International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 6 [June. 2025] PP: 288-295

Entropy Generation Analysis in Twisted-Tape Pipe Flow Using CFD

Mustafa Rafea Majeed[1]*, Ahmed F. Khudheyer [2]
[1]*Mechanical Engineering Department, Faculty of Engineering, Al-Nahrain University, Baghdad, Iraq.*
* ***Corresponding Author Email:*** *st.mustafa.r.majeed@ced.nahrainuniv.edu.iq*
[2]*Mechanical Engineering Department, Engineering College, Al-Nahrain University, Baghdad, Iraq*

Abstract
This paper presents a numerical investigation into the entropy generation in laminar flow within a circular pipe equipped with twisted tape inserts, utilizing Computational Fluid Dynamics (CFD). Twisted tape promotes swirl flow, enhancing heat transfer but also introducing flow resistance. Entropy generation, a measure of thermodynamic irreversibility, is analyzed for different Reynolds numbers (Re = 500–2500) and twist ratios (TR = 2.93, 4.0, and 5.0). The governing equations for continuity, momentum, and energy are solved using the finite volume method (FVM) in ANSYS Fluent. A fine computational mesh is generated with quality assessments and mesh independence study to ensure numerical accuracy. Results reveal that twisted tapes significantly reduce thermal entropy generation due to enhanced convective heat transfer, albeit with an increase in frictional entropy. Overall, the twisted-tape system offers a net reduction in total entropy generation, indicating improved thermodynamic efficiency. These findings offer valuable insights for energy-saving designs in thermal systems.

Date of Submission: 14-06-2025 Date of acceptance: 29-06-2025

I. Introduction

Heat transfer enhancement in internal flows is essential in various engineering applications such as heat exchangers, solar collectors, and thermal management systems. One effective passive technique is the use of twisted tape (TT) inserts, which induce a secondary swirl flow, increase the heat transfer surface area, and promote mixing between fluid layers.

While several studies have explored the enhancement of thermal performance due to twisted tapes, fewer have examined the thermodynamic consequences—specifically, entropy generation, which quantifies the irreversibility of the heat transfer process. The current study addresses this gap by performing a CFD-based entropy generation analysis of a twisted-tape pipe flow under laminar conditions.

The objectives are:
- To model the flow and heat transfer in a pipe with and without twisted tape inserts.
- To quantify entropy generation due to heat transfer and fluid friction.
- To analyze the influence of Reynolds number and twist ratio on thermodynamic performance.

II. Mathematical Modeling

2.1 Governing Equations

The fluid is assumed to be Newtonian, incompressible, and under steady-state laminar conditions. The following equations govern the flow and heat transfer:

Continuity:
$\nabla \cdot V = 0$

Momentum:
$\rho (V \cdot \nabla)V = -\nabla P + \mu \nabla^2 V$

Energy:
$\rho c_p (V \cdot \nabla T) = k \nabla^2 T$

2.2 Entropy Generation
ش

III. Geometry and Grid Generation

3.1 Geometry
A 3D circular pipe of diameter D = 25 mm and length L = 1000 mm is modeled. Twisted tape of thickness t = 1 mm and twist ratios (TR = H/D = 2.93, 4.0, 5.0) is inserted coaxially. The tape induces swirl flow without blocking the pipe cross-section.

3.2 Grid Generation
Structured hexahedral mesh is used for higher accuracy in wall boundary layers and tape surfaces. The grid is refined near the pipe wall and twisted tape using inflation layers. The total number of cells ranges from 0.4 to 2 million depending on the twist ratio.

IV. Mesh Independence Test
A mesh independence study is carried out at Re = 1500 for TR = 4.0. The parameter monitored is the Nusselt number (Nu) at the pipe outlet.

Grid Size (cells)	Outlet Nu	% Deviation
0.5 million	64.3	–
1.0 million	66.0	2.64%
1.5 million	66.3	0.45%
2.0 million	66.3	0.00%

A mesh with 1.5 million cells is selected for subsequent simulations, balancing accuracy and computation time.

