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

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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 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 less than in the base case with ordinary twisted tape. The Nusselt number in the modified twisted tape with lateral projection is higher than that of the ordinary twisted tape because the lateral projection diverts the fluid towards the boundaries, thereby increasing the thermal performance factor. 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 enhance the system's efficiency, thereby reducing its size and cost. Primarily, swirl flow is utilised to improve heat transfer by breaking down the thermal boundary layer, thereby 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. Researchers were also focusing on similar works [2] [3] in the past years. Novel augments supported with nanomaterials 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].

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A twisted tape is the most preferred choice of passive augment due to its low cost, ease of manufacture, and other factors. 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 Promvonge 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 a single twisted tape. However, as the pressure drop increases, additional energy is required to overcome the frictional resistance. Also, it has been observed that the heat transfer increases with a decrease in the twist ratio. Promvonge 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 a higher heat transfer enhancement index than 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 folded twisted tape inserts are higher than those of 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.

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 observed that it produces better results at low Reynolds numbers than at high Reynolds numbers. 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 observed that at Reynolds numbers in the range of 200-2000, the wire coil is more efficient, while 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 those of a tube using an ordinary twisted tape.

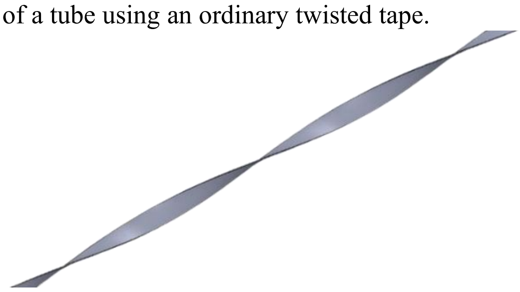

Fig 1. Geometry of conventional twisted tape

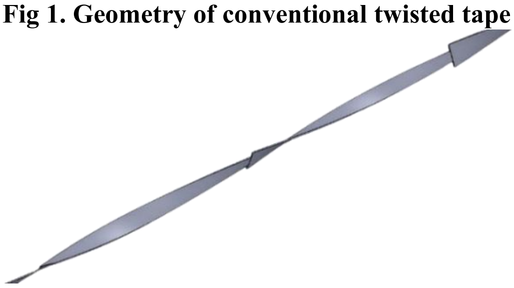

Fig 2. Modified twisted tape without lateral projection

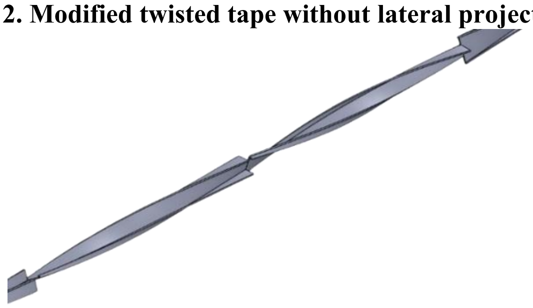

Fig 3. Modified twisted tape with lateral projection

II. PHYSICAL MODEL

A schematic diagram representing twisted tape, modified twisted tape without lateral projection, and modified twisted tape with lateral forecast is shown in Figs. 1, 2, and 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 (θ=720°), tape pitch (y=225 mm), tape width (w=18 mm) are kept constant. The tapes are placed 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 1500/W/m2. The fluid flow is assumed to be incompressible, Newtonian, and 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

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

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,

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

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

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

The total energy equation is given by,

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

$$\text{htot h+U}^2 \tag{5}$$

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,

$$\frac{\partial(pk)}{\partial t} + \frac{\partial(pkui)}{\partial x x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t \partial k}{\sigma_k \partial x_j}\right] + 2\mu_t E_{ij} E_{ij} - \rho\varepsilon \tag{6}$$

Parameter definition:

$$Q = hA\Delta T \tag{7}$$

$$q = \frac{Q}{A} \tag{8}$$

$$h = \frac{q}{\Delta T} \tag{9}$$

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

$$Re = \frac{\rho u D}{\mu} \tag{10}$$

$$Nu = \frac{hD}{k} \tag{11}$$

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

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

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III. VALIDATION OF NUMERICAL MODEL

To validate the numerical model, a theoretical correlation for the Nusselt number and the friction factor, as proposed by B. Salam et al., was employed [16]. The values were adopted and then 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 presented in Fig. 4, and the effect of the friction factor on the Reynolds number is illustrated 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%.

