International Journal on Recent and Innovation Trends in Computing and Communication
Volume: 5 Issue: 5
ISSN: 2321-8169
338 – 345

Numerical Investigation of Thermal Performance Factor for different Twisted Tape Configurations

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Abstract: In this article an attempt has been made to study the heat transfer variations for different twisted tape geometry. Twisted tapes of different pitch and split ratios arranged in alternate clock and counter clockwise for fully developed laminar flow were used to study heat enhancement. The numerical analysis was carried out in different Reynolds number ranging between 400-1000 for a different pitch ratio (y = p/w, 3.2, 6.5 and 13) and split ratio (S=L/n, n=2, 3, 4), every split arranged in a counter clockwise with preceding one. The investigation revealed that decrement in pitch ratio and increment in split ratio enhances the heat transfer rate. Thermal Performance factor (TPF) is also calculated for different tape configurations and its variation is also notified in the work.

***Keywords**: Clockwise, Counter Clockwise, Twisted Tape Inserts, Thermal Performance factor, Enhancement, Pitch Ratio, Split Ratio.*

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I. INTRODUCTION

Many augmentation techniques are used to increase the performance of heat ex-changers with passive techniques in different application in order to avoid the complexity of manufacturing parts and equipment with simple geometries, low cost to increase thermal performance efficiency. Among different passive techniques, twisted tape inserts are most promising. The whirl flow generated by twisted tapes develops the turbulence effect across the tape, thus reducing the boundary layer thickness and promotes higher heat transfer coefficient. These device find space application where there is a need for miniaturization of heat exchanger.

