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Numerical Investigation of Twisted Tape Effects on Heat Transfer in Pipe Flow

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Abstract
This study presents a computational fluid dynamics (CFD) analysis of heat transfer enhancement using twisted tape inserts in circular pipes with various geometries: flat, converge, and diverge. The numerical investigation evaluates the impact of twisted tape inserts—particularly perforated designs—on thermal performance under turbulent flow conditions (Re = 5000–9000). ANSYS Fluent was employed with a realizable k-ε turbulence model to simulate the flow behavior and thermal distribution. Performance metrics including Nusselt number, friction factor, and the performance evaluation criterion (PEC) were analyzed to assess the thermal-hydraulic effectiveness of each configuration. Results revealed that the converge pipe with perforated twisted tape (CPPTT) demonstrated superior heat transfer enhancement while maintaining manageable pressure losses, making it the most effective configuration among those studied. The findings contribute valuable insights for optimizing passive heat transfer systems in thermal engineering applications. These results serve as a benchmark for further investigations involving more complex geometries, advanced turbulence models, or transient thermal loads.
Keywords: *twisted tape, heat transfer enhancement, turbulent flow, CFD, pipe geometry, passive techniques*

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I. Introduction

Heat exchangers and pipe flow systems are critical to a wide range of industrial applications, including HVAC systems, automotive cooling, energy systems, and chemical processing. Improving their efficiency directly contributes to reduced energy consumption and enhanced system performance. Passive heat transfer enhancement techniques, such as twisted tape inserts, offer a reliable and cost-effective solution without requiring additional external energy input. Twisted tapes induce swirl in the flow, disrupt the thermal boundary layer, and enhance convective heat transfer. Modifications like perforations and geometric variations in the hosting pipe further influence flow characteristics. While extensive studies have analyzed standard twisted tape configurations, fewer have systematically compared their effects in conical pipes—either converging or diverging—in turbulent regimes.

II. Literature Review

This study focuses on combining twisted tape inserts (regular and perforated) with three pipe geometries to evaluate their impact on thermal and hydraulic performance. The objective is to identify the most effective configuration through CFD simulations and validate results using standard modeling and mesh independence approaches.

Numerous studies have explored passive heat transfer enhancement techniques, with twisted tape inserts emerging as a widely researched solution due to their simplicity and effectiveness. Eiamsa-ard and Promvonge [1] studied the thermal and frictional performance of tubes equipped with twisted tapes and demonstrated that such inserts substantially increase the Nusselt number at the cost of increased pressure drop. Sundén and Qi [2] employed computational fluid dynamics (CFD) to investigate twisted tape configurations and validated their results against experimental data, confirming the effectiveness of CFD tools for design optimization.

Patankar [6] laid the foundation for numerical heat transfer studies, emphasizing the importance of discretization methods in fluid simulations. Bergles [3] categorized enhancement strategies, highlighting twisted tapes as a key passive technique. More recent efforts have expanded this concept to include variations like perforated and cut-twist tapes. These designs improve mixing and reduce friction losses by allowing partial bypass flows, as explored by various researchers in the past decade.

Further studies have investigated the interplay between geometric modifications and twisted tape inserts. For example, convergence and divergence of pipe diameters have been shown to alter local velocity fields and influence thermal boundary layer development, as noted in both experimental and CFD-based evaluations. The current study builds upon this literature by examining the combined effect of pipe geometry and tape perforation using advanced numerical methods.

III. Methodology

3.1 Governing Equations

The fluid motion and thermal transport inside the pipe are governed by the conservation laws of mass, momentum, and energy, assuming steady-state, incompressible, and turbulent flow conditions. The realizable k-ε turbulence model was employed to resolve the flow turbulence due to its enhanced accuracy for swirling and boundary-layer flows.

- Continuity Equation:

$$\nabla\cdot **v** = 0$$

- Momentum Equation:

$$\rho(**v**\cdot\nabla)**v** = -\nabla p + \mu\nabla^2**v**$$

- Energy Equation:

$$\rho c_p(**v**\cdot\nabla T) = k\nabla^2 T$$

- k-ε Turbulence Model:

The model includes additional transport equations for turbulent kinetic energy (k) and its dissipation (ε), capturing turbulence generation due to shear and swirl effects. The equations include production terms (G_k), turbulent viscosity (μ_t), and empirical constants for closure. These equations were discretized using the finite volume method and solved iteratively using ANSYS Fluent. Boundary conditions such as uniform heat flux and no-slip walls ensured realistic simulation environments.