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

$$f = 25.475\, Re^{-1.0173} . (^{y}/_{w})^{2.4015} \tag{15}$$

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

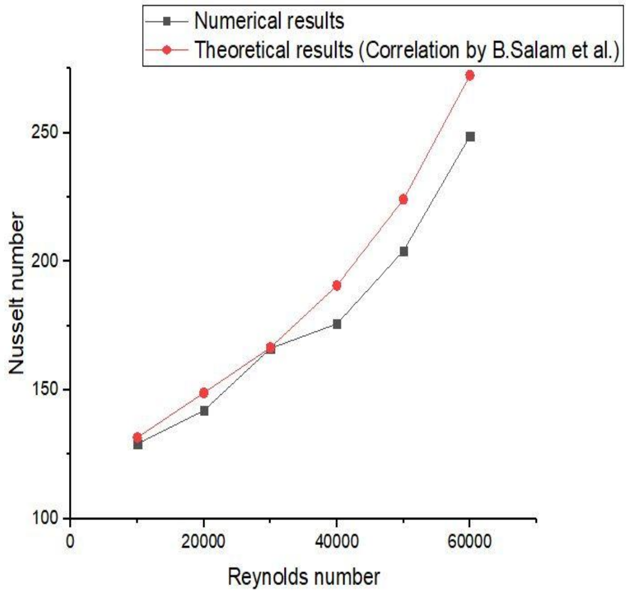

Fig 4. Nusselt number Vs Reynolds number

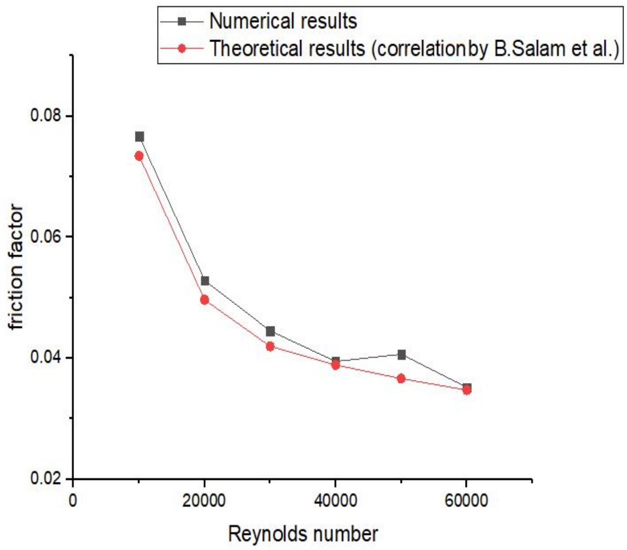

Fig 5. Friction factor Vs Reynolds number

A. Mesh sensitivity analysis:

A mesh sensitivity analysis has been performed to ensure an adequate mesh size, ensuring the results are independent of mesh size. A minimum of three elements is kept in the small aspects of the geometry. The mesh is created by using fine elements near the curved walls, which is made possible by the curvature option available in the 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 Nusselt number. It can be observed from Fig. 6 that the results for mesh sizes below 0.0446 m exhibit no significant variation. Furthermore, the difference in the last three values is slight, at approximately 0.04%. Additionally, reducing the mesh size below 0.0446 m results in a significant increase in the number of elements that require high computational time. Hence, the mesh size is limited to 0.0446 m for further analysis.

