CFD Analysis on Heat Transfer Enhancement Characteristics of Tube Inserted with Centrally Hollow Narrow Twisted Tapes

Ghanshyam Nageshwar, Dr. Nitin Shrivastava
Department of Mechanical Engineering, University Institute of Technology, RGPV Bhopal
Department of Mechanical Engineering, University Institute of Technology, RGPV Bhopal

Abstract: In this study, a new tube insert, named centrally hollow narrow twisted tape, is developed and its effect on the heat transfer enhancement performance of a tube under laminar flow conditions is numerically simulated. The model defines two study variables—hollow width and clearance—and then incorporates the concept of a unilateral twisted tape; the effect of the number of unilateral twisted tapes on the tube heat transfer performance is then examined. The results show that the tube with cross hollow twisted tape inserts has the best overall heat transfer performance for different hollow widths of the tape.

Keywords: Twisted-tape, Turbulent flow, Friction factor, Heat transfer performance

1. INTRODUCTION

Nowadays, heat exchangers with twisted-tape inserts have widely been applied for enhancing the convective heat transfer in various industries such as thermal power plants, chemical processing plants, air conditioning equipment, refrigerators, petrochemical, biomedical and food processing plants. In general, twisted tape insert introduces swirl into the bulk flow which consequently disrupts a thermal boundary layer on the tube surface. The thermal performance of heat exchangers can be increased by heat transfer enhancement methods. Tape insert is one of the passive heat transfer enhancement method and used in most heat transfer application, for example, air conditioning and refrigeration systems food processes.

Enhancing the thermal performance of heat exchange affects directly on energy, material and cost savings. Consequently, improving the heat exchange can significantly improve the thermal efficiency in applications involving heat transfer processes as well as the economics of their design and operation [1]. DPHEs are primarily adapted to high temperature and high-pressure applications due to their small diameters. They are low cost, but the space they occupy is relatively high compared to the other types. To achieve the desired heat transfer rate in the given design and length of the heat exchanger at an economic pumping power, numerous techniques have been used. These improvement techniques are classified as active and passive techniques [2, 3]. Heat exchangers are used in different procedures spanning from conversion, consumption & recovery of thermal energy in various industrial, industrial & domestic applications. Some general examples include steam generation & concentration in power & cogeneration plants; sensible heating &

cooling in thermal processing of chemical, pharmaceutical & agricultural products; fluid heating in manufacturing & waste heat recovery etc. Increase in Heat exchanger's performance can lead to more economical design of heat exchanger which can help to make energy, material & cost savings related to a heat exchange process. The need to increase the thermal performance of heat exchangers, thereby effecting energy, material & cost savings have led to advancement & use of many techniques as Heat transfer Augmentation. These methods are also known as Heat transfer Enhancement or Intensification. Augmentation techniques increase convective heat transfer by decreasing the thermal resistance of equipment.

2. PHYSICAL MODEL (Pengxiao et al. 2015)

The variables for the centrally hollow narrow twisted tape are the hollow width of the cross hollow twisted tape (C), clearance (S), and the number of unilateral twisted tapes (n). C is set as 0, 2, 4, 6, 8, 10, and 12 mm. S is set as 0.5, 1, 1.5, and 2 mm, and n is set as 1–6 for the simulation.

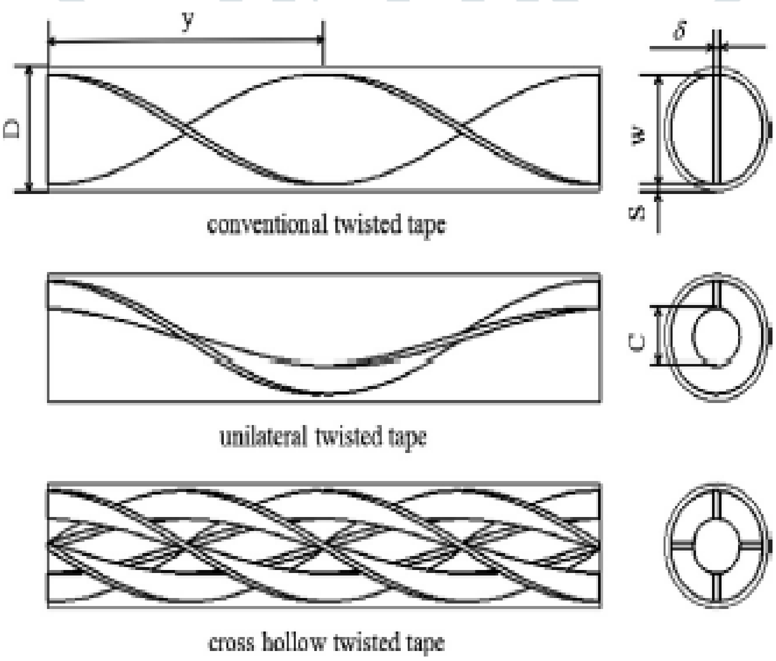


Fig. 1: Tube fitted with conventional, unilateral, and cross hollow twisted tapes

Table 1: Parameters of model

D (mm)	δ (mm)	y/w	w (mm)	y (mm)
18	0.5	3	$D-2S$	$3w$

The simulation uses water as the working fluid. To simplify the calculations, the following assumptions are made regarding the physical properties of water: (A) The physical properties of water are constant. They are set as ρ = 998:2 kg=m^3, μ = 1.003 x 10^{-3} kg/m s, cp = 4182 J/kg K, and k = 0.6 W/mK, respectively. The flow is considered to be single-phase steady flow. The effect of thermal radiation is ignored. The Reynolds number in the tube ranges from 400 to 1200, whereas the corresponding inlet velocity of the fluid medium ranges from 0.10 to 0.38 m/s.

3. NUMERICAL CONSIDERATION

Due to the advances in computational hardware and available numerical methods, CFD is a powerful tool for the prediction of the fluid motion in various situations, thus, enabling a proper design. CFD is a sophisticated way to analyse not only for fluid flow behaviour but also the processes of heat and mass transfer.

4. GOVERNING EQUATION

The steady-state fluid flow characteristic in the three-dimensional computational domain can be described using the following governing incompressible fluid flow equations.

