

Convective Heat Transfer Enhancement using Novel Twisted Tape-A Numerical Investigation

Prince Abraham Benjamin, Nithin Mohan Mohana Anitha



Abstract: Convective heat transfer and pressure drop characteristics have been investigated numerically in a tube fitted with a twisted tape and a modified twisted tape. A novel geometry of the tape with lateral projection and without lateral projection is introduced for comparison. The results obtained from ordinary twisted tape are compared with those of the Modified twisted tape with lateral projection and modified twisted tape without lateral projection. The experiments reveal that the pressure drop is lower in the modified twisted tape without lateral projection than in the modified twisted tape with lateral projection. However, the Nusselt number in the modified twisted tape without lateral projection is slightly lesser than in the base case with ordinary twisted tape. The Nusselt number in the modified twisted tape with lateral projection is higher than the ordinary twisted tape because the lateral projection diverts the fluid towards the boundaries, and the thermal performance factor is increased. Thus, the Modified twisted tape without lateral projection increases the thermal performance factor to 1.0065 by decreasing the pressure drop, and the modified twisted tape with lateral projection increases the thermal performance factor to 1.1584 by increasing the Nusselt number.

Keywords: Heat Transfer, Swirl Flow, Twisted Tape, CFD, Passive Augments.

I. INTRODUCTION

Heat transfer analysis is performed to improve the system's efficiency, thereby reducing the size and cost of the system. Mainly swirl flow is employed to enhance heat transfer because it breaks down the thermal boundary layer, transferring heat efficiently to the system. This swirl flow is generally achieved with the help of either active augments or passive augments. Recently, Anurag Shrivastava et al. [1] proposed an optimal arrangement of augments, such as baffles and fins, to enhance the heat transfer in the cooling of solar panels. Similar works were also being focused on by researchers [2] [3] in the past years. Novel augments supported with nanomaterial for better heat transfer were also proposed [4]. Among these, passive augments are preferred as they do not require external energy, but active augments require external power [5].

A twisted tape is the most preferred choice of passive augment because of its low cost, easy manufacturability, etc. Numerous pieces of research have been undergone to improve heat transfer by modifying the twisted tape geometries. Considering the hydrodynamic and thermal boundary layer effects, S.N. Sarada et al. [6] and H.Bas et al. [7] analysed the heat transfer performance by modifying the tape width and placing the tape at a little distance from the pipe wall. Peripheral cuts and perforations were also considered by the researchers [8] [9] in view of improving the convective heat transfer by redirecting the fluid flow. In general, it is found that heat transfer is better at a high Reynolds number due to the increased mass flow rate of fluid [10]. Smith Eiamsa et al. [11] and Promvong et al. [12] investigated the heat transfer characteristics with dual twisted tape. They reported that doubling the twisted tape increases heat transfer to a greater extent than single twisted tape. However, the pressure drop increases and needs additional energy to overcome the frictional resistance. Also, it has been observed that the heat transfer increases with a decrease in the twist ratio. Promvong et al. [13] investigated the heat transfer and friction characteristics in a circular tube equipped with typical twisted tape and alternate clockwise and counter-clockwise twisted tapes. The results reveal that alternate clockwise and counter-clockwise twisted tapes provide a higher heat transfer rate and heat transfer enhancement index than the conventional twisted tapes under similar testing conditions. Shyy Woei Chang et al. [14] have performed an experimental study of measuring the axial heat transfer distributions and pressure drop coefficients of the tube fitted with a broken twisted tape. Local Nusselt number and mean Fanning friction factors in the tube fitted with the broken twisted tape increase as the twist ratio decreases. Yong-zhang et al. [15] investigated the heat transfer characteristics and pressure drop in a circular tube with edge fold twisted tape insert and with spirally twisted tape insert of the same twist ratio. The results reveal that the Nusselt number and friction factor of the tube with the edge folded twisted tape inserts is higher than the standard twisted tape inserts. Bodium Salam et al. and Nakhchi et al. [16][17] have investigated the heat transfer coefficient, friction factor and heat transfer enhancement efficiency of a circular tube fitted with a rectangular-cut twisted tape insert. The results reveal that the Nusselt number in a tube with a rectangular-cut twisted tape insert was enhanced than that of the smooth tube. Smith Eiamsa et al. [18] have investigated the heat transfer characteristics of twisted tape with centre wings, alternate axes, and so on. It is reported that the twisted tape with a centre wing and alternate axis has higher heat transfer characteristics than that of centre wings alone or alternate axis alone or with typical twisted tape.