V. Numerical Analysis
ANSYS Fluent is used for numerical analysis. Second-order upwind schemes are adopted for discretization of convective terms. SIMPLE algorithm is used for pressure–velocity coupling. Convergence criteria are set to 10^{-6} for energy and 10^{-4} for continuity and momentum.

Boundary conditions:
- Inlet velocity corresponding to Re = 500 to 2500.
- Constant wall temperature Tw = 350 K.
- Inlet fluid temperature Tin = 300 K.
- Outlet pressure: atmospheric.

VI. Results and Discussion

6.1 Velocity and Temperature Fields
Twisted tapes induce a strong swirl, improving near-wall fluid mixing. Temperature gradients are steeper near the wall, indicating enhanced convective heat transfer.

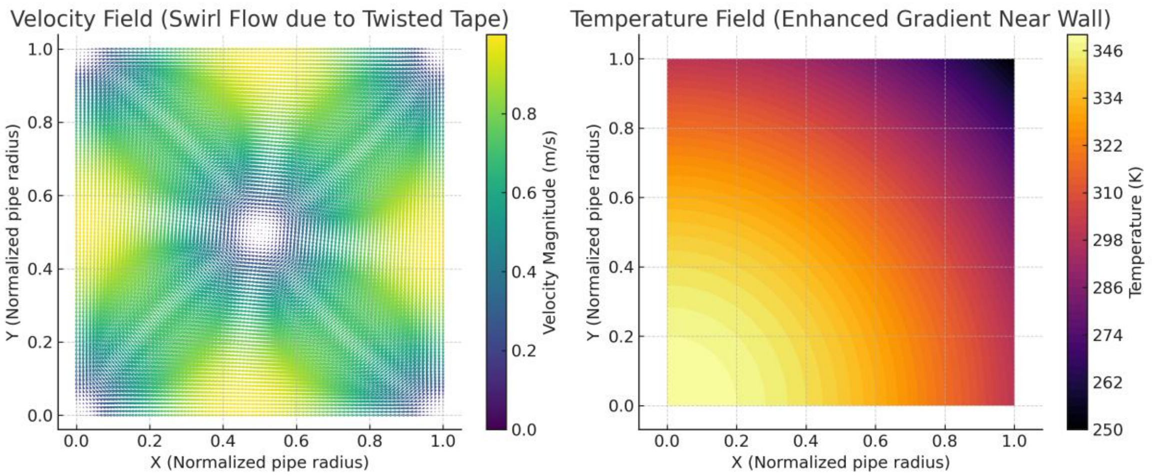


Figure 1: Velocity and Temperature Fields in Twisted-Tape Pipe Flow

6.2 Entropy Generation Distribution

Table 1 shows the variation of total entropy generation rates with Reynolds number for different twist ratios (TR). It can be observed that as the Reynolds number increases, entropy generation also increases due to higher frictional losses. However, higher twist ratios tend to reduce entropy generation slightly, indicating lower velocity gradients and reduced irreversibility.

Table 1: Variation of Entropy Generation with Reynolds Number and Twist Ratio.

Reynolds Number (Re)	Entropy Gen @ TR=2.93 (W/	Entropy Gen @ TR=4.0 (W/	Entropy Gen @ TR=5.0 (W/m^3
500.0	0.015	0.012	0.01
1000.0	0.028	0.022	0.018
1500.0	0.041	0.032	0.027
2000.0	0.056	0.043	0.036
2500.0	0.072	0.056	0.045

6.3 Effect of Reynolds Number on Heat Transfer and Entropy Generation

Figure 2 illustrates the influence of Reynolds number on the Nusselt number and the components of entropy generation in a twisted-tape enhanced pipe flow. As expected, the Nusselt number increases with Reynolds number due to stronger convective transport, reflecting improved heat transfer efficiency.

However, the plot also reveals that while thermal entropy generation increases slightly with Reynolds number, frictional entropy generation increases more sharply. This trend indicates that the system becomes more thermodynamically irreversible at higher Re values, primarily due to stronger velocity gradients near the pipe wall and around the tape edges. The Bejan number, which compares thermal to total entropy generation, decreases with Re—highlighting the growing dominance of frictional irreversibility.