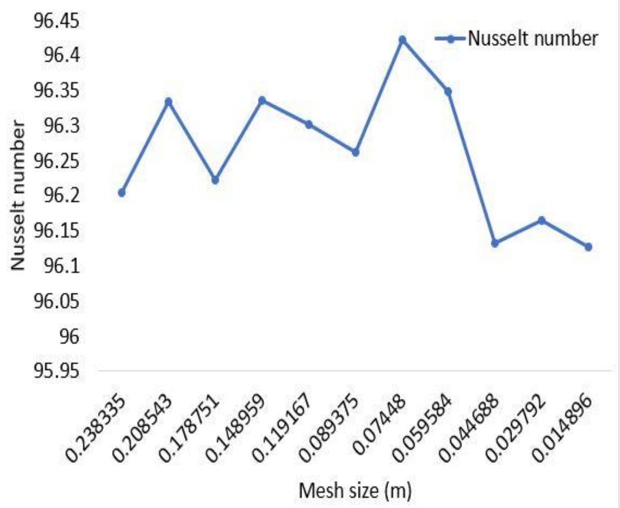

Fig. 6. Mesh Sensitivity Analysis

IV. RESULTS AND DISCUSSION

The Nusselt number and friction factor for convective heat transfer with a twisted tape having a twist ratio of 12.5 have 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. The results show 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 the modified twisted tape with lateral projection compared to the other two cases. That is because the lateral forecast provided in the tape enhances the swirl flow and the contact with the boundaries, thereby strengthening 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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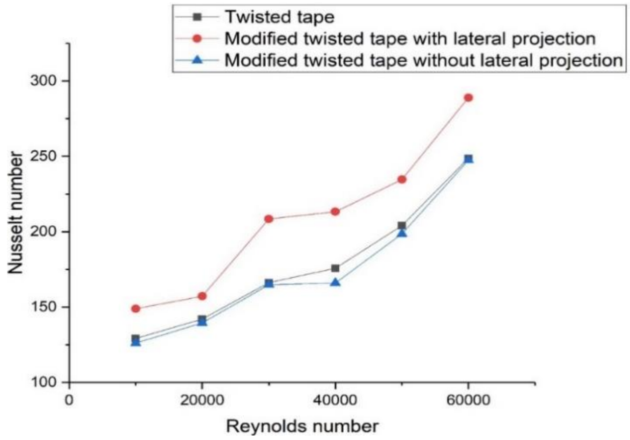


Fig 7. The variation of the Nusselt number with the Reynolds number

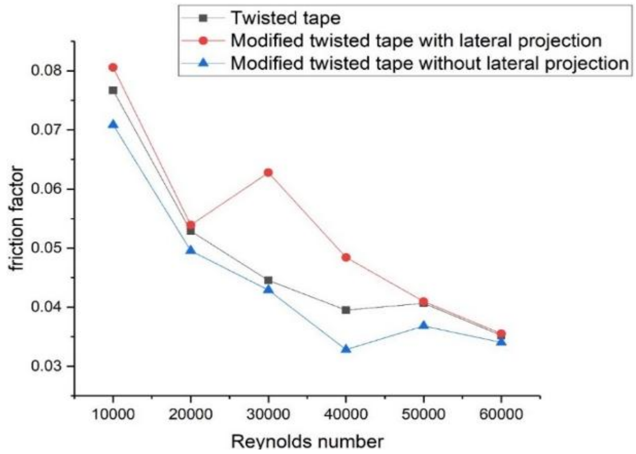
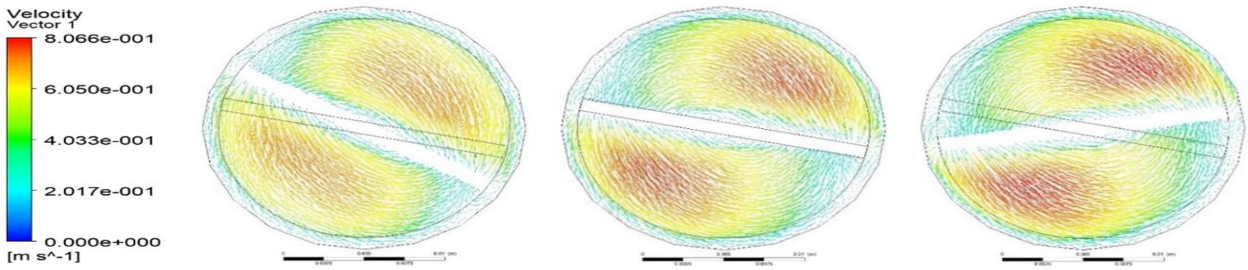


Fig 8. Variation of friction factor with Reynolds number

The change in friction factor concerning the Reynolds number is shown in Fig. 8. It can be observed from the figure that the friction factor decreases as the Reynolds number increases. The modified twisted tape with lateral projection has the highest friction factor among all the Reynolds numbers, surpassing the other two cases due to the additional lateral projection. The lowest friction factor is observed in the modified twisted tape without lateral forecast, due to the angular cut provided, which eliminates the pressure drop offered by the tape.