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Sibel Gunes et al. [19] investigated the heat transfer characteristics in a tube fitted with equilateral triangle cross-sectioned coiled wire inserts. It has been absorbed that it produced better results at a low Reynolds number than with a high Reynolds number. Garcia et al. [20] performed a comparative study on the heat transfer enhancement of corrugated tubes, dimpled tubes and wire coil inserts. It has been absorbed that at a Reynolds number in the range of 200-2000, the wire coil is more efficient, and at Reynolds numbers above 2000, the deformed tubes are more efficient. Masoud Rahimi et al. [21] have performed an analytical study on the heat transfer and friction factor characteristics of a tube fitted with modified twisted tape inserts, namely perforated twisted tape, notched twisted tape and jagged twisted tape. The results reveal that jagged twisted tape has higher heat transfer enhancement than the other two. The present study aims to study the heat transfer and pressure drop characteristics in a tube fitted with twisted tape with novel configurations. A modified (Novelly configured) twisted tape with a lateral projection, and a modified twisted tape without lateral projection are analysed. The results are compared with the result of a tube with an ordinary twisted tape.



Fig 1. Geometry of conventional twisted tape



Fig 2. Modified twisted tape without lateral projection



Fig 3. Modified twisted tape with lateral projection

II. PHYSICAL MODEL

A schematic diagram representing twisted tape, modified twisted tape without lateral projection and modified twisted tape with lateral projection is shown in Fig 1, Fig 2 and Fig 3, respectively. The heat transfer enhancement and pressure drop characteristics in tubes equipped with three different tapes have been investigated. Length of the tube ($L=1000$ mm), diameter of the tube ($D=20$ mm), thickness of the tube ($T_b=1$ mm), twist ratio ($y/w=12.5$), tape thickness ($T_t=1$ mm), twist angle ($\theta=720^\circ$), tape pitch ($y=225$ mm), tape width

($w=18$ mm) are kept constant. The tapes are placed at a distance of 50 mm from both ends of the tube. The inlet temperature (T_i) of the working fluid (water) is 300K, and the tube wall (T_w) is provided with a constant heat flux of 1500W/m^2 . The fluid flow is assumed to be incompressible, Newtonian and the flow is three-dimensional. The inlet velocity (u_i) is calculated based on the Reynolds number, and the pressure at the outlet (P_o) is zero. The effect of gravity is considered negligible, and the no-slip boundary condition is applied to the walls. The Reynolds number is varied between 10,000 and 60,000 and the simulation is performed.

Governing equations:

The equation for conservation of mass used in the numerical analysis is given as follows

$$\frac{\partial \rho}{\partial t} + \nabla(\rho U) = 0 \quad (1)$$

Where ρ is the density and U is the velocity component of the fluid, and t is the time

The momentum equation is given by,

$$\frac{\partial(\rho U)}{\partial t} + \nabla(\partial U \phi U) = -\nabla p + \nabla \tau + S_M \quad (2)$$

Where the stress tensor τ is related to the strain rate by

$$\tau = \mu(\nabla U + (\nabla U)^T - \frac{2}{3} \delta \nabla U) \quad (3)$$

The total energy equation is given by,

$$\partial(\rho h_{wt}) - \frac{\partial p}{\partial t} + \nabla(\rho U h_{tot}) = \nabla(\lambda \nabla T) + \nabla(U \tau) + U * S_M + S_E \quad (4)$$

$$h_{tot} = h + U^2 \quad (5)$$

where h_{tot} is the total enthalpy, h is the static enthalpy, $\nabla(U \tau)$ represents the work due to viscous forces, and $U * S_M$ represents the work due to external momentum sources.

The energy equation (K epsilon equation) is given by,

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\frac{\mu_t \partial k}{\sigma_k \partial x_j} \right] + 2\mu_t E_{ij} E_{ij} - \rho \epsilon \quad (6)$$