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0$$

Momentum balance without gravity force:

$$\rho u_i \frac{\partial u_i}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

Energy equation:

$$\rho c_p \frac{\partial (u_i T)}{\partial x_i} = \frac{\partial}{\partial x}\left(\lambda_{\text{eff}} \frac{\partial T}{\partial x_i}\right)$$

In conservative form, the partial differential equations for the RNG k−ε model are

Turbulent kinetic equation:

$$\rho u_j \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\mu_{\text{eff}}\, \alpha_k \frac{\partial k}{\partial x_j}\right] + \tau_{ij} \frac{\partial u_i}{\partial x_j} - \rho\varepsilon + G_k + G_b$$

Turbulent kinetic dissipation equation

$$\rho u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\mu_{\text{eff}}\, \alpha_\varepsilon \frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon} \frac{\varepsilon}{k}(G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon}^{*} \rho \frac{\varepsilon^2}{k}$$

The above Reynolds Averaged Navier-Stokes (RANS) turbulence models offer the most economic approach for computing complex turbulent industrial flows.

Generally, the Navier-Stokes equations describe the motion of the turbulent flow. However, it is too costly and time-consuming to solve these equations for complex flow problems [26]. Alternatively, two methods have been suggested in the past: (i) Large Eddy Simulation (LES) where the large energy containing eddies are simulated directly while the small eddies are accounted for by averaging. The separation of large and small eddies requires following, (ii) Reynolds averaging (RANS) where all eddies are accounted for by Reynolds stresses obtained by averaging the Navier-Stokes equations (time averaging for statistically steady flows, ensemble averaging for unsteady flows).

5. BOUNDARY CONDITIONS

In the present investigation, the commercial CFD software FLUENT 6.3, which is based on the finite volume method, is used for the numerical computation, and the SIMPLE algorithm is used for finding a solution for the coupling between the pressure and velocity. The finite-element model is built and meshed using the software Gambit, and unstructured grids are used. The tetrahedral grid is used for meshing the models, and the grid in the region near the tube wall, which is highly refined, is considered as the boundary layer. Fig. 4.3 shows the meshing grid at z = 20 mm. The inlet and outlet conditions used in the calculation are periodic boundary conditions. The upstream temperature is 301.15 K, and the temperature of the tube wall is 343.15 K. No slip conditions are imposed on the tube wall and the surfaces of the twisted tape. The convergence criterion is that all the norms of the residuals for the continuity, momentum, and energy equations should be less than 10^{-6}.