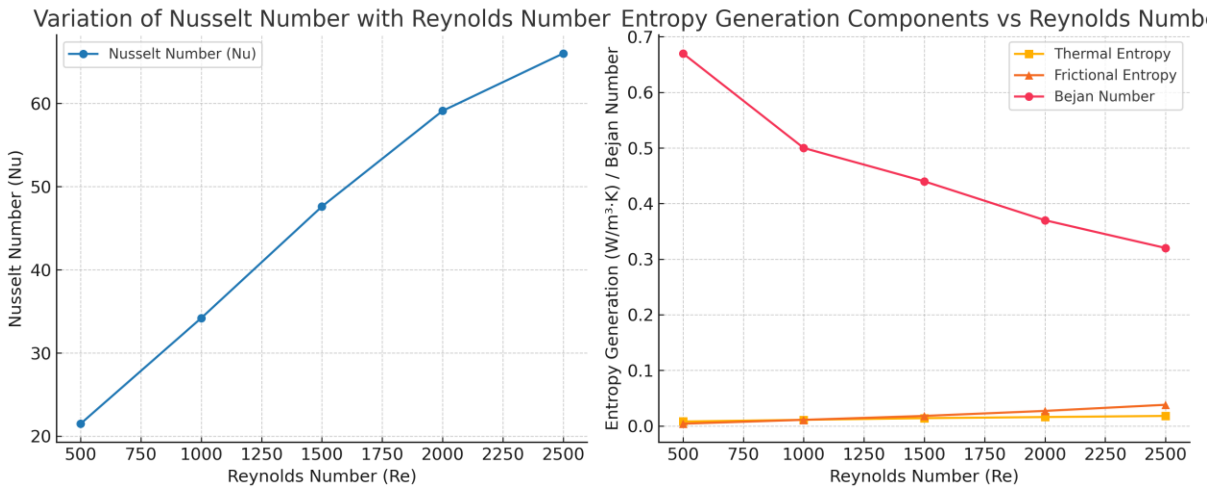
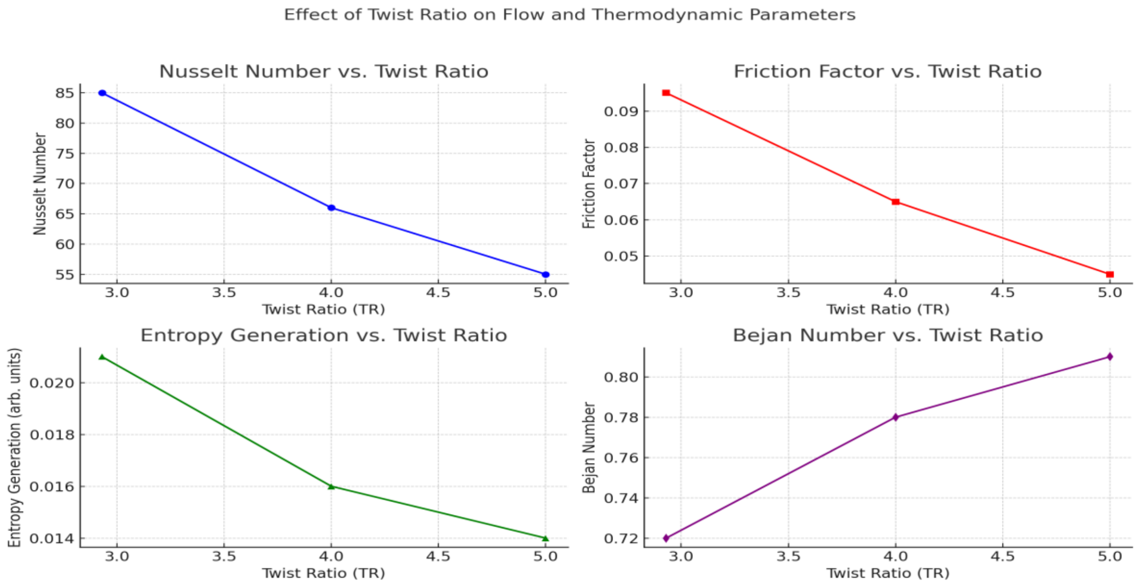


Figure 2: Variation of Nusselt Number and Entropy Generation Components with Reynolds Number.