Parameter definition:

$$Q = hA\Delta T \quad (7)$$

$$q = \frac{Q}{A} \quad (8)$$

$$h = \frac{q}{\Delta T} \quad (9)$$

The dimensionless parameters (Re , Nu , f and η) in this analysis are expressed as follows

$$Re = \frac{\rho u D}{\mu} \quad (10)$$

$$Nu = \frac{hD}{k} \quad (11)$$

$$f = \frac{2D}{L} \frac{\Delta p}{\rho u^2} \quad (12)$$

$$\eta = \frac{Nu/Nu_s}{(f/f_s)^{(1/3)}} \quad (13)$$

III. VALIDATION OF NUMERICAL MODEL

To validate the numerical model, a theoretical correlation for Nusselt number and friction factor by B. Salam et al.[16] is adopted, and the values were compared. It is observed that there is a good agreement between the proposed numerical model and the theoretical model by B. Salam et al.[16]. The graph showing the relationship between the Nusselt number and the Reynolds number is shown in Fig.4, and the effect of the friction factor on the Reynolds number is shown in Fig.5. The plots show a good agreement with the results of the theoretical model and the numerical model presented in this work. The maximum difference between values from the numerical and theoretical models is 10%.

$$Nu = 0.00023 Re^{1.42} \cdot (y/w)^{-0.01} \quad (14)$$

$$f = 25.475 Re^{-1.0173} \cdot (y/w)^{2.4015} \quad (15)$$

Where Nu is the Nusselt number and f is the friction factor. y is the pitch of the twisted tape, and w is the tape width.

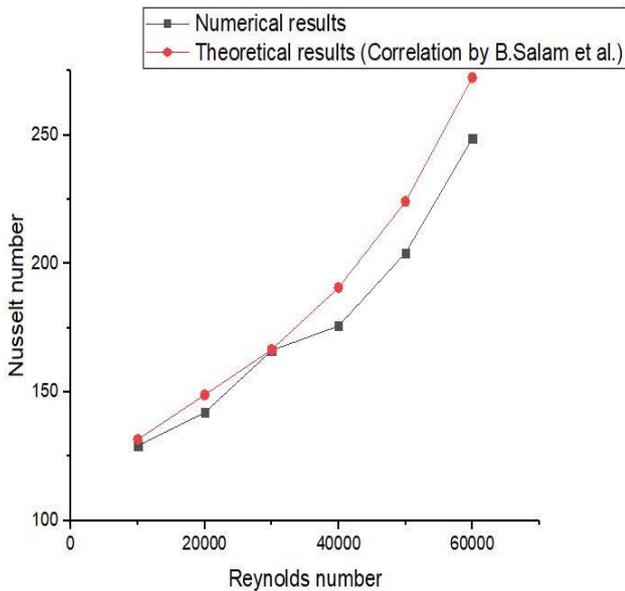


Fig 4. Nusselt number Vs Reynolds number

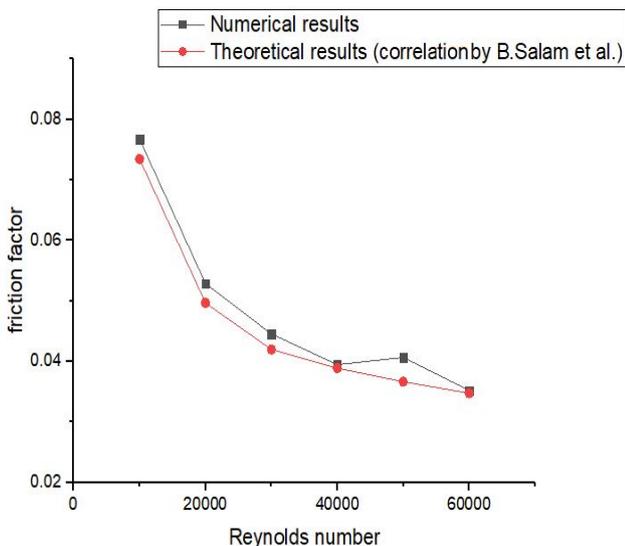


Fig 5. Friction factor Vs Reynolds number

A. Mesh sensitivity analysis:

The mesh sensitivity analysis has been performed to ensure adequate mesh size so that the results are independent of the mesh size. A minimum of three elements is kept in the small elements in the geometry. The mesh is created by having fine elements nearer to the curved walls using the curvature option available in Ansys Workbench software. The maximum face size of the mesh is varied from 0.014896 m to 0.238335 m to study its effect on the Nuselt number. It could be observed from Fig 6 that the results from the mesh size below 0.0446 m do not show much variation. Further, the difference in the last three values is shallow at about 0.04%. Also, reducing the mesh size below 0.0446 m results in a drastic rise in the number of elements that require high computational time. Hence, the mesh size is limited by 0.0446 m for further analysis.