Bodius Salam et.al, [1] carried out an experimental investigation for rectangular cut twisted tape insert at Reynolds numbers varied in the range 10000-19000 with heat flux variation 14 to 22 kW/m^2 for smooth tube, and 23 to 40 kW/m^2 for tube with insert. The Nusselt number and friction factor increased by 2.3 to 2.9 times and 1.4 to 1.8 times respectively compared to that of smooth tubes. Heat transfer enhancement, efficiency ranges from 1.9 to 2.3 as the Reynolds number increases. Muhammad Mostafa Kamal Bhuiya et.al, [2] investigation on helical tape inserts with different twist ratios made up of mild steel to evaluate the heat transfer performance for turbulent flow. The experimental study indicated that the Nusselt number, friction factor and thermal performance factor were enhanced as the twist ratio decreases. Siva Rama Krishna et.al, [3] carried out experiments to study the effect of tape fin of different materials and twist ratio in Reynolds number 200 to 2000 to improve Nusselt number. Result reveal that the maximum improvement in Nusselt number range from 50-100% for Aluminium tapes, 40-94% for Stainless Steel and 40-67% for insulated tapes. J.D. Zhu, H.Chen, [4] described the numerical study on the single-phase enhanced convective heat transfer effect with single, double, triple twisted tape inserts. The result reported increase in heat transfer by 1.8-4.5 times and flow resistance by 6-21.2 times for different forms of twisted tape inserts. Sabbir Hossain et.al, [5] presented a Finite Element based model of the heat transfer problem with Reynolds number 1600-2400 using insert to diffuse the fulid particle in the laminar flow. The optimum distance between the inserts showed the greater efficiency of the heat transfer rate. Smith Eiamsa-ard , Pongjet Promvonge [6] in his article represented the performance assessment in a heat ex-changer tube with alternate clockwise and counterclockwise twisted-tape inserts, results showed that the Nusselt number and performance were more than the typical twisted tapes at similar operating conditions. The Nusselt number in the tube fitted with the C–CC twisted tapes are higher than those with the typical twisted tape and the plain tube is around 12.8–41.9% and 27.3–90.5%, respectively. K. Nanan et.al, [7] carried out numerical and experimental study to investigate heat transfer enhancement in circular tubes with transverse twisted baffles and result reveal that the use of insert results enhanced heat transfer rate with low pressure drop and the thermal performace factor increases as baffle width ratio increases and twist ratio decreases. Dr. A. G. Matani1, Swapnil A. Dahake [8] study on heat transfer enhancement in a tube using counter/co-swirl generation indicates that the tube with the various inserts demonstrate that friction factor (f) and thermal enhancement index (η) increase with decreasing twist ratio (y/w). The results also show that the wire coil twisted tapes are more efficient than the twisted tapes for heat transfer enhancement. S. V. Patil, P. V. Vijaybabu [9] reported results of friction factor and heat transfer characteristics of a square duct fitted with twisted tapes of different twist ratios at uniform wall temperature conditions. The thermohydraulic performace is anyalyzed to identify the potential benefits of using a twisted tape. Ali Habibi Khalaj et. al, [10] demonstrated effectiveness of soft computing techniques in thermo-hydraulic behavior modeling of passive heat transfer enhancement (HTE) techniques (ANN and ANFIS). The results were compared with experimental data and found mean effective error (MRE) to be less than 3% and 1.5% for thermo-hydraulic behaviour modeling of wire coil and twisted tape inserts, respectively. Mazen M. Abu-Khader [11] illustrated the effect imposed by twisted tapes at various laminar, transition and turbulent flow regimes. At the laminar flow, tube insert technology is more effective than turbulent region because of the larger enhancement ratio and also the laminar Nusselt number rises with decreased inside tube diameter and the effect of the twist ratio appears significantly. Shyy Woei Chang et.al, [12] performed heat transfer and pressure drop measurements with $3{,}000 \leq Re < 14{,}000$. The local Nusselt numbers in the tubes fitted with single, twin, and triple twisted tapes were, respectively, 1.5-2.3, 1.98-2.8, and 2.86-3.76 times of the Dittus-Boelter levels and found significant increase in Nusselt in the laminar flow regime than those developed in the turbulent flow regime. And also reported for each tested Re, f values increased when the number of twisted-tape increased; but the friction ratios f/f_{ref} decreased with the increase of Re for turbulent flows. S. Naga Sarada et,al, [13] in his work explained the variation of heat transfer coefficient and pressure drop using variable width twisted tape. The Nusselt number increased from 36-42% (full width) as the twist ratio decreases for reduced tape width, compared with plain tube Sombat Tamna et.al, [14] carried out an experimental work with Re number from 5300 to 24000 at constant wall heat-flux for double twisted tapes common with 30^0 V-shaped ribs. The maximum thermal enhancement factor is about 1.4 for the v-ribbed twisted tape at blockage ratio 0.09, but for twisted tape with no rib it is around 1.09. Kiran Prakashrao Deshmukh et.al, [15] performed numerical simulation on CFD for helical tapes with and without rod. The results show that Nusselt number increased by 160%, 150%and 145% for full length helical tape with and without rod and regularly spaced tapes respectively, in comparison with plain tube. Jiju jose et. al, [16] conducted a project with different twist ratio and observed that heat transfer effectiveness are 0.49, 0.67 and 0.758 for plain tube, twist ratio y=8.00 and y=5.25 respectively, which indicate effectiveness increases as the twist ratio decreases. Shivalingaswamy B.P and Narahari G A, [17] used circular-ring turbulators with different diameter and pitch ratios, reported that for the Reynolds number varied from 4000 and 20,000 heat transfer augmented around 57% to 195% compared to plain tube. Maheshkumar J.Patel et.al, [18] in their experimental work observed that Nu number, overall heat transfer coefficient and and friction factor increased by 22 to 68, 620 to 1500 and 0.008 to 0.19 respectively for twisted tape insert and with sponge inserts for Re 2700 to 13000. S. Vahidifar and M. Kahrom [19] investigation using wire-coil and Rings shows the highest uncertainties of Nusselt number, friction factor and Reynolds number as approximately ±7.9%, ±8.1% and ±5% respectively. The overall enhanced efficiency of 128% is reported for rings in good condition. Kumbhar D. G. [20] performed experimental analysis on a dimpled tube heat exchanger with regularly spaced twisted tape inserts and Reynolds number ranging from 4,200 to 16,000. Tests were conducted for twisted tape with full length with twist ratio (y/D = 2,3,4), space ratio (s/D = 4.5, 9.0) equipped with dimpled tube with pitch ratio (P = 1.5, 3.0). Result reveal rate of heat transfer increases with decrease in pitch ratio and smaller space ratio. Also full length twisted tapes equipped in dimpled tube perform better compared to other combination. Swapnil A. Dahake et al. [21] conducted tests using the twisted tapes (TT) with twist ratios (y/w = 3.5, 2.66 and 2.25) and wire coil along with twisted tapes (WCTT) pitch ratio of 1.17 for Reynolds numbers range between 5000 and 18,000 under uniform heat flux conditions. The results show that the WCTT are more efficient than the TT for heat transfer enhancement. P. Eiamsa-ard et al. [22] explained the effects of the regularly-spaced twisted tape (RS-TT) of a full length twisted tape with twist ratios (y = P/W, 6.0 and 8.0) and space ratios (s= S/P, 1.0, 2.0 and 3.0). At similar conditions, full length twisted tapes gave higher heat transfer rate, friction factor and thermal performance factor than regularly-spaced ones. In this article numerical investigation is performed to study the thermal performance ratio for different twisted tape under uniform surface temperature using CFD (fluent). The heat transfer enhancement and thermal performance ratio were analyzed for different Reynolds number of fully developed steady states in the laminar flow regime. The heat enhancement can be further improved by replacing with nano fluid [23].