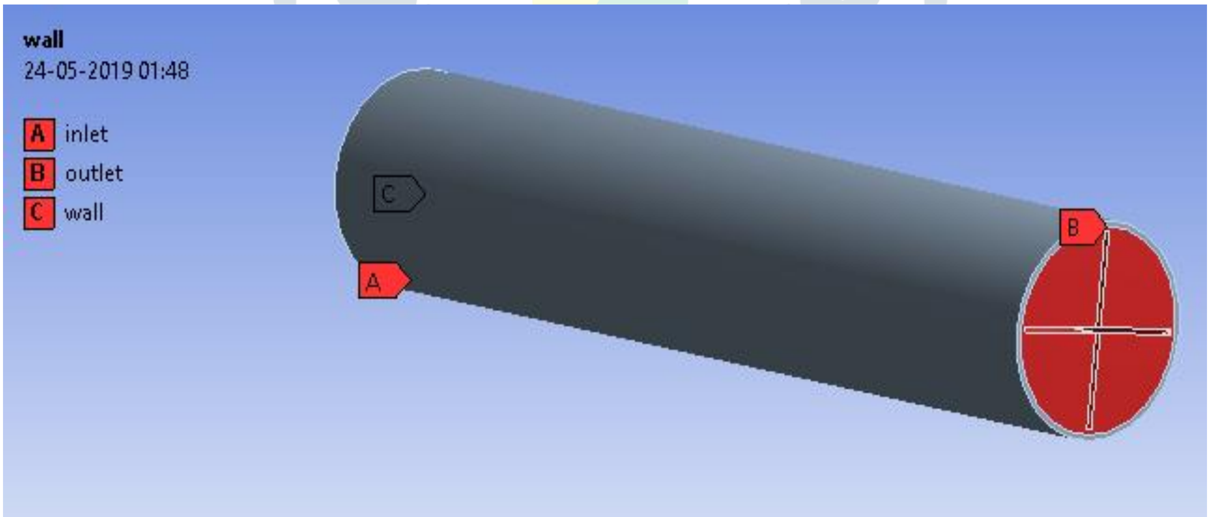


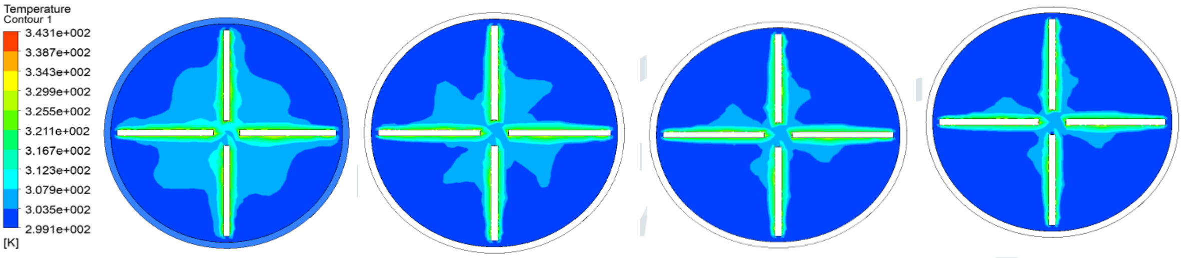
Fig. 2: Boundary condition in CFD

6. RESULTS AND DISCUSSION

6.1 Effect of the Central Clearance Width

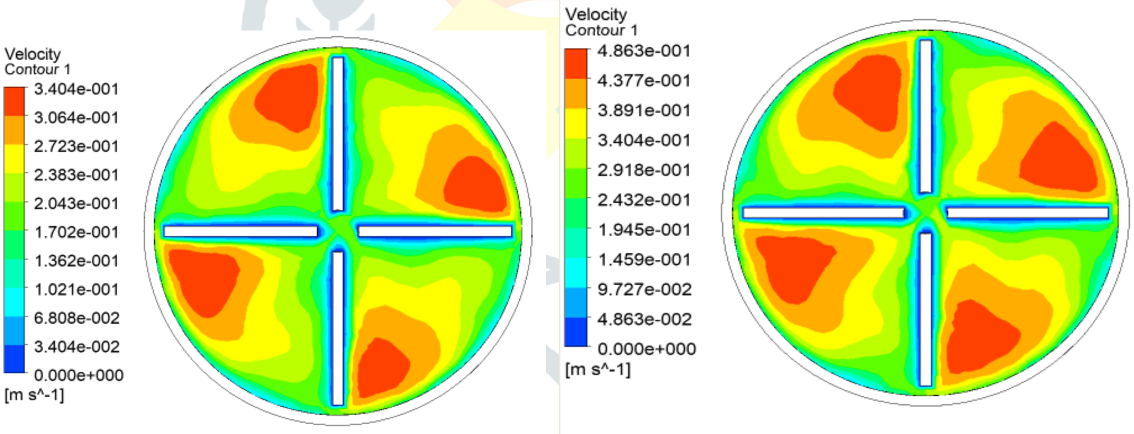
When the width increases to 8 mm, the effect of the irregular disturbance plays a more important role and the heat transfer coefficient increases as a result. At the meantime, the disturbance of the boundary layer is not weakened excessively. Because of the effect of irregular disturbance, the mixing of the core flow and boundary flow through the hollow part increases. When the hollow width continues to increase, the intensity of the swirls generated by the twisted tape reduces sharply, and simultaneously, the irregular disturbance in the hollow part is reduced, thereby reducing the heat transfer capability quickly.

However, the intensity of the irregular disturbance increases not so much under small Reynolds number because the velocity is low. The weakening of the swirls caused by the narrower twisted tape reduces the Nu and the effect accounts for a larger proportion than the effect of irregular disturbance. Thus, Nu shows a decreasing trend. When the hollow width C increases to 8 mm, the heat transfer enhancement caused by the irregular disturbance makes Nu to decrease slowly or increase slightly.

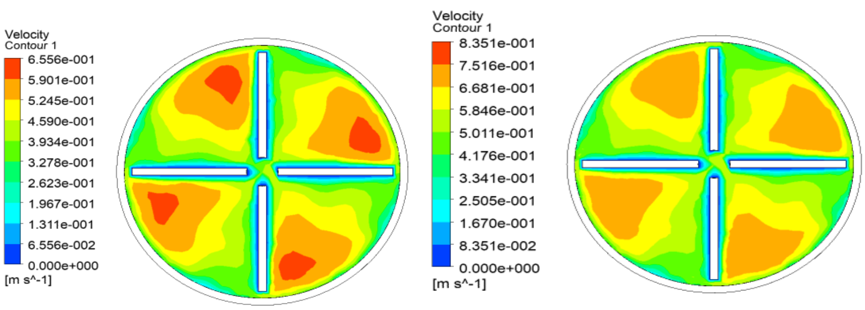


(a) Re = 4000 (b) Re = 6000 (c) Re = 8000 (d) Re = 10000

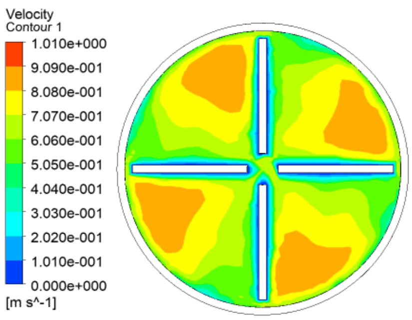
Fig. 3: Temperature contours on cross-sectional planes with cross hollow twisted tapes of hollow width (C= 2)



(a) Re = 4000 (b) Re = 6000



(c) Re = 8000 (d) Re = 10000



(e) Re = 12000

Fig. 4: Velocity contours on cross-sectional planes with cross hollow twisted tapes of hollow width (C= 2)

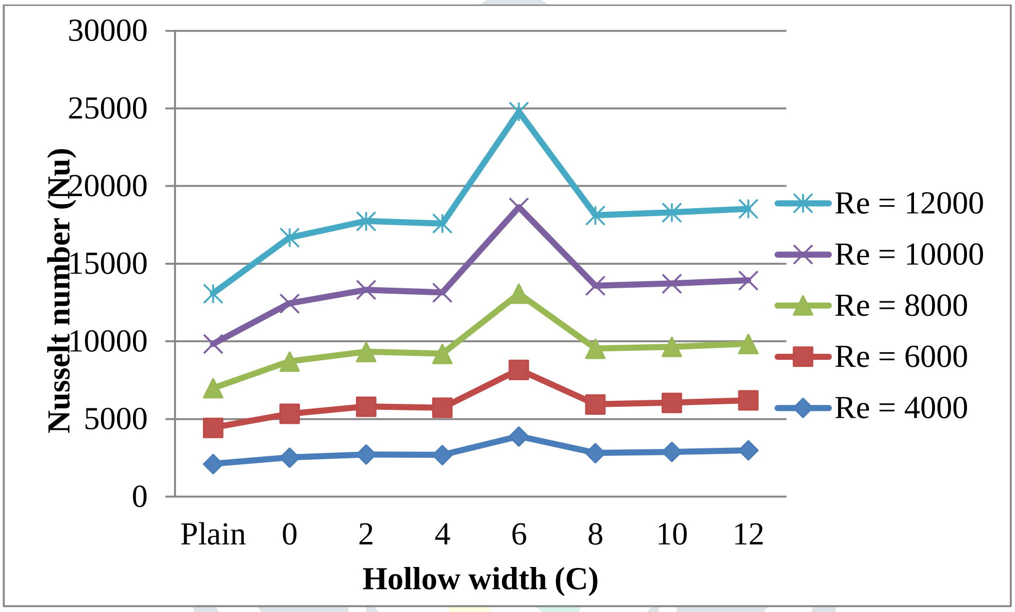


Fig. 5: Variation of Nusselt number with the hollow width (C)

It can be seen from fig. 5, when the Reynolds number increases, the Nusselt number also increases for both the tapes. And we can find a hollow width to maximize the heat transfer capability. The enhancement mechanism about heat transfer of the centre-cleared twisted tape consists of two parts. (1) The twisted tape generates swirls, which enhance the heat transfer. The enhancement is weakened as the hollow width increases. (2) The hollow part generates irregular disturbance. As the hollow width increases, the irregular disturbance makes the fluid in the core region and boundary region to mix more evenly, leading to an increase in the heat transfer. However, when the hollow width increases beyond a certain value, the irregular disturbance is reduced.