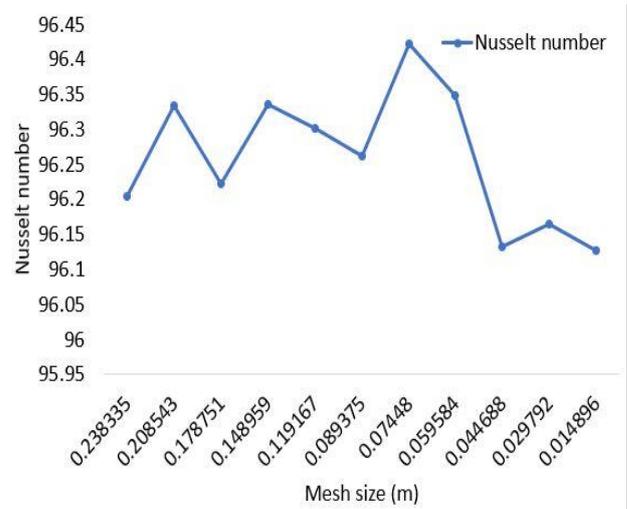


Fig 6. Mesh Sensitivity Analysis

IV. RESULTS AND DISCUSSION

Nusselt number and friction factor for the convective heat transfer with twisted tape with a twist ratio of 12.5 has been investigated. A novel configuration of twisted tape with an angular cut has been introduced. Further, a projection is added to the angular plate, and the performance characteristics are compared. The variation of the Nusselt number with the Reynolds number for twisted tape, modified twisted tape with lateral projection, and modified twisted tape without lateral projection is shown in Fig.7. It is observed from the result that the Nusselt number increases with an increase in the Reynolds number for all three cases. A Higher Nusselt number is achieved in all Reynolds numbers for modified twisted tape with lateral projection compared to the other two cases. That is because the lateral projection provided in the tape enhances the swirl flow and the contact with the boundaries, thereby enhancing the Nusselt number. The lowest Nusselt number is observed in the modified twisted tape without lateral projection. However, the pressure drop is reduced to a greater extent because of the angular cut provided in the tape.

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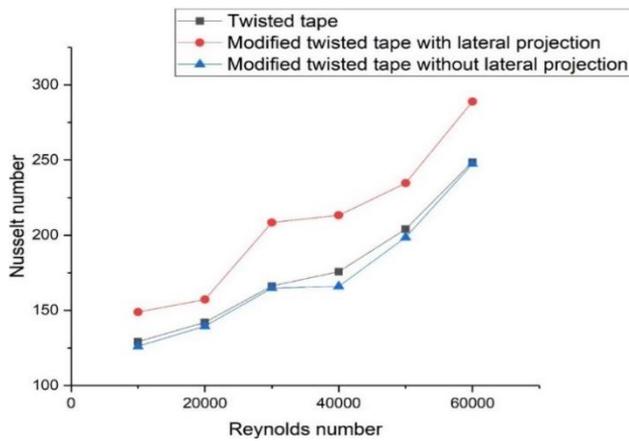


Fig 7. The variation of Nusselt number with Reynolds number

The change in friction factor with Reynolds number is shown in Fig 8. It can be observed from the figure that the friction factor decreases with an increase in Reynolds number, and the modified twisted tape with lateral projection has the highest friction factor in all the Reynolds numbers than the other two cases because of the lateral projection provided additionally. The lowest friction factor is observed in the modified twisted tape without lateral projection because of

the angular cut provided since the angular cut eliminates the pressure drop offered by the tape.

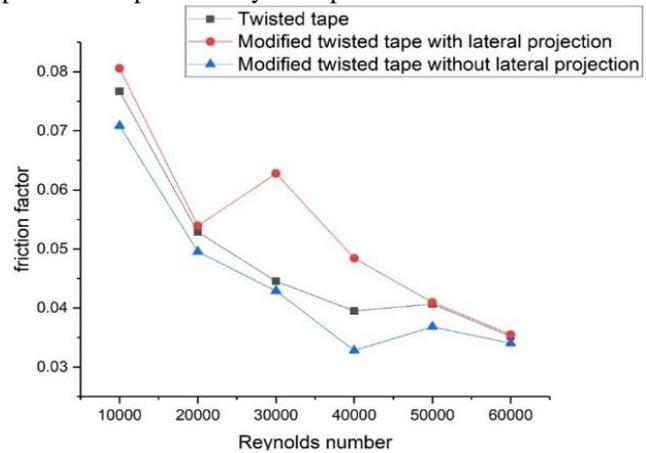


Fig 8. Variation of friction factor with Reynolds number

The main objective of introducing the twisted tape is to create a tangential velocity in the flow domain. The vector plot of the tangential velocity at three pipe cross-sections is plotted in fig. 9,10 and 11 for the different configurations. Fig.9 shows a uniform distribution of tangential velocity along the cross-sections, which increased gradually from the inlet to its outlet.