II. NUMERICAL SIMULATIONS

Computational fluid dynamics is having a vide application in industry as it gives approximate computer based solutions. In this article CFD is used to study the numerical model for fluid flow and heat transfer in a circular tube using governing equation to perform steady 3Dimensional calculation at constant surface temperature for imcompressible laminar flow. The Navier - Stokes equations are the governing equations based on the conservation law of Continuity, Momentum, and Energy equation of continuity developed by employing the law of conservation of mass to a small volume element within a flowing fluid.

2.1 Governing Equation

Conservation of Mass (Continuity Equation)

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

Conservation of Linear Momentum

$$u_i \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + v\frac{\partial^2 u_i}{\partial x_j^2} \tag{2}$$

Conservation of Energy

$$\left[u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right] = \alpha\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right] \tag{3}$$

2.2 Design and Modeling

Twisted tapes are designed and modeled using ANSYS Workbench. First, we have designed a circular tube without insert and then with inserts of different configuration . Heat exchanger tube with inner diameter 40mm and length 1000mm was modeled into which full length aluminium tape of width 38 mm is inserted. For every pitch ratio, tape was cut for number of splits (n=2, 3, 4) with split ratio L/n. These split lengths, were arranged in opposite direction with respect to that of the former split length from clockwise to counterclockwise and vice versa. Different configuration of twists are modeled using pitch ratio and split ratio for producing swirl flow in opposing direction with respect to former split length. The modeled geometry of twist with twist ratio y=3.2 and split ratio L/n (n=2) is shown in Fig. 1.