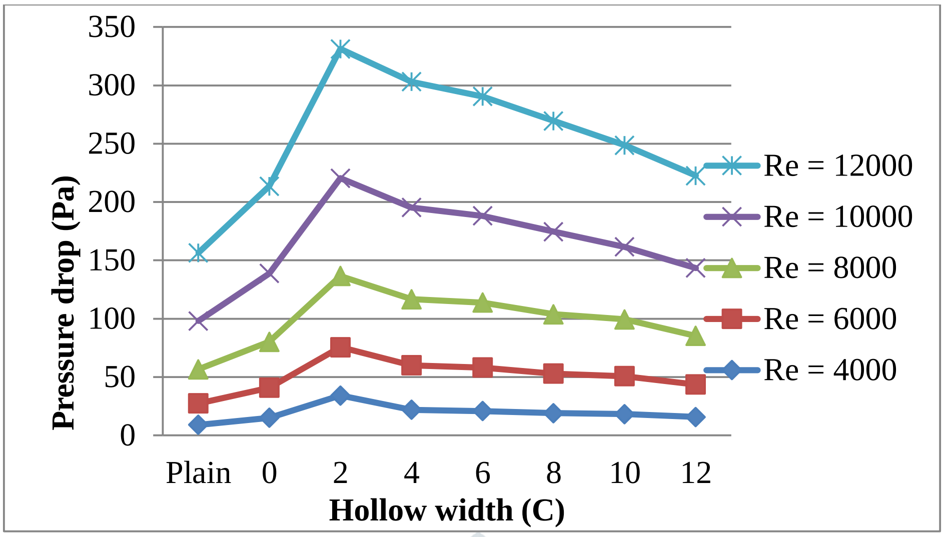


Fig. 6: Variation of pressure drop with the hollow width (C)

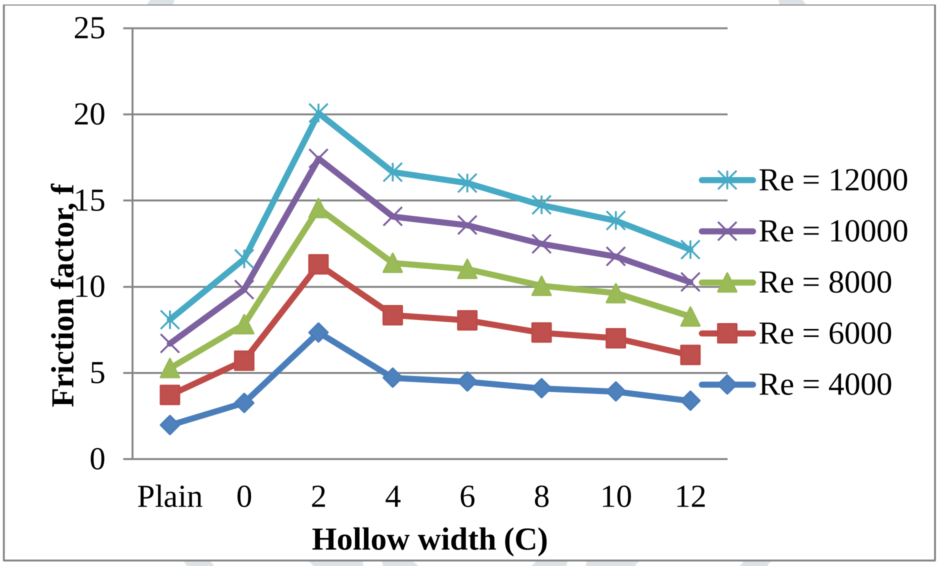


Fig. 7: Variation of friction factor with hollow width (C)

Fig. 7 indicates that when the hollow width increases, the friction factor decreases significantly for both the centre-cleared twisted tape and cross hollow twisted tape. When the hollow width C is 8 mm, the f of the cross hollow twisted tape decreases by 38.5–44.8% compared with that of the cross twisted tape. And the f of the cross hollow twisted tape is larger than that of the centre-cleared twisted tape with the same hollow width because a larger area of the tape is in contact with the fluid. Therefore, it is necessary to make a hollow part on the twisted tape to reduce the resistance.

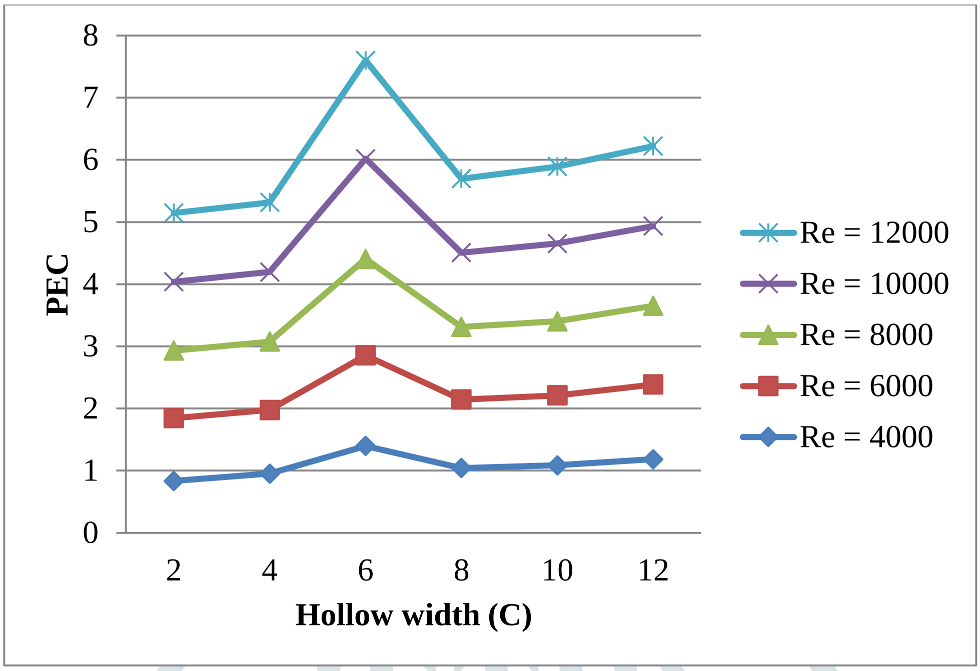
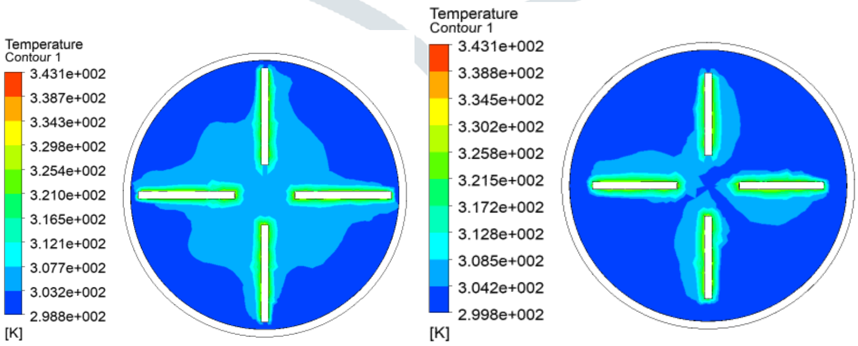