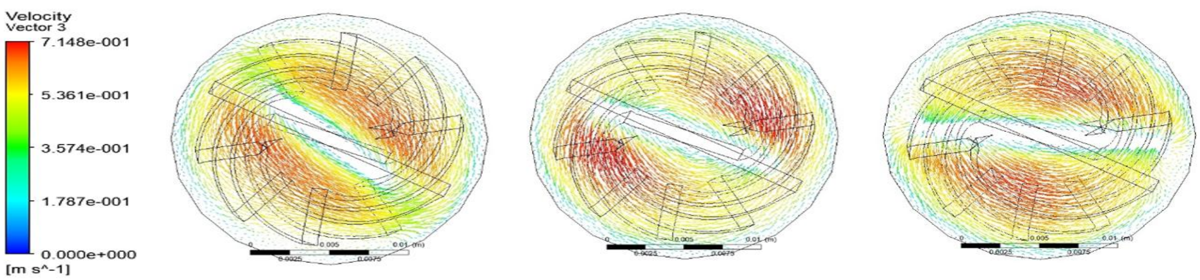
The main objective of introducing the twisted tape is to create a tangential velocity in the flow domain. The vector plot of the tangential velocity at three pipe cross-sections is plotted in Figures 9, 10, and 11 for the different configurations. Fig. 9 shows a uniform distribution of tangential velocity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



a) 0.25 m b) 0.5 m c) 0.75 m

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.



a) 0.25 m b) 0.5 m c) 0.75 m

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

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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 a tangential velocity of the flow and increases the Nusselt number to 143.87 from 129.17 at a Reynolds number of 10,000. Due to the lateral projection, the pressure drop rises to 521.17 from 496.07 at a Reynolds number of 10,000. Due to the rapid increase in Nusselt number compared to the pressure drop, the thermal performance factor increases slightly.

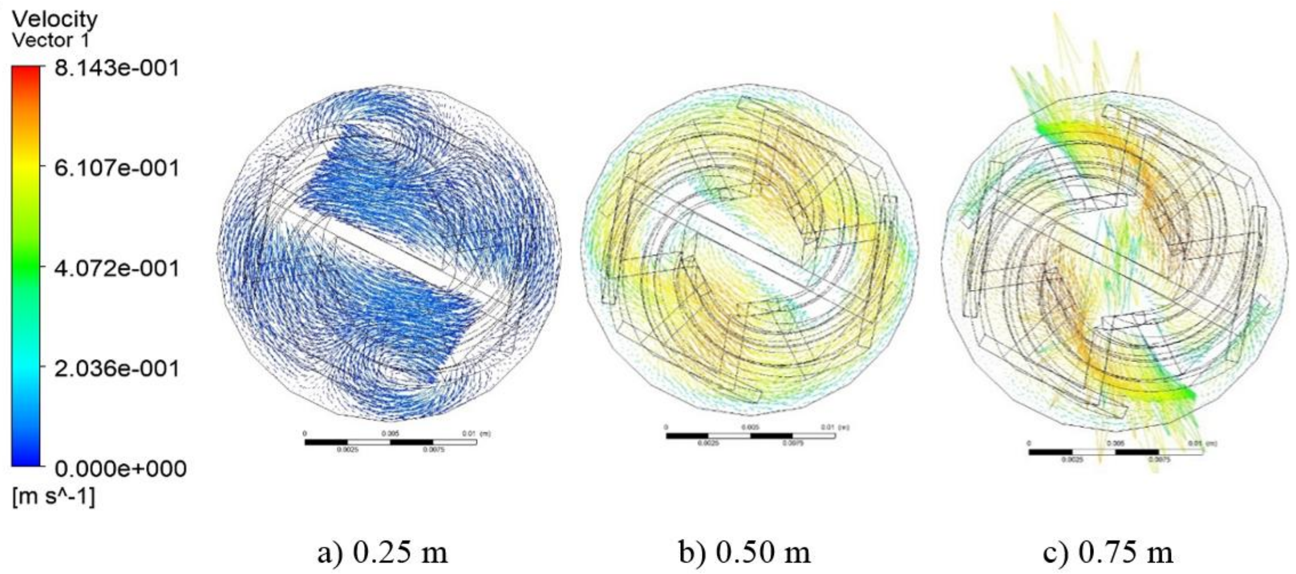


Fig 11. Tangential velocity vectors for the water fluid flow at different positions of the modified twisted tape with lateral projection (Re 10,000)