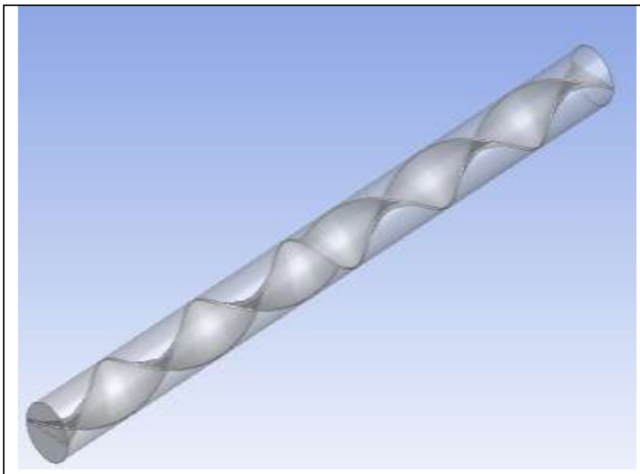

Fig. 1 Geometry of twist with twist ratio y=13 and split ratio S=L/2

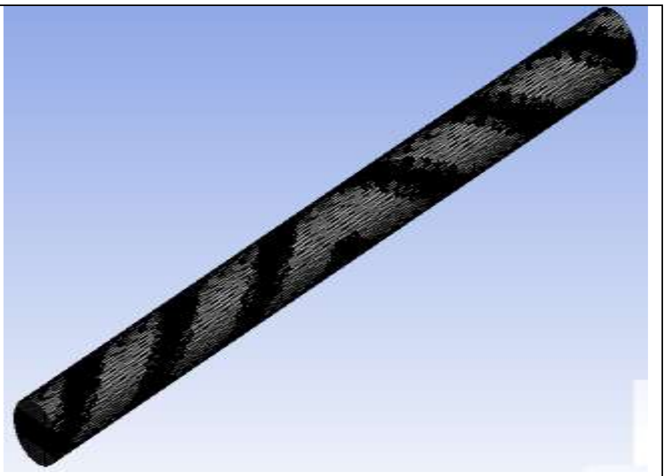

Fig. 2 CFD meshed geometry used for analysis

2.3 Mesh Independency and Code Validation

Discretization is a method of dividing the element into the domain. Finite Volume Method is used, to find if the Naviers-Stokes equation is applied to control Volume is satisfied, then it will satisfy the whole domain. Mesh independence was carried out to evaluate the domain accuracy of the simulated results. A test was conducted for laminar flow at Re=1000 for different mesh volumes. Fig. 2. Shows the CFD meshed geometry used for Simulation. It is observed that there is a substantial change in the results as the number of nodes increased thereafter the accuracy became constant around domain with mesh volume 1376886. Hence the simulation results were carried out at this cell. Validation test was performed for the results of the Nusselt number for plain tube in order to validate the CFD simulation results with a constant value of the Nusselt number in forced convection for fully developed laminar flow. The results obtained by numerical simulation agree with a discrepancy of 4.64% in the Nusselt number.

2.4 Boundary Conditions

The experiment is conducted in steady state fully developed laminar flow at isothermal boundary condition. The typical boundary conditions in CFD are incorporated without slippage and constant surface temperature of 333K and inlet temperature of water as 293K (assuming ambient temperature). The mass flow rates for incompressible laminar flow are given as input to fully developed flow as periodic conditions considering pipe inlet and outlet as periodic interfaces.

III. Results and Discussions

Fig 3.1 depicts the velocity contour for pitch ratio y=13 and split ratio S=L/2 at Re=1000. The whirl flow due to twist resulted in the reduction of boundary layer thickness and the increase in the flow velocity. The boundary layer disturbance was occured due to the axial velocity component, the rotational flow induced by the twisted tape inserts and turbulence intensity caused due to whirl. This results in high pressure loss in the tube than the plain tube because of a higher surface area and the dissipation of dynamic pressure of the fluid at a high viscosity loss near the tube wall. Moreover, the pressure loss had a high possibility to occur by the interaction of the pressure forces with inertial forces in the boundary layer. Fig 3.2 shows velocity contour for twist ratio y=13 and split S=L/3 . For the same pitch ratio at Re=1000, as the split ratio increased from L/2 to L/3 the velocity increased form $5.019\text{x}10^{-2}$ to $5.231\text{x}10^{-2}$. This is due to the increase in split ratio, as the split ratio increases the velocity increases due to encumbrance of reversal of twist at perodic interval. This result in higher heat transfer coefficient. Fig. 3.3 depicts the velocity contour for pitch ratio y=6.5 and S=L/3. The velocity increased due to fluid turbulence intensity of decreased twist ratio. The maximum velocity is $6.063\text{x}10^{-2}$m/s for y=3.2 and S=L/4 (Fig. 3.4) which is maximum compared to lowest pitch ratio y=13 and split ratio S=L/2. As the velocity increased the Nusselt number increased by ±52% compared to twist ratio y=13 and split S=L/2. The above result, reveals that with the decreases in the pitch ratio and increase in twist ratio, subject to whirl flow and transcription of twist in alternate clockwise and counter clockwise direction increases velocity, which result in heat enhancement.