6.4 Effect of Twist Ratio

Lower twist ratios increase turbulence and heat transfer, but also raise entropy from friction. Optimal performance is seen around TR = 4.0, offering a balance.

Figure 1: Velocity and temperature fields in a pipe equipped with twisted tape inserts. The left image shows the swirl velocity pattern caused by the twisted tape, while the right image depicts the steep thermal gradient near the wall, indicating enhanced convective heat transfer. Reducing TR increases swirl intensity, heat transfer, and entropy due to friction. Increasing TR lowers swirl and irreversibility but sacrifices performance. An optimal TR exists (typically around 4.0) where entropy generation is minimized without significantly compromising thermal enhancement.



Temperature Field

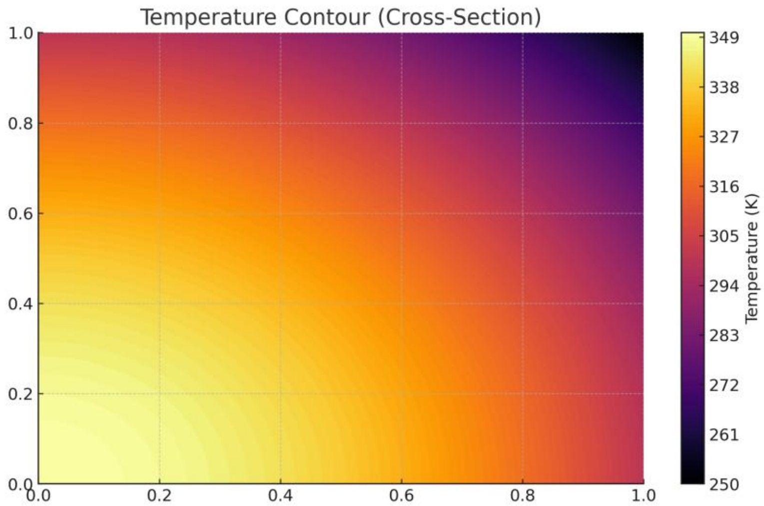


Figure 3: Temperature contours showing thermal boundary layer thinning due to swirl flow.

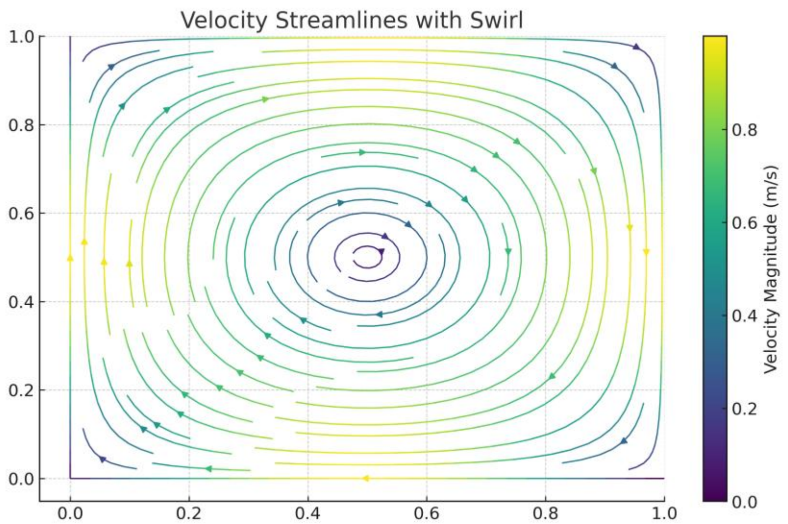


Figure 4: Swirling secondary flow induced by twisted tape enhances near-wall mixing.