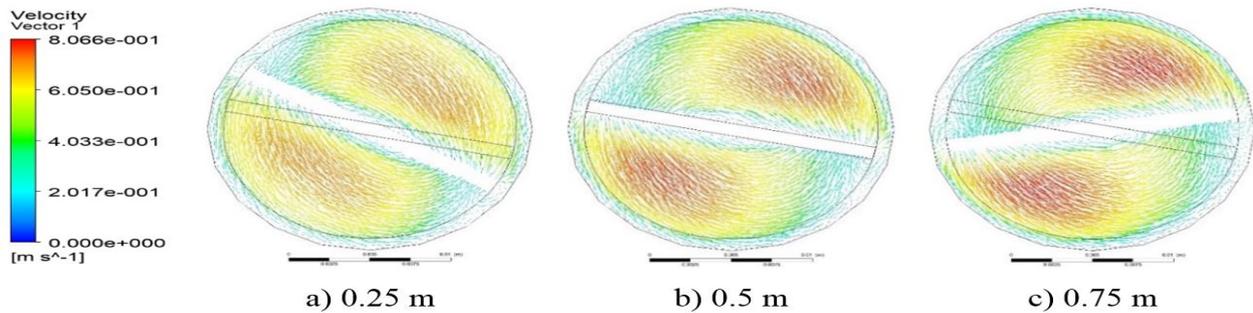


Fig 9. Tangential velocity for the water fluid flow at different positions of twisted tape (Re 10,000)

The tangential velocity vector plot for the proposed twisted tape with an angular cut is shown in Fig. 10. Here, the tangential component of the velocity is slightly reduced because of the angular cut. However, the pressure drop is reduced to 7.6% from the ordinary twisted tape due to the

reduction in the obstructing geometry of the tape. Furthermore, the Nusselt number, in this case, is reduced by 2.33% as the tangential component of the velocity is reduced. Nevertheless, the thermal performance factor is slightly increased because of the drastic reduction in pressure drop.

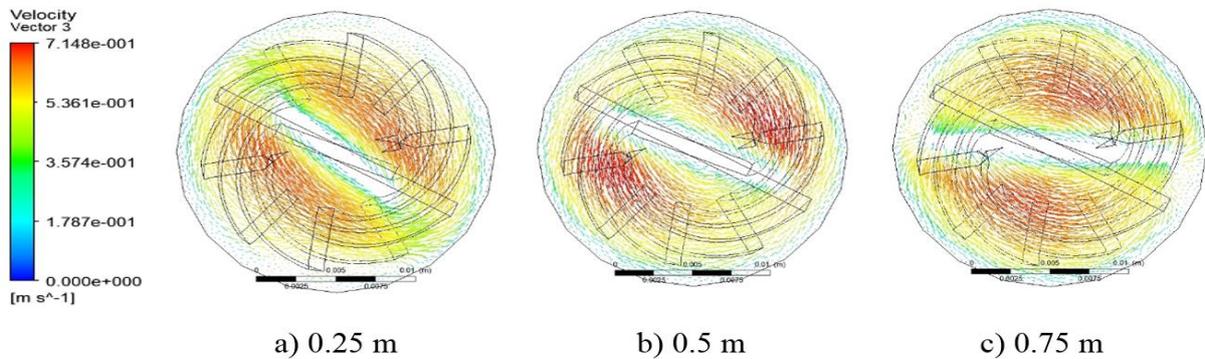


Fig 10. Tangential velocity vectors for the water fluid flow at different positions of modified twisted tape without lateral projection (Re 10,000)

The tangential velocity vectors for the proposed twisted tape with lateral projection are shown in Fig 11. It is observed that the lateral projection provided in the twisted tape gives rise to the tangential velocity of the flow and increases the Nusselt number to 143.87 from 129.17 at Reynolds number 10,000.

Due to the lateral projection, the pressure drop is also increased to 521.17 from 496.07 at a Reynolds number of 10,000. Due to the rapid increase in Nusselt number than the pressure drop, the thermal performance factor slightly increases.