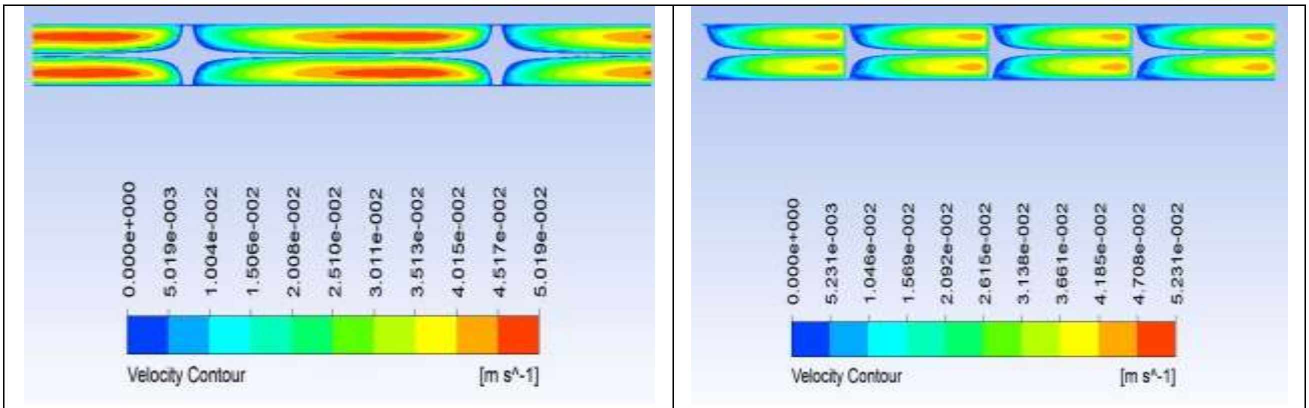

Fig. 3.1 Twisted tape with y=13 and S=L/2

Fig. 3.2 Twisted tape with y=13 and S=L/2

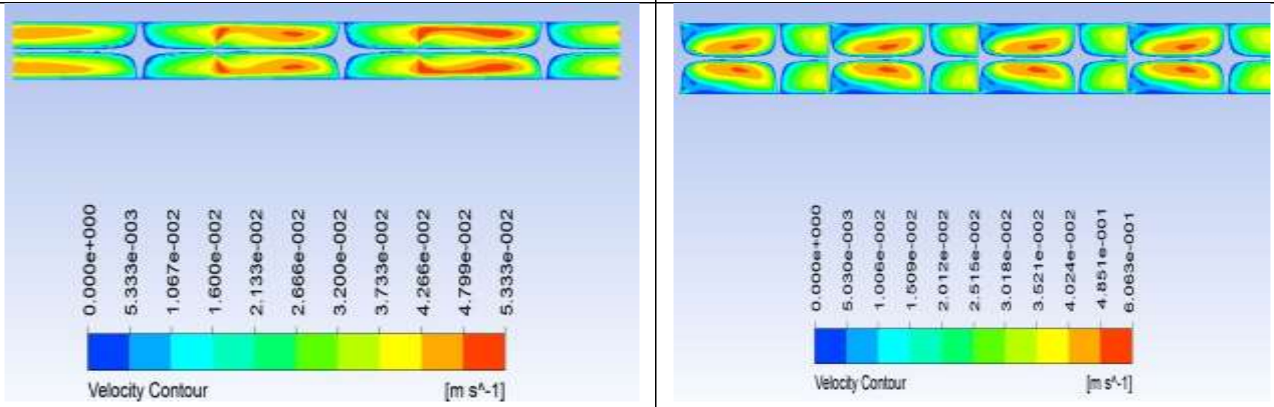

Fig. 3.3 Twisted tape with y=6.5 and S=L/3

Fig. 3.4 Twisted tape with y=3.2 and S=L/4

Fig. 3: Velocity contours for various twisted tapes with Pitch ratios y = 3.2, 6.5 and 13 and split ratio (S=L/n) arranged in alternate counter and counter-clockwise direction for each spit.