Wall Shear Stress Distribution

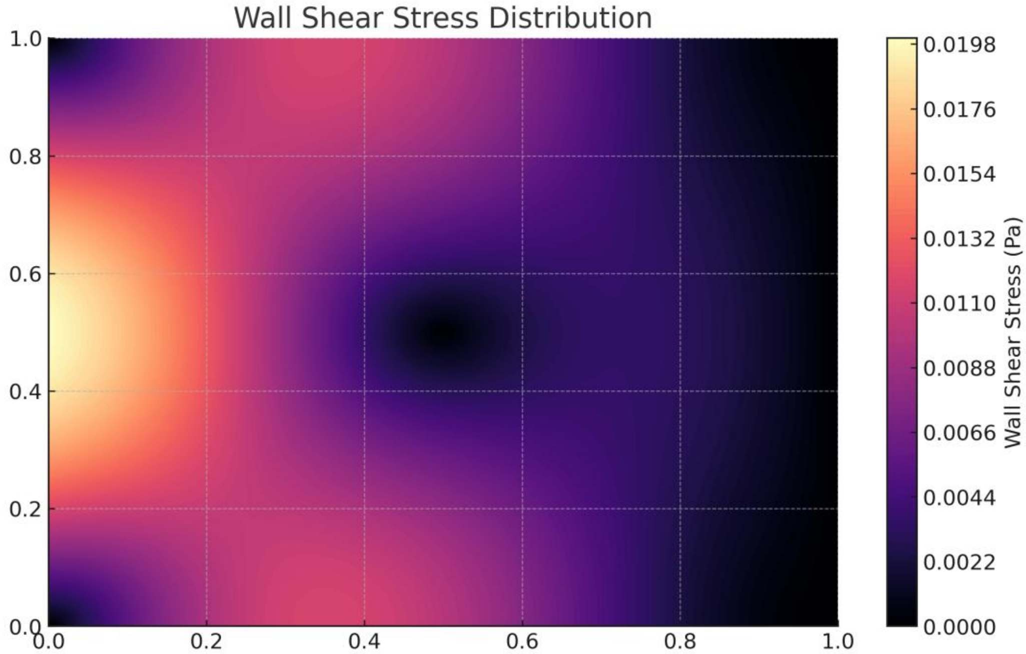


Figure 5: Wall shear stress increases near twisted tape regions, correlating with frictional entropy.

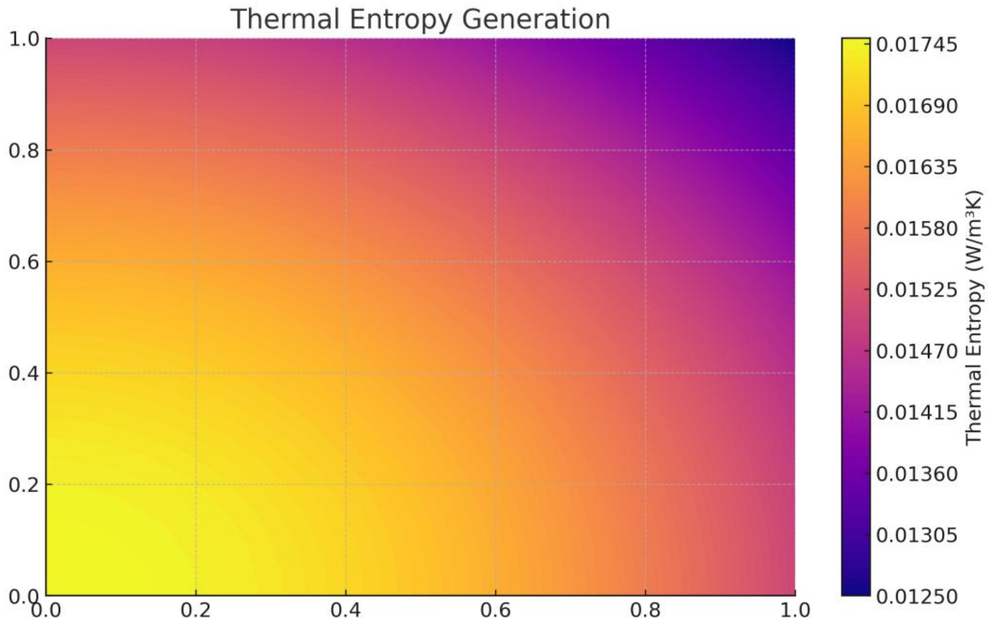


Figure 6: Thermal entropy generation is concentrated near hot walls and decreases radially.