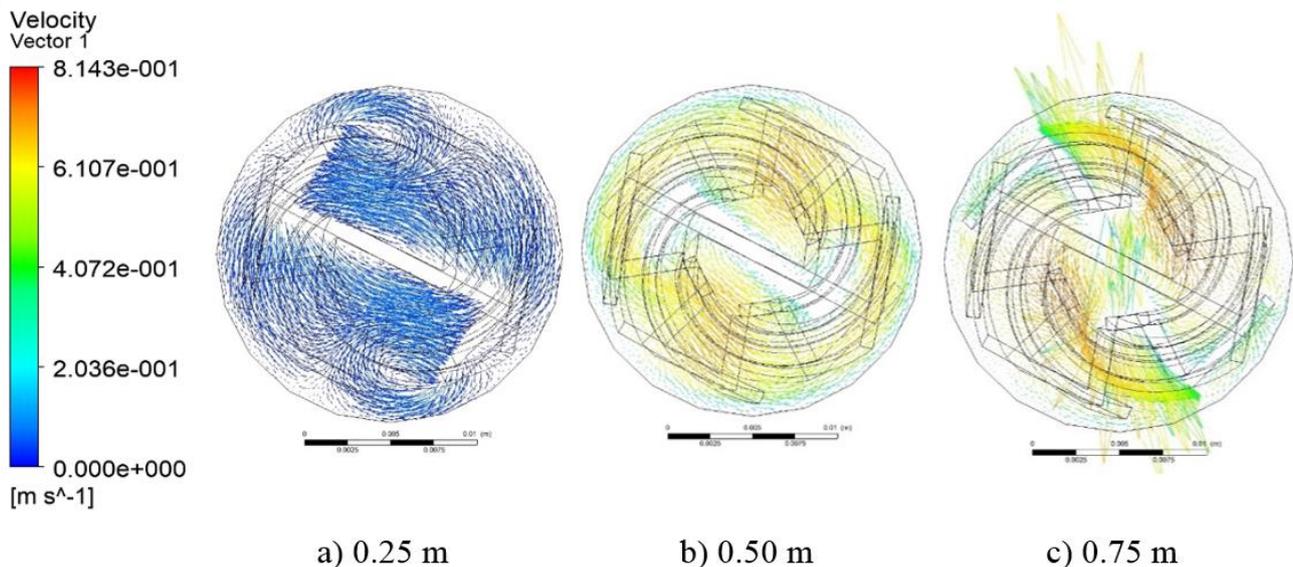


Fig 11. Tangential velocity vectors for the water fluid flow at different positions of Modified twisted tape with lateral projection (Re 10,000)

The temperature contour at Reynolds number 10,000 for various positions from the inlet is shown in Fig 12. The temperature contours show how the heat is efficiently transferred to the fluid and how the geometry helps in improving heat transfer. It is observed that the temperature increases gradually from the inlet towards its outlet. The

twisted tape helps create a swirl flow, breaking the thermal boundary layer. The fluid contact with the wall increases because of the twisted tape's obstruction; heat is transferred to the interior part of the fluid domain as the fluid moves from the inlet towards the outlet.