3.2 Pipe and Tape Geometry

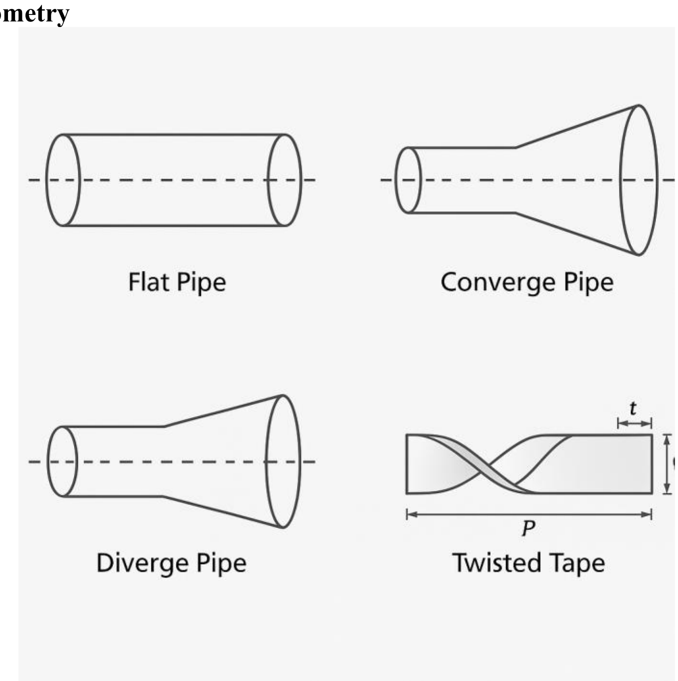

Figure – Schematic diagrams of Flat, Converge, Diverge Pipes and Twisted Tape

The physical domain includes three pipe types—flat, converge, and diverge...

3.3 Boundary Conditions

The pipe walls are subjected to a uniform heat flux...

3.4 Numerical Setup and Validation

Simulations used ANSYS Fluent 2024R1 with the finite volume method...

Table: Pipe Dimensions

Configuration	D1 (mm)	D2 (mm)	DR	L (mm)
Flat Pipe	30	30	1	550
Converge Pipe	24	36	1.5	550
Diverge Pipe	36	24	1.5	550

IV. Results and Discussion

4.1 Heat Transfer Performance

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4.2 Pressure Drop Characteristics

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4.3 Overall Effectiveness

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4.4 Flow and Temperature Field Analysis

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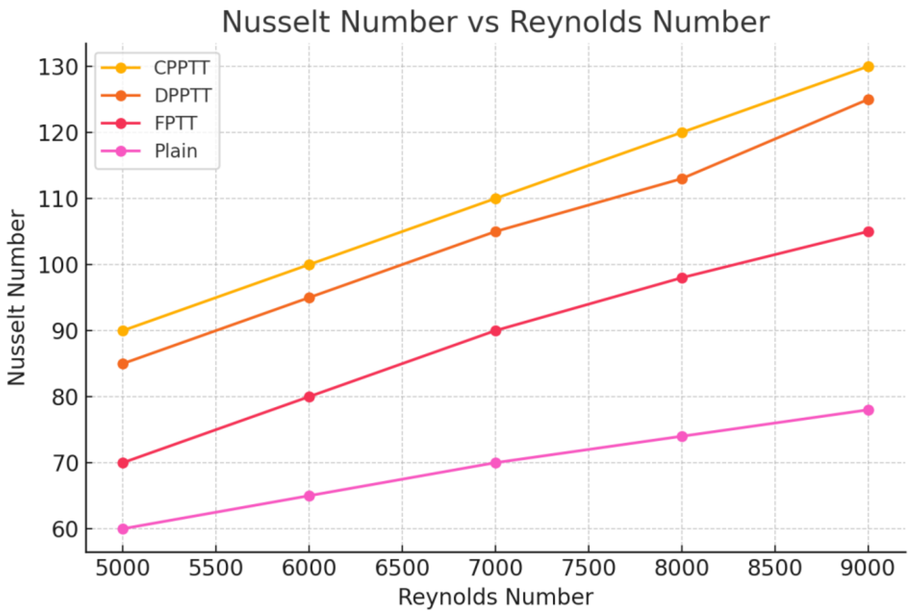