The temperature contour at a Reynolds number of 10,000 for various positions from the inlet is shown in Fig. 12. The temperature contours illustrate how heat is efficiently transferred to the fluid and how the geometry enhances 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 due to the obstruction caused by the twisted tape; heat is transferred to the interior part of the fluid domain as the fluid moves from the inlet to the outlet.

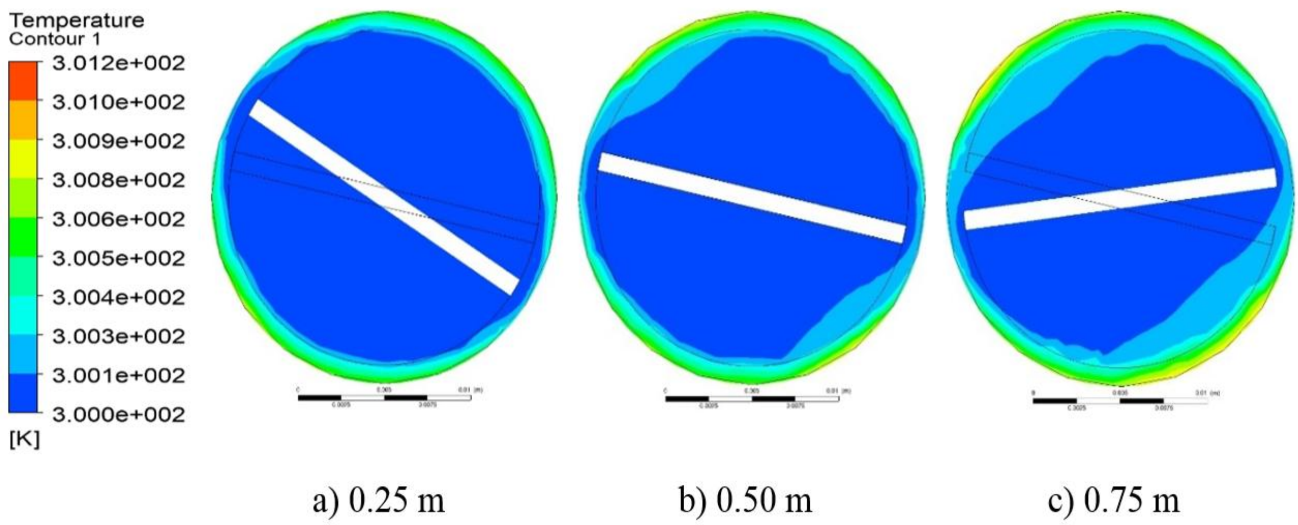
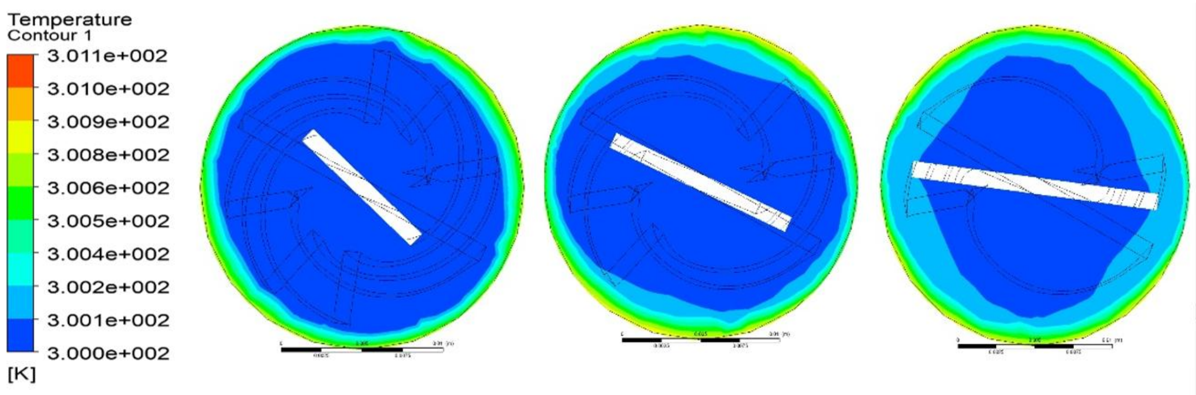