The comparison results of convection heat transfer of alternate clockwise and counter-clockwise twisted tapes with different pitch ratio and split ratio are shown in **Fig. 4.** With the increase in the Reynolds number, Nusselt number increases consistently for all the C-CC twists due to the disordered mixing. This disordered mixing was responsible for breaking the thermal boundary layer between the core and tube wall flow and increase in flow velocity. Reynolds number was calculated on inner diameter for tube with twisted tape. For Re=400 and Re 1000 as the pitch ratio decreases and the split ratio increases Nusselt number increased by 146% and 94% respectively. At lower Reynolds number there is considerable increase in the Nusselt number as pitch ratio is decreased and split ratio increased. As the Reynolds number increased, the Nusselt number increased from 47-87%. The alternate clockwise and counterclockwise arrangement is responsible for the turbulence intensity which lead to higher heat transfer coefficient. **Fig. 5** show the relation between the twist ratio and the Nusselt number for Re=1000. It is observed that for a split ratio (S=L/2), as the pitch ratio decreases, the Nusselt number increases by 78%. This is due to the continuous change in the flow path of the fluid through out the length of flow. At every split ratio,the larger portion of fluid are directed to the opposing direction provoking stronger whirl flow, leading to thinner boundary and resulting transfer of heat more efficiently.