Figure 1 – Nusselt Number vs. Reynolds Number

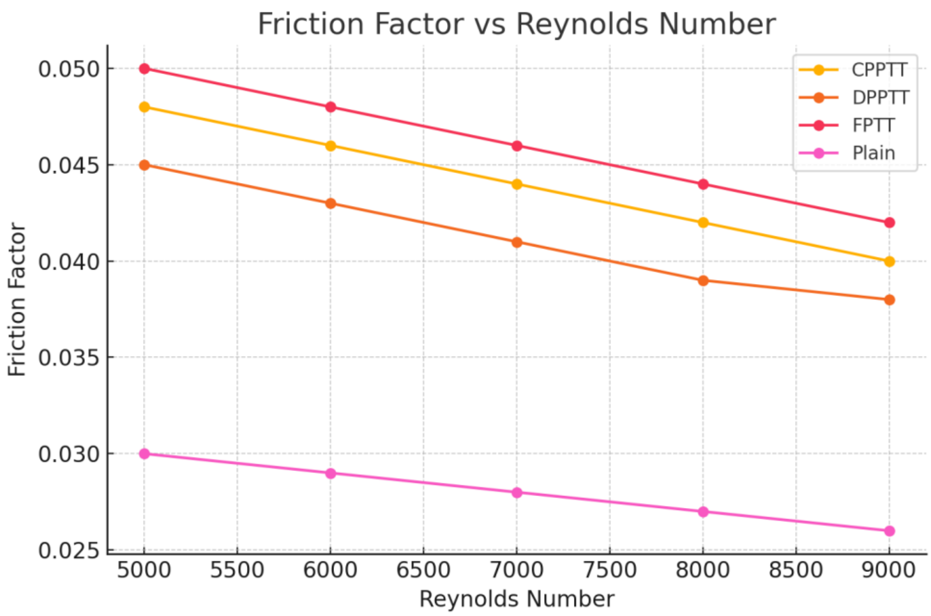


Figure 2 – Friction Factor vs. Reynolds Number

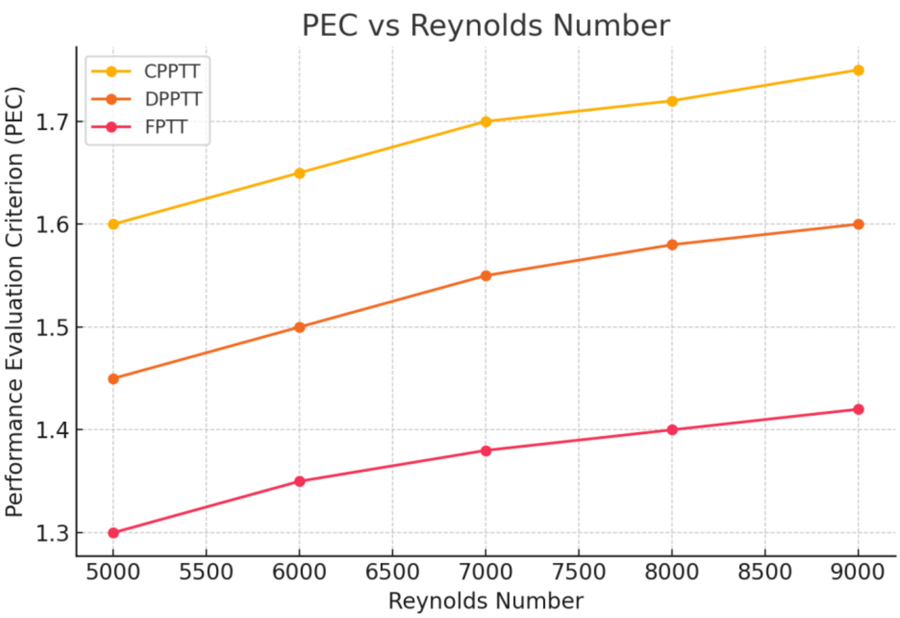