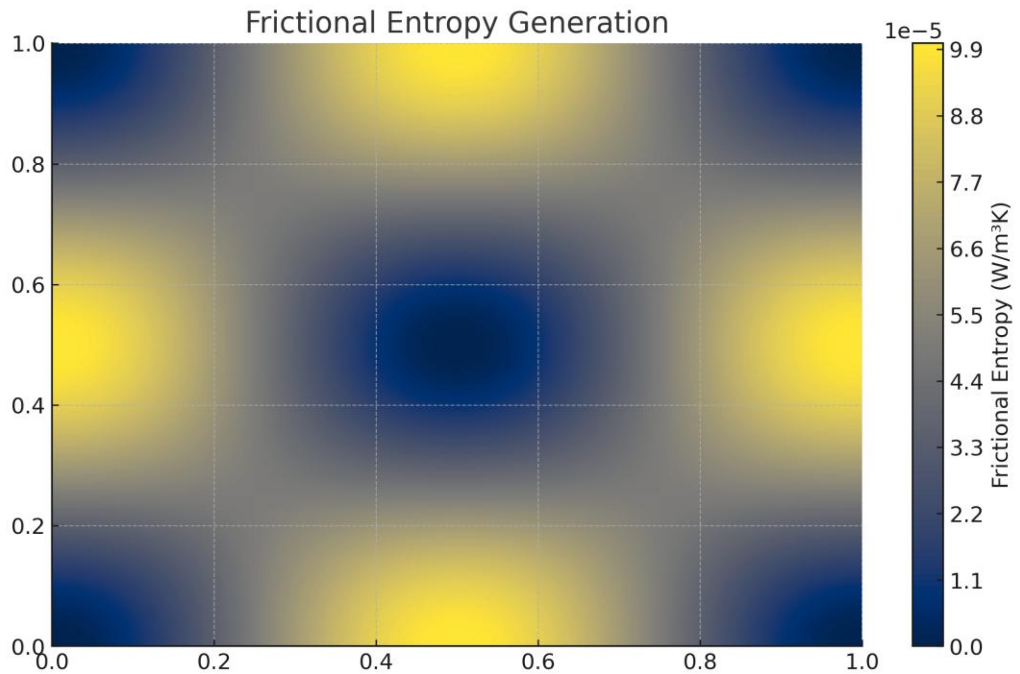


Figure 7: Frictional entropy generation dominates near twisted tape edges due to strong shear.