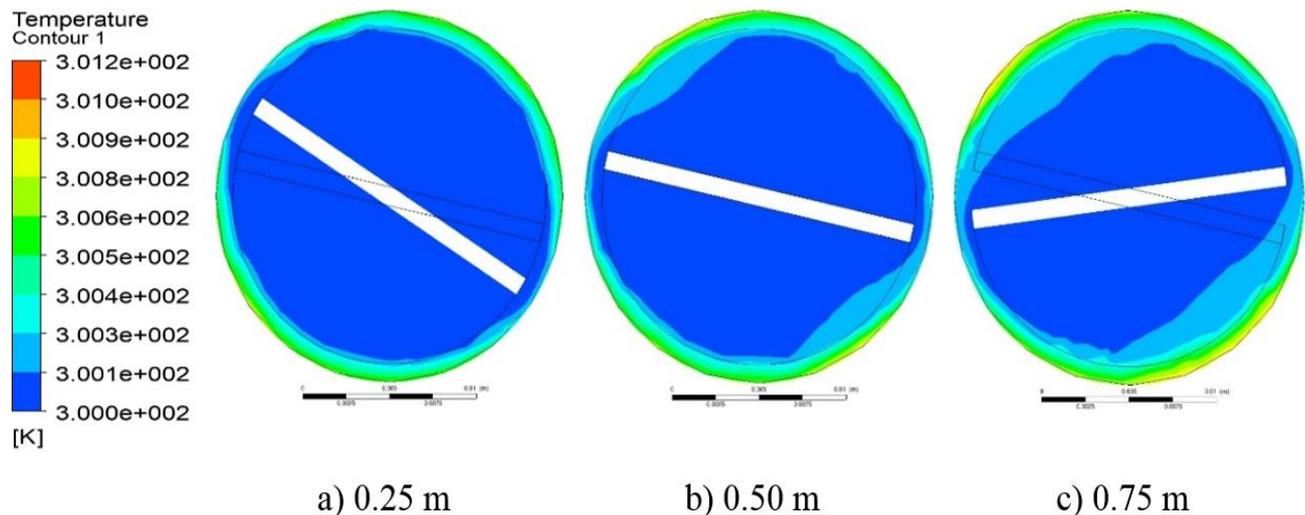


Fig 12. Temperature contour at various positions of twisted tape (Re 10,000)

The temperature contour at Reynolds number 10,000 for various positions of modified twisted tape without lateral projection is shown in Fig 13. It can be noted that the heat transfer is slightly reduced in comparison with that of an

ordinary twisted tape because of the angular cut provided in the tape. Moreover, the convective heat transfer progresses as the fluid moves towards the outlet.

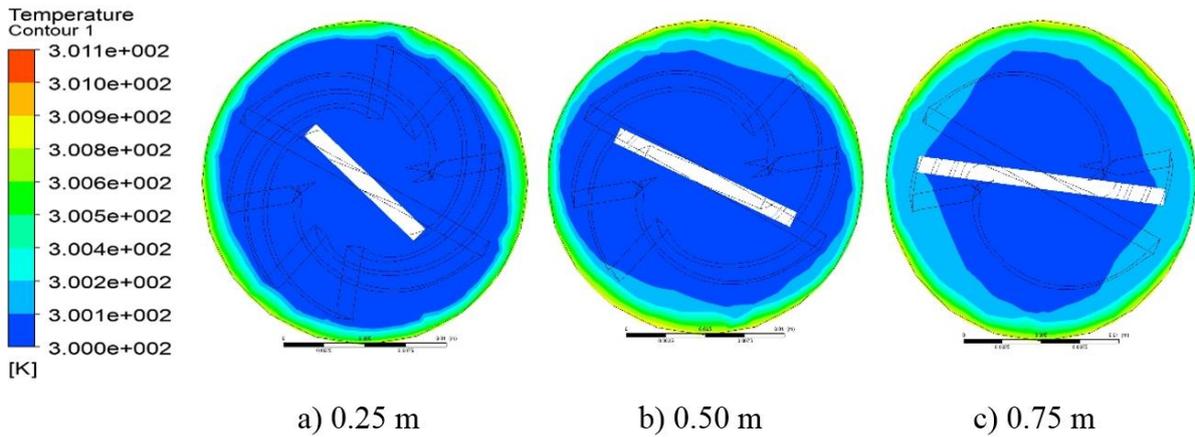


Fig 13. Temperature contour at various positions of modified twisted tape without lateral projection (Re 10,000)

The temperature contour at Reynolds number 10,000 for various positions of modified twisted tape with lateral projection at various positions from the inlet is shown in Fig 14. Modified twisted tape with lateral projection shows

enhanced heat transfer than the ordinary twisted tape because the lateral projection directs the fluid toward the boundaries and increases the contact time at the wall. Hence, the temperature of the fluid is observed to be high at the outlet.

