double pipe heat exchanger with elliptical cut twisted tape inserts. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 48(1), 2618512.
9. Jadhao, R. R., Chitragar, P., & Kamble, D. (2025). A chronological review of heat transfer enhancement using inserts in channel flows. Physica Scripta, 100(3), 032002.
10. Jlidi, N., Mehrez, Z., & El Cafsi, A. (2026). Thermal performance enhancement of a double tube heat exchanger using ternary nanofluid and disk-type turbulators: A numerical study. The European Physical Journal Plus, 141(5), 487.
11. Kadhim, S. A., Al-Amiery, A. A., & Kadhum, A. A. H. (2025). Influence of the typical twisted tape inserts into the inner tube of double-pipe heat exchangers: A review. Results in Engineering.
12. Khargotra, R., Kumar, A., & Maithani, R. (2023). A review of different twisted tape configurations used in heat exchangers and their impact on thermal performance of the system. Heliyon, 9(6), e16834.
13. Mohadjer, A., Nobakhti, M. H., Nezamabadi, A., & Ajarostaghi, S. S. M. (2024). Thermohydraulic analysis of nanofluid flow in tubular heat exchangers with multi-blade turbulators: The adverse effects. Heliyon, 10(9).

14. Rahman, M. T., Islam, M. A., & Saha, S. K. (2023). Effect of porous density of twisted tape inserts on heat transfer enhancement in a double-pipe heat exchanger. Heliyon, 9(12), e22823.
15. Sah, H., & Prasad, L. (2026). Experimental assessment of thermo-hydraulics of elliptical tube heat exchanger with perforated hollow circular ring inserts. International Communications in Heat and Mass Transfer, 174, 110911.
16. Shin, Y. H., Gwon, J. G., Choi, H. K., & Park, Y. G. (2026). CFD simulation for thermal performance analysis of twisted oval double-pipe heat exchangers with ANN prediction. Journal of Mechanical Science and Technology, 1–18.
17. Voddepalli, S., Nath, S., & Biswas, A. (2025). Comparative heat transfer analysis with modified twisted tapes using Taguchi method and CFD. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 09544089261451258.
18. Waware, S. Y., Bote, M. A., Biradar, R., Ahire, P. P., Kadam, A. A., Patil, S. P., & Kurhade, A. S. (2025). Experimental investigation of heat transfer improvement using perforated helical twisted tapes in a tube-in-tube heat exchanger. Journal of Mines, Metals & Fuels, 73(7).
19. Waware, S. Y., Kore, S. S., Mache, A., & Kurhade, A. S. (2025). Integrated CFD and experimental approach for thermal performance evaluation of a tubular minijet heat exchange.
20. Yadav, A. S., Shrivastava, V., Dwivedi, M. K., & Shukla, O. P. (2021). 3-dimensional CFD simulation and correlation development for circular tube equipped with twisted tape. Materials Today: Proceedings, 47, 2662–2668.
21. Yıldırım, O., & Güven, H. (2026). A hybrid CFD–RSM approach for optimizing heat transfer in channels with biomimetic S-shaped turbulators. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 48(2), 73.