Fig 12. Temperature contour at various positions of twisted tape (Re 10,000)

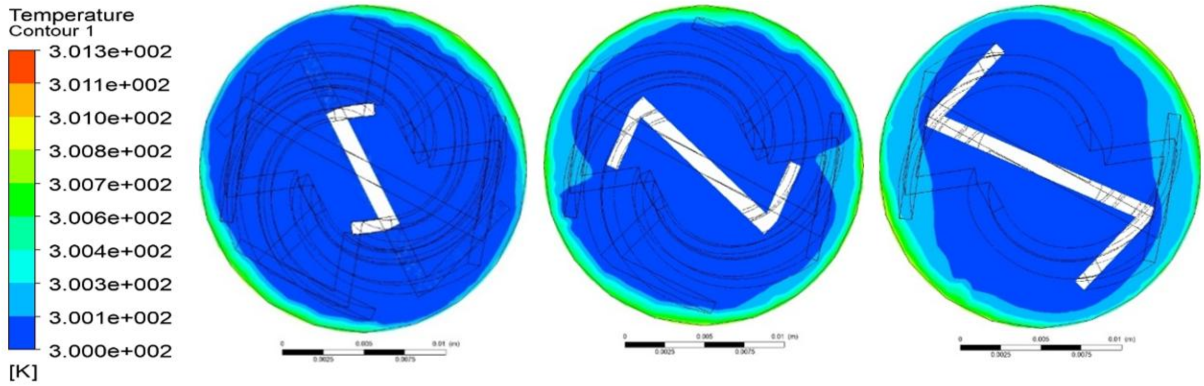
The temperature contour at a Reynolds number of 10,000 for various positions of the modified twisted tape without lateral projection is shown in Fig. 13. It can be noted that the heat transfer is slightly reduced compared to that of an ordinary twisted tape due to the angular cut provided in the tape. Moreover, the convective heat transfer progresses as the fluid moves towards the outlet.



a) 0.25 m b) 0.50 m c) 0.75 m

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

The temperature contour at a Reynolds number of 10,000 for various positions of the modified twisted tape with lateral projection at different positions from the inlet is shown in Fig. 14. A modified twisted tape with lateral projection exhibits enhanced heat transfer compared to the ordinary twisted tape, as the lateral projection directs the fluid toward the boundaries and increases the contact time at the wall. Hence, the temperature of the liquid is observed to be high at the outlet.



a) 0.25m b) 0.50 m c) 0.75 m

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, ranging from 10,000 to 60,000, were investigated to examine the effects 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 those of ordinary twisted tape. The following conclusions were made from the numerical analysis

- The. An 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 by 7.9% and 2.3%, respectively. Due to the drastic decrease in pressure drop compared to the ordinary twisted tape, the thermal performance factor increases to a maximum extent of 1.0065 at a Reynolds number of 60,000.
- The modified twisted tape with lateral projection shows more pressure drop than the ordinary twisted tape. Although the angular cut in the tape reduces the pressure drop due to lateral forecast, the pressure drop increases slightly. Additionally, the Nusselt number increases due to the lateral projection, which directs the fluid domain towards the boundary. On average, the pressure drop and Nusselt number of the modified twisted tape with lateral projection increase by 12.03% and 16.7%, respectively. Due to the drastic increase in Nusselt number compared to the pressure drop, the thermal performance factor reaches its maximum extent of 1.1584 at a Reynolds number of 60,000, surpassing that of an ordinary twisted tape.

List of Abbreviations:

A	Area of the tube
D	Diameter of the tube
f	Friction factor

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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
ɳ	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 to Conceptualisation, Methodology, Supervision, writing, editing, and Project Administration. Nithin Mohan Mohana Anitha contributed to software, Formal analysis, Validation, Investigation, and Data curation.

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