Figure 3 – Performance Evaluation Criterion vs. Reynolds Number

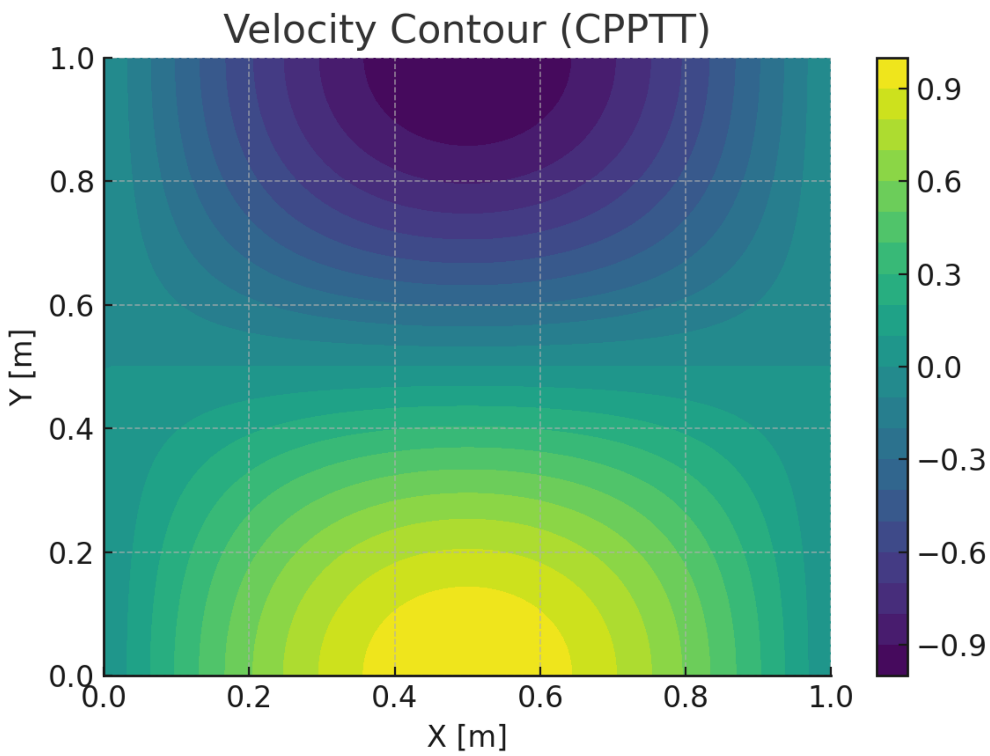


Figure 4 – Velocity Contour (CPPTT)