Fig. 8: Variation of PEC with hollow width (C)

As shown in Fig. 8, the PEC of the cross hollow twisted tape has the best value when the hollow width (C) is 6 mm. The best PEC of cross hollow twisted tape is 12.3% larger than that of centre-cleared twisted tape and 27.4% larger than that of cross twisted tape when Re = 1200. Under low Reynolds numbers, the resistance of the cross hollow twisted tape is very large, which leads to a worse PEC than that of the centre-cleared twisted tape.

6.2 Effects of the Boundary Clearance Width

Clearance is defined as the width between the twisted tape and tube wall. In this subsection, the effects of the clearance on the heat transfer performance at a hollow width of 8 mm are described.



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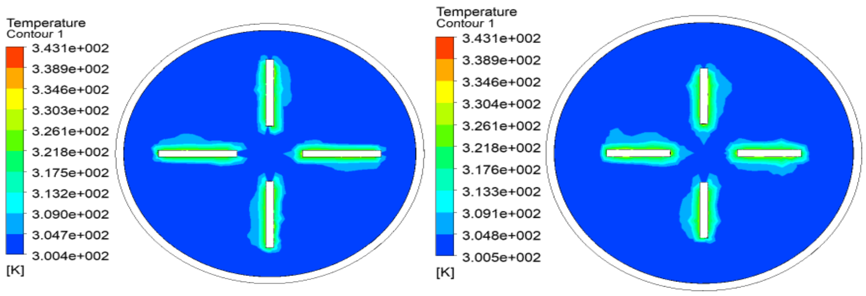
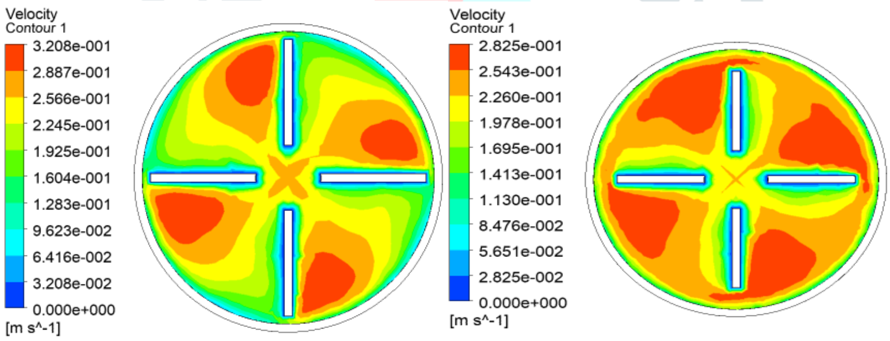


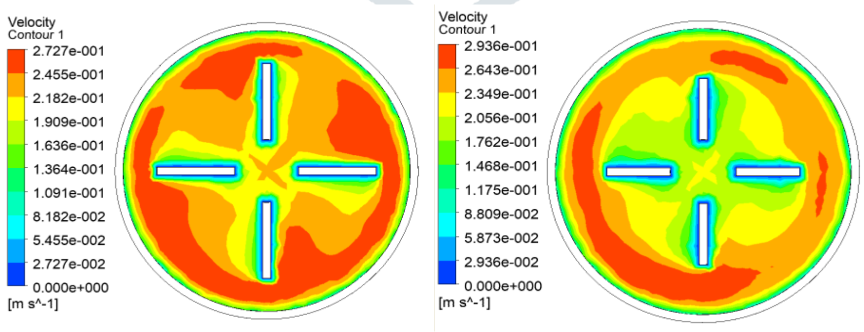
S = 1.5 **S = 2**

Fig. 9: Temperature contours on cross-sectional planes in tubes fitted with cross hollow twisted tapes of different clearances (S)

The fluid flows through the clearance because of the inertia force caused by the swirls, resulting in irregular disturbance in the clearance region. The contours shown in Fig. 9 shown that when the clearance is very small (S = 0.5 mm), a dead flow zone exists in one side of the twisted tape. Thus, as shown in the temperature field, the temperature of side 1 is high. As the clearance increases, more fluid from side 1 flows through the clearance to the other side (Side 2) under the effect of inertia force and swirls, are resulting in the temperature of both sides of the twisted tape becoming similar. With an increase in the clearance, the temperature boundary layer begins to thicken.



S = 0.5 **S = 1**



S = 1.5 **S = 2**

Fig. 10: Velocity contours on cross-sectional planes in tubes fitted with cross hollow twisted tapes of different clearances (S)

When the clearance increases, the heat transfer performance of the cross hollow twisted tape weakens. This is because when the clearance increases, longitudinal swirls of high intensity caused by the twisted tape are located far away from the tube wall, as shown in Fig. 10. Fluid can strongly scour the wall with a small clearance, leading to an increase in heat transfer.

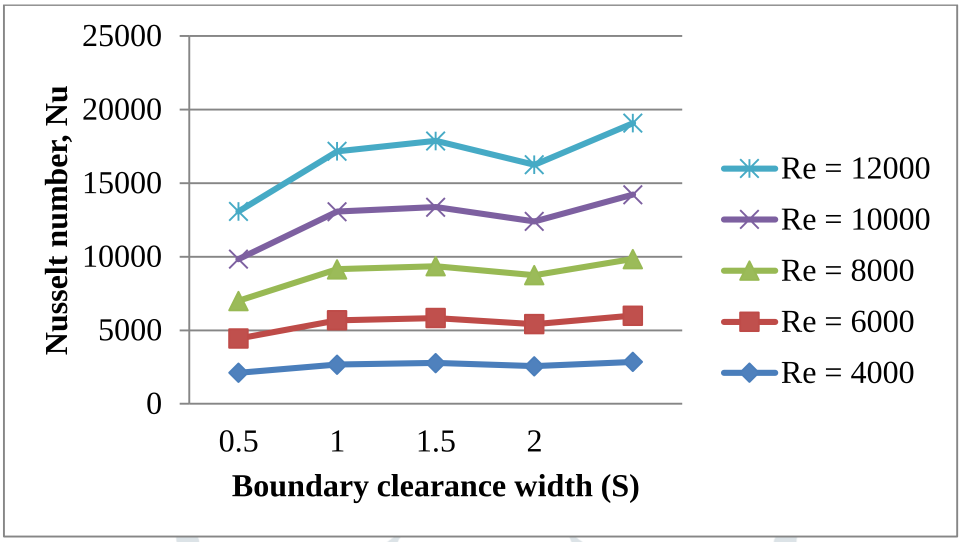


Fig. 5.13: Variation of Nusselt number with boundary clearance width (S)