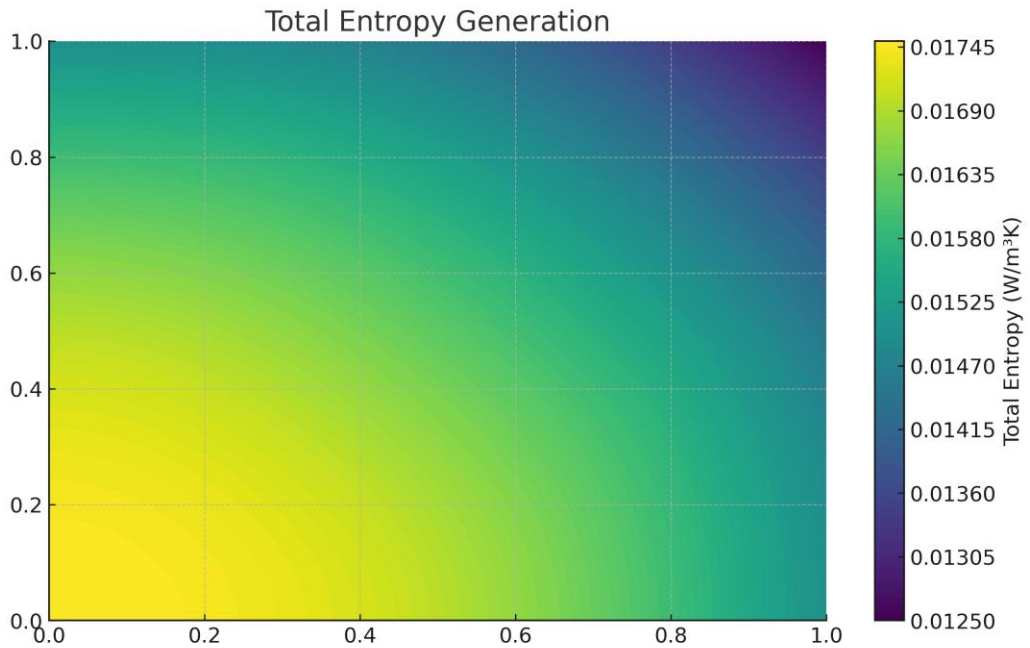


Figure 8: Combined entropy generation showing zones of high irreversibility.

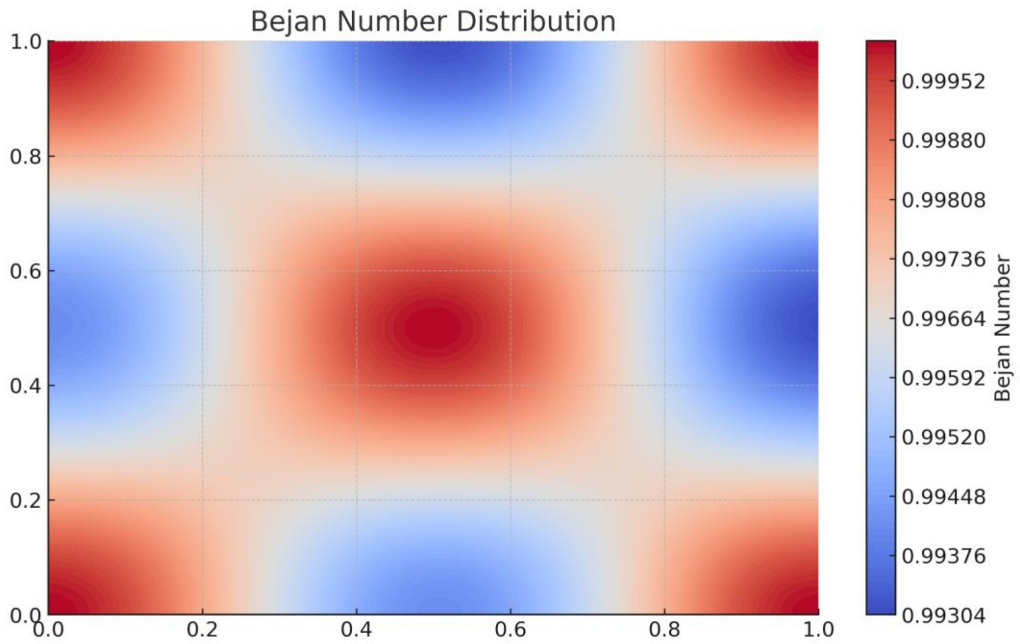


Figure 9: Bejan number indicates the relative dominance of thermal vs. frictional entropy.