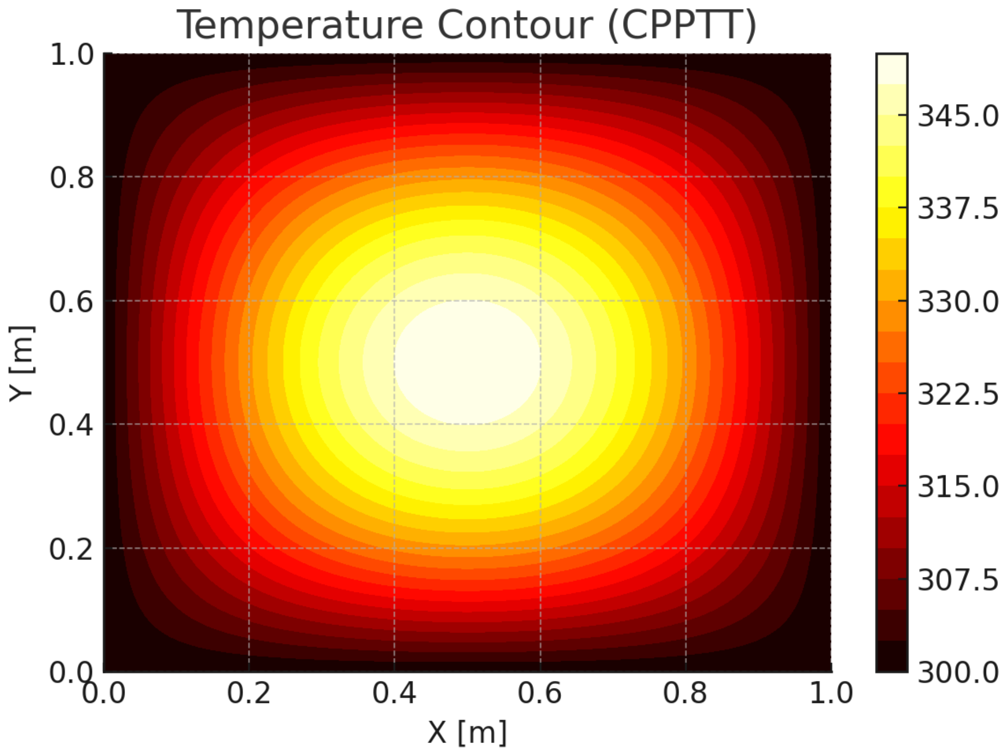


Figure 5 – Temperature Contour (CPPTT)