When the clearance increases to 1 mm, more fluid flows through the clearance and the dead flow zone disappears. As we know, throttling will increase the pressure drop and enhance the irregular disturbance. Because of larger zone of disturbance on boundary layer and the irregular disturbance caused by the clearance, pressure drop suddenly increases when the fluid flows through the clearance, and hence, the friction factor increases. When the clearance continues to increase, swirls are located far away from the tube wall and the velocity gradient near the wall becomes smaller.

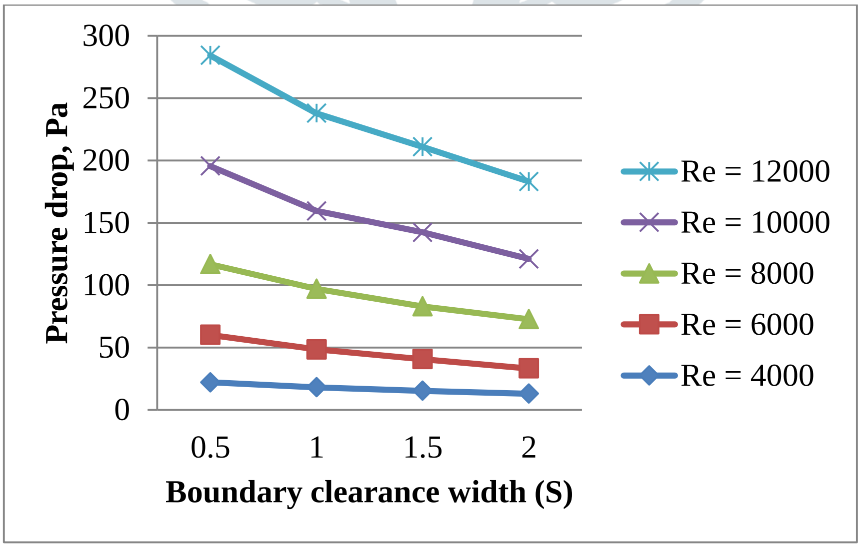


Fig. 11: Variation of pressure drop with boundary clearance width (S)

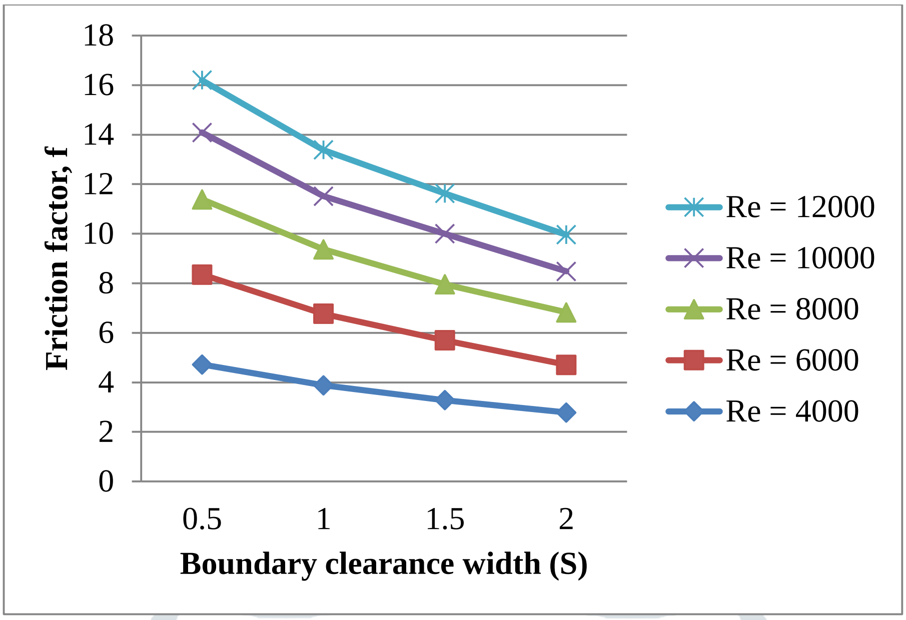


Fig. 12: Variation of friction factor with boundary clearance width (S)

Fig. 12 shows the variation of the friction factor (f) with the clearance (S) at different Reynolds numbers (Re). As shown in the temperature fields, when Re = 4000 and S = 0.5 mm, a dead flow zone exists in side 1 of the twisted tape. When the clearance increases to 1 mm, more fluid flows through the clearance and the dead flow zone disappears. As we know, throttling will increase the pressure drop and enhance the irregular disturbance. Because of larger zone of disturbance on boundary layer and the irregular disturbance caused by the clearance, pressure drop suddenly increases when the fluid flows through the clearance, and hence, the friction factor increases. When the clearance continues to increase, swirls are located far away from the tube wall and the velocity gradient near the wall becomes smaller. Therefore, the friction factor decreases. The same results are obtained when Re = 6000–12000. At low Reynolds numbers (e.g. Re = 4000), for a clearance of 1 mm, the dead flow zone may not completely disappear.