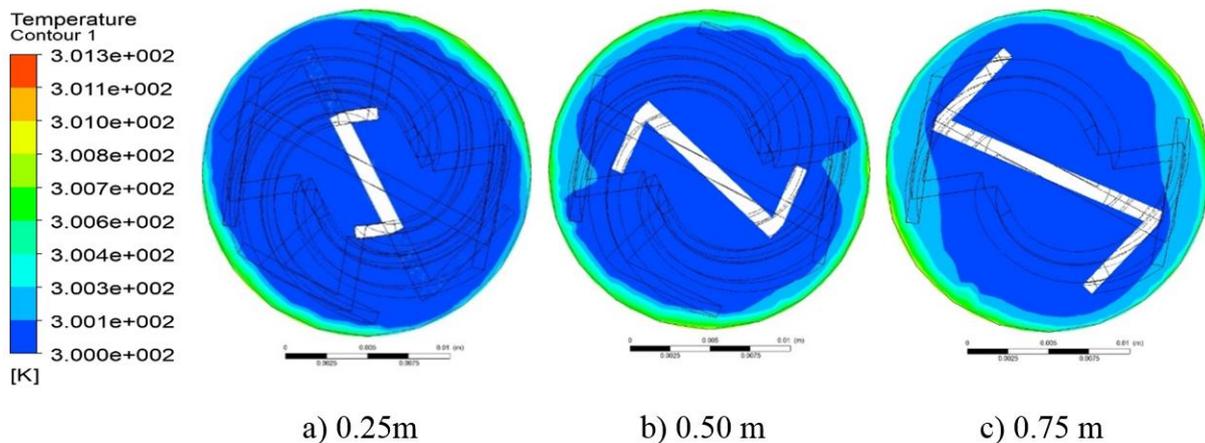


Fig 14. Temperature contour at various positions of Modified twisted tape with lateral projection (Re 10,000)

V. CONCLUSIONS

Two cases of modified twisted tape (modified twisted tape with lateral projection and modified twisted tape without lateral projection) with varying Reynolds numbers in the range of 10,000 – 60,000 were investigated to examine the effect of heat transfer and pressure drop characteristics. Initially, the numerical results are validated with the experimental results obtained by B.Salam et al. [16] for a twisted tape without modification. Further, the results were compared with that of ordinary twisted tape. The following conclusions were made from the numerical analysis

- The angular cut in the modified twisted tape without lateral projection shows a lesser pressure drop than the ordinary twisted tape. Still, the Nusselt number is also slightly reduced because of the angular cut. On average, the pressure drop and Nusselt number of modified twisted tape without lateral projection are reduced to 7.9% and 2.3%, respectively. Due to the drastic decrease in pressure drop, while compared with pressure drop, the thermal performance factor is increased to a maximum extent of 1.0065 at 60,000 Reynolds number in comparison with that of ordinary twisted tape.

- The modified twisted tape with lateral projection shows more pressure drop than the ordinary twisted tape. Even though the angular cut in the tape reduces the pressure drop because of the lateral projection, the pressure drop gets slightly increased. Also, the Nusselt number is increased because of the lateral projection that directs the fluid domain towards the boundary. On average, the pressure drop and Nusselt number of modified twisted tape with lateral projection are increased to 12.03% and 16.7%, respectively. Due to the drastic increase in Nusselt number, while compared with the pressure drop, the thermal performance factor is increased to a maximum extent of 1.1584 at 60,000 Reynolds number compared to that of ordinary twisted tape.

List of Abbreviations:

A	Area of the tube
D	Diameter of the tube
f	Friction factor
h	Convective heat transfer coefficient

H	Enthalpy
K	Thermal conductivity of the fluid
L	Length of the tube
Nu	Nusselt number
P	Pressure
Q	Heat transfer rate
q	Heat flux
Re	Reynolds number
T	Temperature
t	Time
u	Velocity
w	Tape width
y	Tape pitch

Greek Symbols:

ρ	Density
μ	Viscosity
τ	Stress tensor
η	Thermal performance factor
θ	Twist angle

Subscripts:

b	Tube
i	Inlet
o	Outlet
t	Tape
Tot	Total
w	Wall

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Authors Contributions	Prince Abraham Benjamin contributed in Conceptualization, Methodology, Supervision, Writing & Editing, Project administration. Nithin Mohan Mohana Anitha contributed in Software, Formal analysis, Validation, Investigation, Data curation.

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Prince Abraham B. is an accomplished author and academic specializing in computational fluid dynamics (CFD) analysis and simulation. With a Bachelor's degree in Automobile Engineering and a Master's degree in Manufacturing Engineering, he has established himself as an expert in various subjects, including fluid mechanics, machinery, automobile engineering, and power plant engineering. Currently serving as an assistant professor at National Engineering College for over 10 years, he has successfully guided and mentored students in their academic pursuits. Alongside his teaching responsibilities, Prince Abraham B is pursuing a part-time PhD program under Anna University, Chennai, further expanding his knowledge and contributing to the field of CFD analysis and simulation. His research endeavors aim to provide innovative solutions and advancements in this area. As an author, he has published numerous research papers in respected journals and conferences, showcasing his expertise and ability to communicate complex engineering concepts effectively.



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