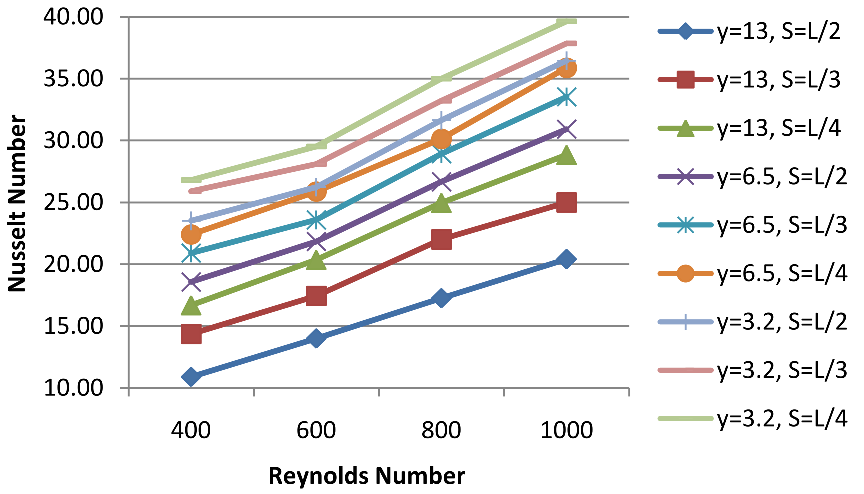

Fig. 4: Variation of Nusselt number with Reynolds number

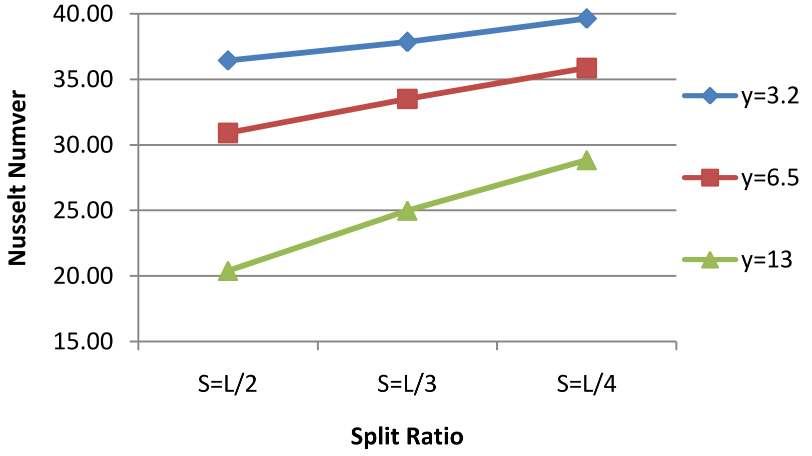

Fig. 5: Variation of Nusselt number with Split ratio

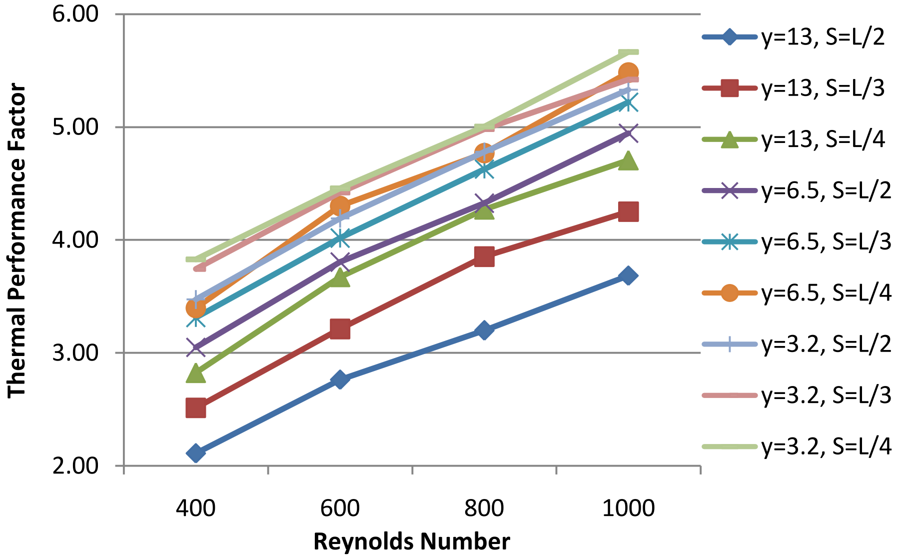

Fig. 6: Variation of Thermal Performance Factor with Reynolds number

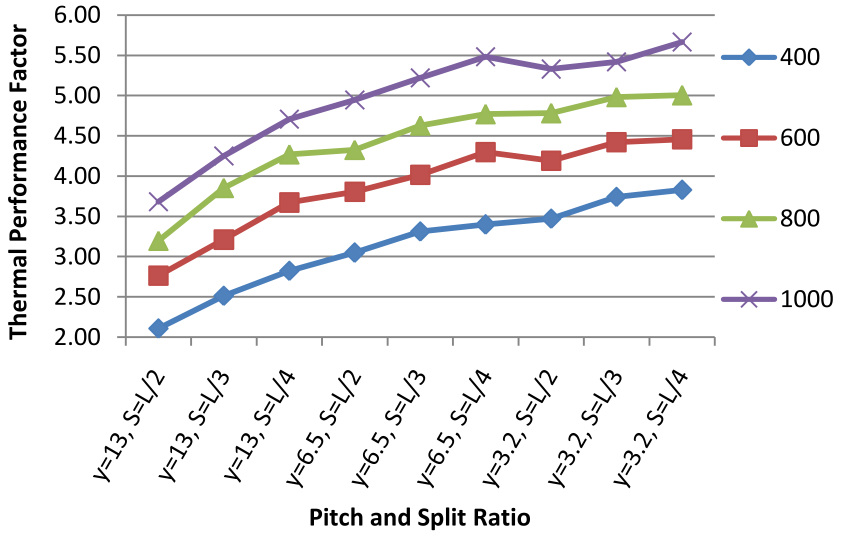

Fig. 7: Variation of Thermal Performance Factor with Pitch and Split Ratio

Fig. 6 shows the thermal performance ratio for the different twists evaluated from Eq. 4 for same pumping power. Siva Rama Krishna, Govardhan Pathipaka, P. Sivashanmugam [3] proposed a performance evaluation analysis of the same pumping power and this method is used in the present study, the performance ratio is defined as