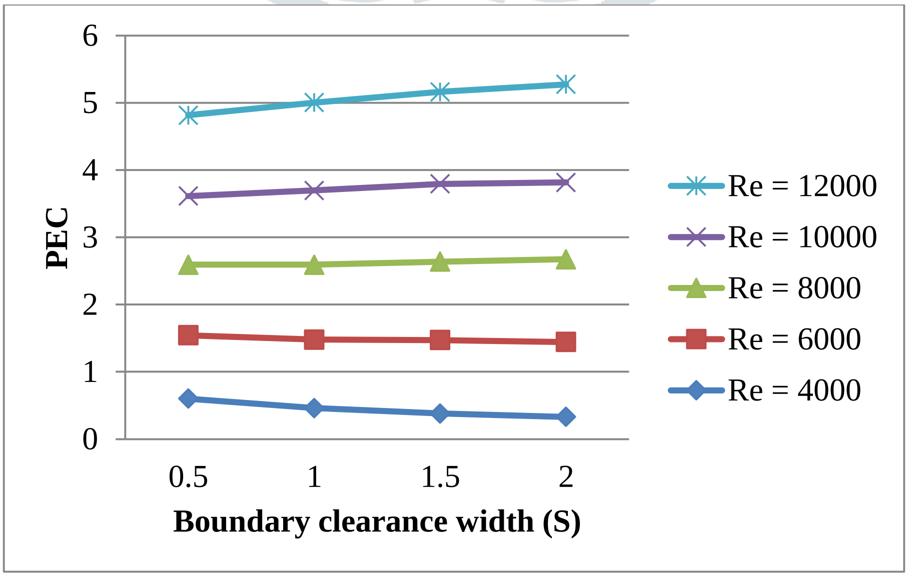


Fig. 13: Variation of PEC with boundary clearance width (S)

As shown in fig. 13, when the clearance increases from 0.5 to 2 mm, the PEC decreases by approximately 41.3–51.3%. Therefore, for a tube with cross hollow twisted tape inserts, the clearance should be as small as possible.

6.3 Effects of the Number of Unilateral Twisted Tapes

This subsection describes the effect of the number of unilateral twisted tapes on the overall heat transfer performance when the hollow width is 8 mm and the clearance is 1 mm.

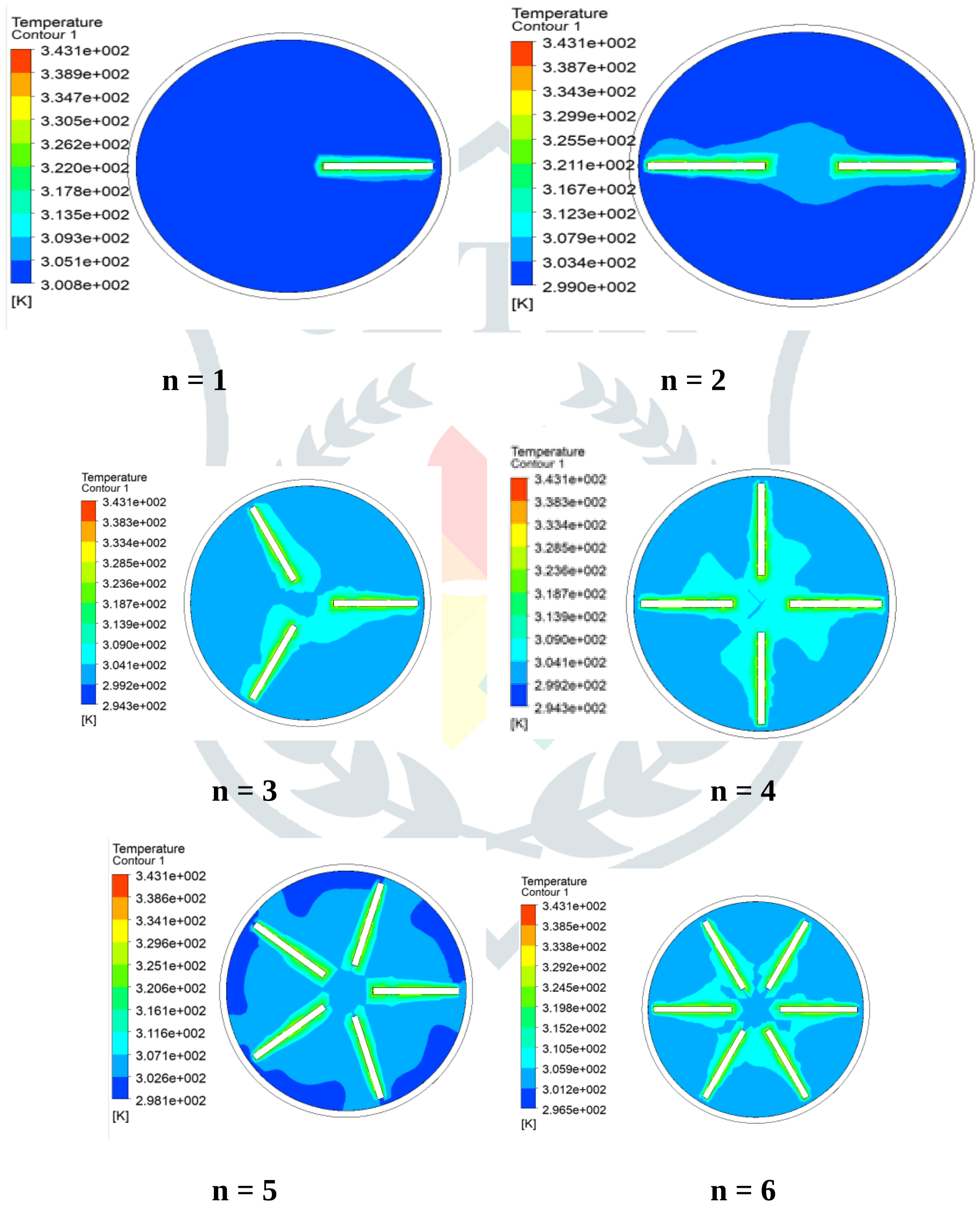


Fig. 14: Temperature contours on cross-sectional planes in tubes fitted with different number of unilateral twisted tapes (n)