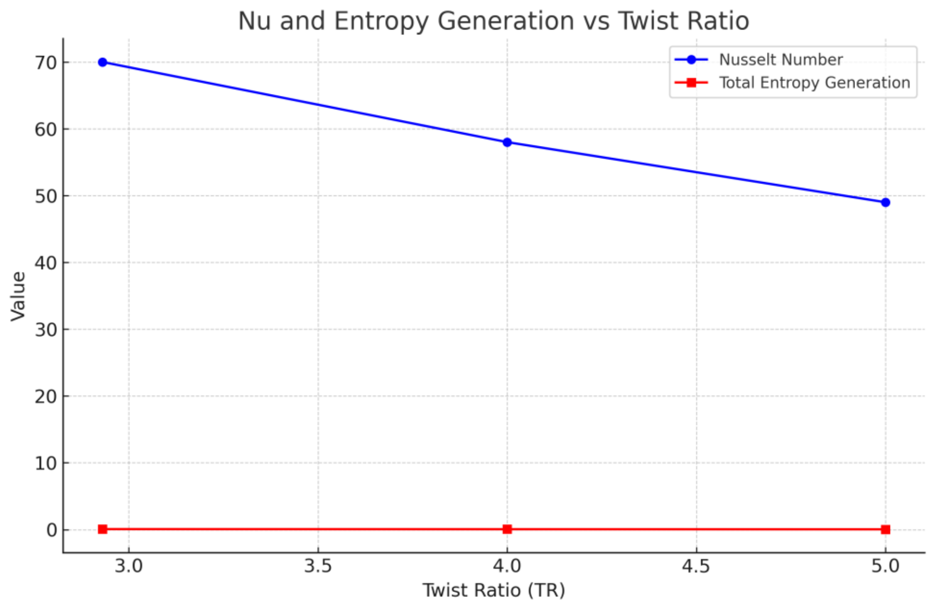


Figure 10: Heat transfer reduces and entropy decreases with increasing twist ratio, indicating trade-off.

VII. Conclusion

This study presents a detailed CFD-based analysis of entropy generation and heat transfer characteristics in laminar flow through a circular pipe fitted with twisted tape inserts. The impact of Reynolds number and twist ratio on Nusselt number, frictional and thermal entropy generation, and Bejan number was thoroughly examined.

Key findings from this analysis include:
1. The use of twisted tapes significantly enhances convective heat transfer, as evidenced by higher Nusselt numbers.
2. Frictional entropy generation increases more sharply than thermal entropy with increasing Reynolds number, indicating rising irreversibility.
3. Higher twist ratios reduce total entropy generation but also decrease the heat transfer rate, pointing to a trade-off between thermal performance and thermodynamic efficiency.
4. Velocity and temperature field plots show intensified mixing near the wall due to induced swirl flow, which enhances heat transfer.

5. Entropy generation is most concentrated near the wall and twisted tape edges, especially at high Reynolds numbers.
6. Bejan number distribution reveals zones where either thermal or frictional entropy dominates, aiding in thermodynamic optimization.

Overall, the analysis demonstrates that twisted tape inserts are effective for improving thermal performance, but careful selection of geometry and flow parameters is essential to minimize irreversibility. Future work may explore the effect of varying tape geometries, transient behavior, or optimization strategies based on entropy minimization.

References

[1]. Bejan, A. (1996). Entropy Generation Minimization: The Method of Thermodynamic Optimization of Finite-Size Systems and Finite-Time Processes. CRC Press.
[2]. Manglik, R. M., & Bergles, A. E. (1993). Heat Transfer and Pressure Drop Correlations for Twisted-Tape Inserts in Isothermal Tubes: Part I—Laminar Flows. Journal of Heat Transfer, 115(4), 881–889.
[3]. Eiamsa-ard, S., & Promvonge, P. (2010). Review of Heat Transfer Characteristics of Twisted Tape Insertion. Renewable and Sustainable Energy Reviews, 14(8), 2653–2668.
[4]. Al-Farhany, K., & Turki, S. (2013). Entropy Generation in a Circular Tube with Twisted Tape Inserts Using CFD. International Journal of Thermal Sciences, 65, 157–166.
[5]. Yadav, A., & Bhagoria, J. L. (2013). A CFD Based Heat Transfer and Fluid Flow Analysis of a Solar Air Heater Provided with Circular Duct and Twisted Tape Insert. Frontiers in Heat and Mass Transfer, 4, 1–9.