$$\eta = \frac{Nu/Nu_{ref}}{(f/f_{ref})^{0.3}} \qquad (4)$$

The overall performance ratio is defined as the ratio of the heat transfer enhancement ratio to the friction factor ratio. This variable is used to compare different passive techniques for the same pressure drop.

Where,

Nu, f, Nu_{ref} and f_{ref} are the Nusselt numbers and friction factors for a duct configuration with and without inserts respectively.

The effect of thermal performance factor with Reynolds number of various pitch and split ratios are shown in Fig.6. The thermal performance factor increases with increasing Reynolds number. The use of alternate clockwise and counterclockwise twisted tape insert in circular tube in the range studied gives thermal performance factor values around 2.1-5.6. The variation of thermal performance factor with pitch and split ratio values are indicated as Fig.7. On the basis of observation and graph obtained, it was observed that the thermal performance factor increases with increase in split ratio and decreased pitch ratio. The TPF increased by 35-44% with the decrease in pitch ratio increased split ratio for particular Re and increased by 62% for range of Re. For Re 1000 at y=3.2, S=L/4 shows the maximum TPF value and highest heat transfer rate, therefore, the optimization between enhancing heat transfer is found at y=3.2, S=L/4.

The TPF at constant pumping power increase with increasing Reynolds number and reaching maximum corresponding to Reynolds number 1000 for all twisted tapes in laminar flow.

IV. Conclusion

In the present work, the numerical simulation was carried by employing a passive technique for heat transfer augmentation for different pitch ratios y=3.2, 6.5, 13 and split ratios S=L/n (n=2, 3, 4), the following conclusions can be drawn from the results obtained:

1. The tapes show a significant heat enhancement for different geometry of twisted tape arranged in alternate clockwise and anticlockwise. The Nusselt number increased by 48 to 87% for a particular pitch ratio with the increase in the Reynolds number due to the periodic change of whirl direction, and turbulence flow. And also the Nu number increased with decreased pitch ratio.
2. As the number of splits increased for the particular pitch ratio there is a substantial increase in the velocity and the Nusselt number increased by ±20%.
3. Twisted tapes showed comparatively better results at low Reynolds number using viscous liquids.
4. The use of alternate clockwise and anticlockwise twisted tape with pitch ratio (y = p/w, 3.2, 6.5 and 13) and split ratio (S=L/n, n=2, 3, 4) increases the heat transfer and thermal performance in the heat exchanger for Reynolds number ranging from 400-1000.
5. As the TPF is greater than one, the use of twisted tape in laminar flow for heat enhancement is efficient in saving energy.

Nomenclature

A	Convective heat transfer surface area, m^2
D	Inner diameter of test section, m
L	length of test section, m
Re	Reynolds number,
u	velocity vector, m/s
h	convective heat transfer coefficient, W/m^2K
k	thermal conductivity of fluid, W/m K
Cp	specific heat at constant pressure, J/Kg K
T	absolute temperature, K
m	mass flow rate of air, Kg/sec
S	split ratio, m
n	number of splits,
y	twist ratio
p	pitch length of insert, m
w	width of insert, m
Δp	pressure drop, Pa
f	friction factor for plain tube
f_{ref}	friction factor obtained using tape inserts
Nu	Nusselt number for plain tube
Nu_{ref}	Nusselt number with tape inserts

Greek symbols

μ	dynamic viscosity, kg/m s
η	over all Performance ratio
ρ	density of water, Kg/m^3

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