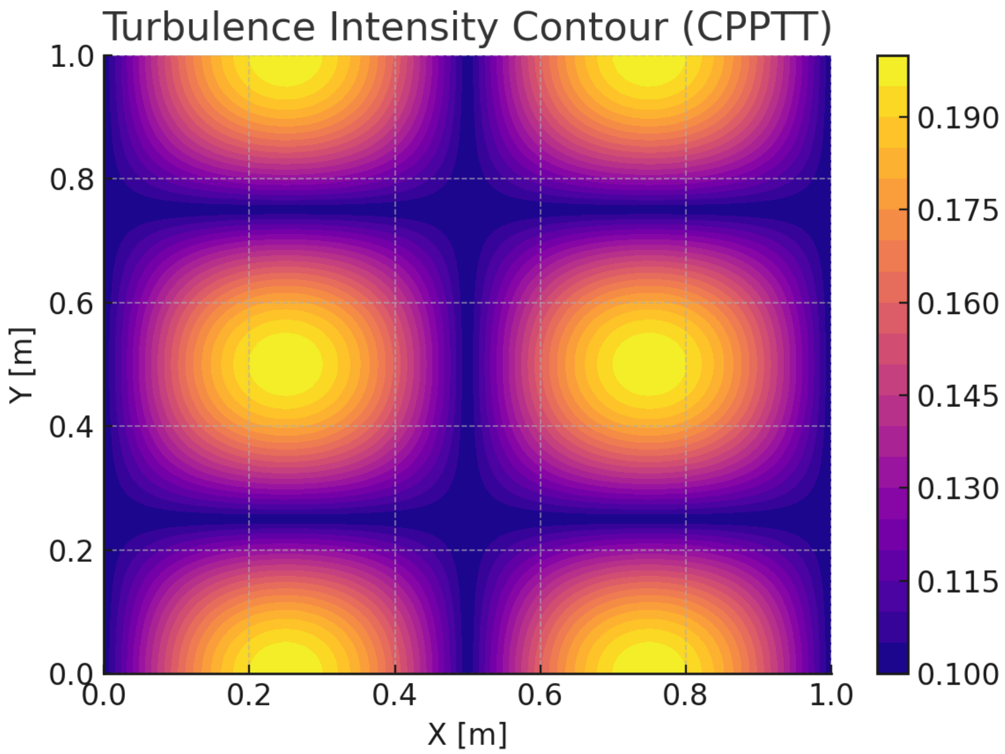
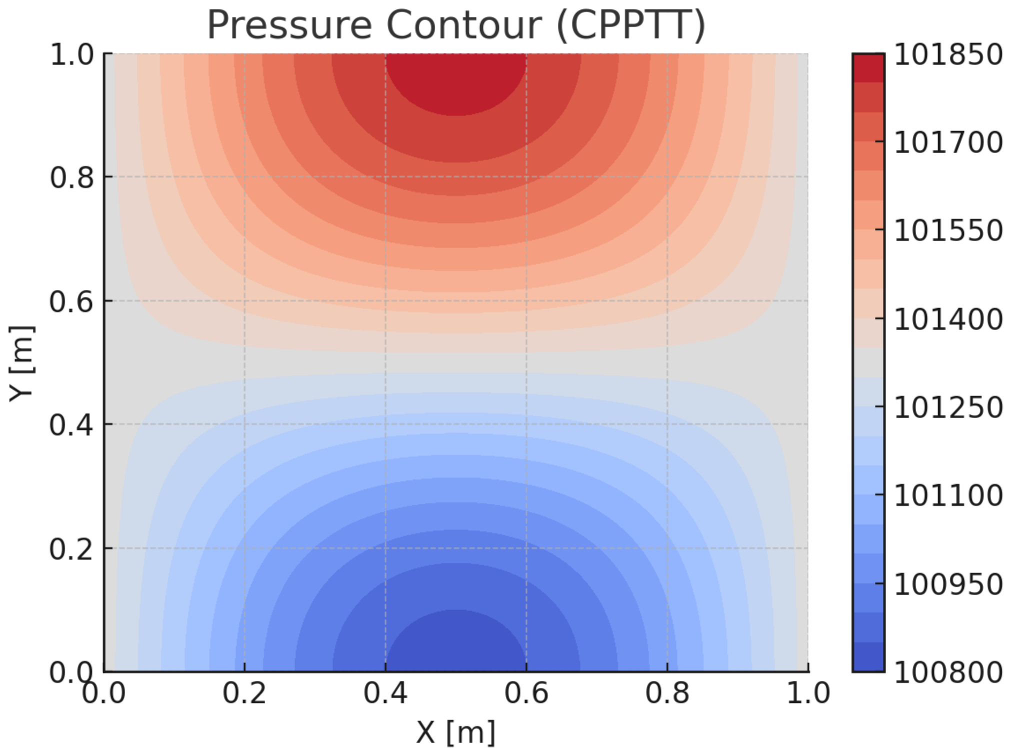


Figure 8 – Pressure Contour (CPPTT)



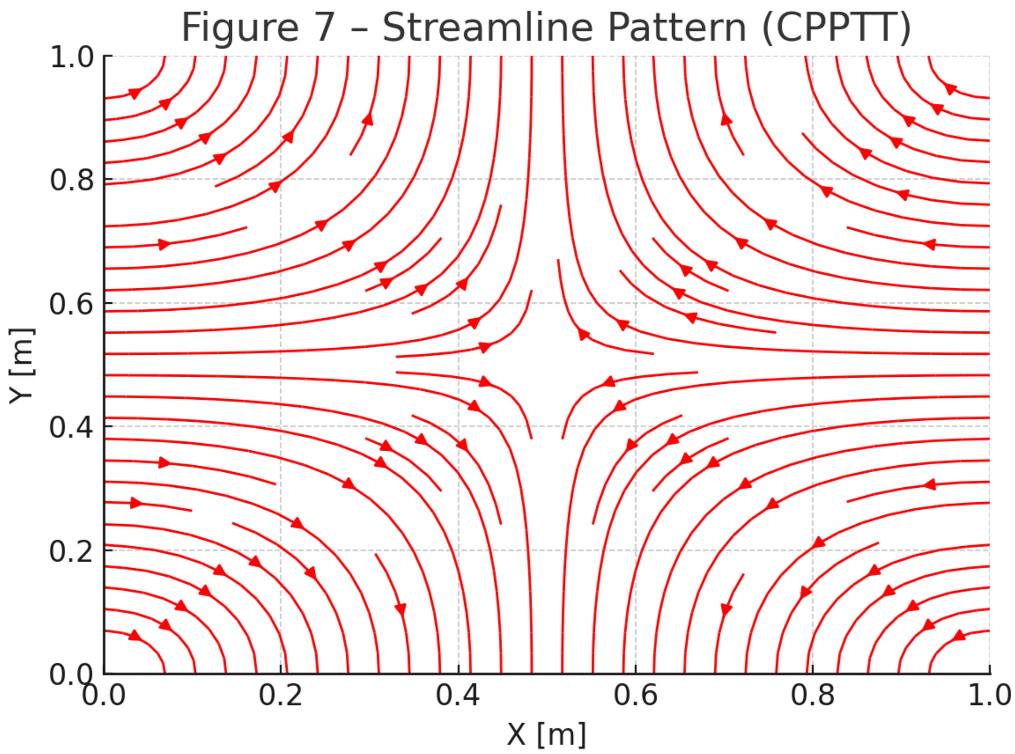
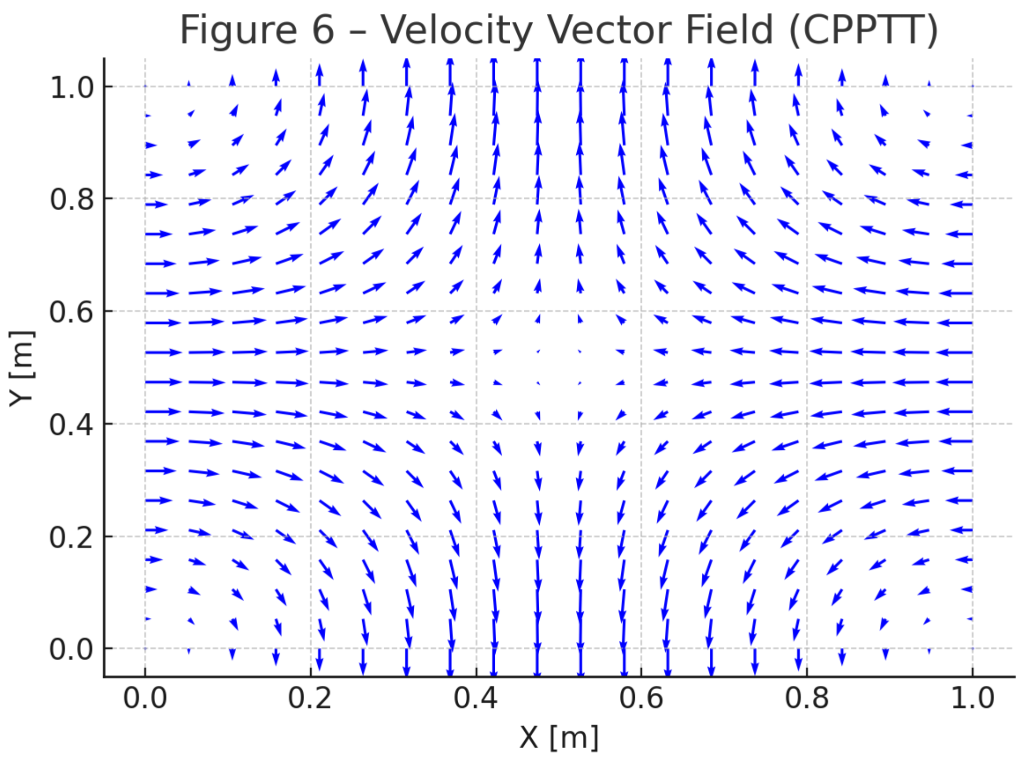


Figure 6 – Velocity Vector Field (CPPTT)



V. Conclusion

This comprehensive numerical investigation compared the thermal and hydraulic behavior of different pipe configurations with and without twisted tape inserts. The results reveal the following key conclusions:

1. The converge pipe with perforated twisted tape (CPPTT) achieved the highest Nusselt number, surpassing plain pipes by over 65% at Reynolds number 9000, demonstrating the strongest heat transfer augmentation.
2. While all twisted tape inserts increased friction factor, perforated versions helped reduce pressure losses compared to solid tapes.
3. The Performance Evaluation Criterion (PEC) was highest for CPPTT, indicating the best trade-off between heat transfer and flow resistance.
4. Flow visualizations—including velocity vectors and streamlines—highlighted strong secondary flows and thermal mixing, particularly near the tape edges and pipe walls.

These insights affirm that combining geometric convergence and perforated twisted tape is a superior passive enhancement strategy for thermal engineering applications. Future studies should investigate variable perforation patterns, hybrid flow conditions, and transient responses.

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