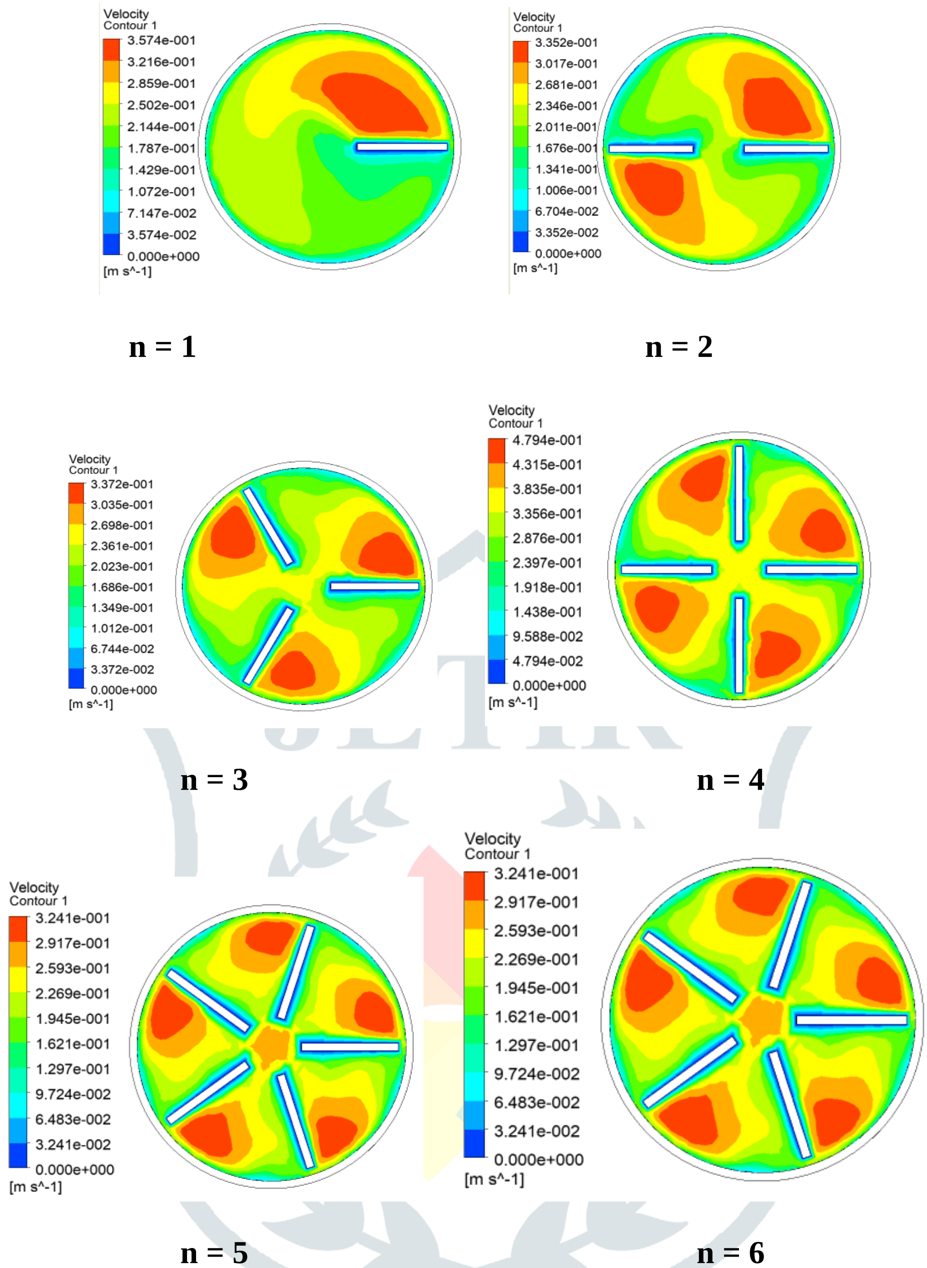


Fig. 15: Velocity contours on cross-sectional planes in tubes fitted with different number of unilateral twisted tapes (n)

As shown in Fig. 15, the number of swirling areas is the same as the number of unilateral twisted tapes. The more the number of inserted twisted tapes, the more is the number of swirling areas. The swirls formed in the side of one twisted tape gradually weaken as they reach the side of another twisted tape. Also it indicates that the twisted tape can produce swirls near the wall, where the flow velocity is high.

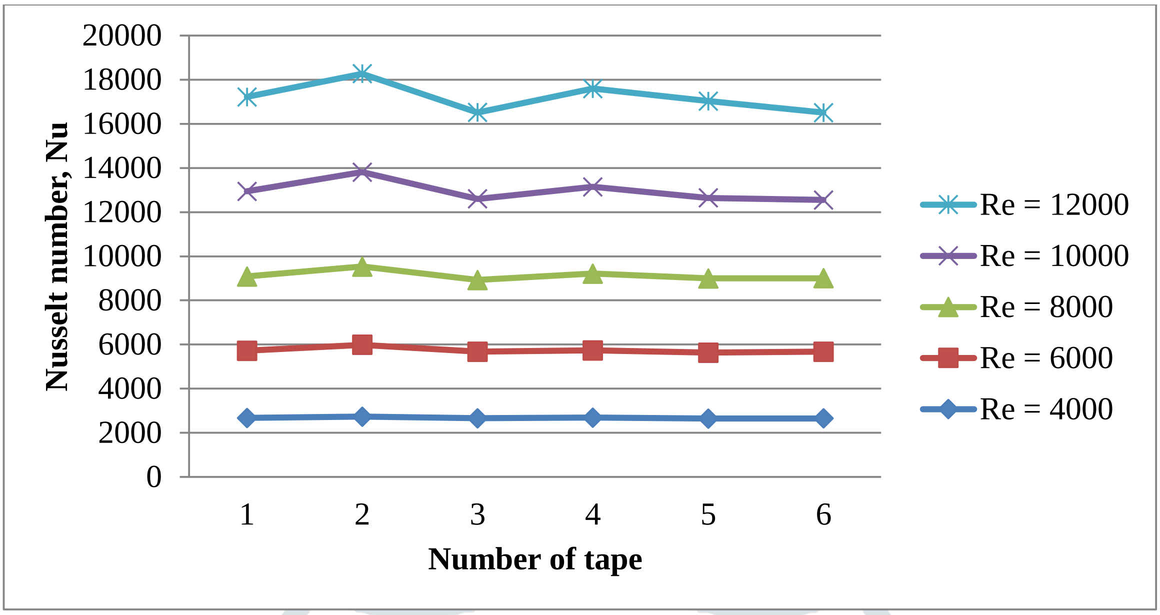


Fig. 16: Variation of Nusselt number with unilateral twisted tapes (n)

As shown in Fig. 16, Nu initially increases and then decreases as the number of unilateral twisted tapes increases. The number of swirls increases as the number of twisted tapes increases from 1 to 4. High-intensity swirls will produce more disturbance in the fluid near the wall, resulting in more heat being transferred. However, when n continues to increase, Nu deceases. The more the number of inserted unilateral twisted tapes, the smaller is the gap between two twisted tapes in the central region. This hinders the mixing of the fluid in the near-wall and central zones. Therefore, the heat transfer performance is weakened if there are too many unilateral twisted tapes.

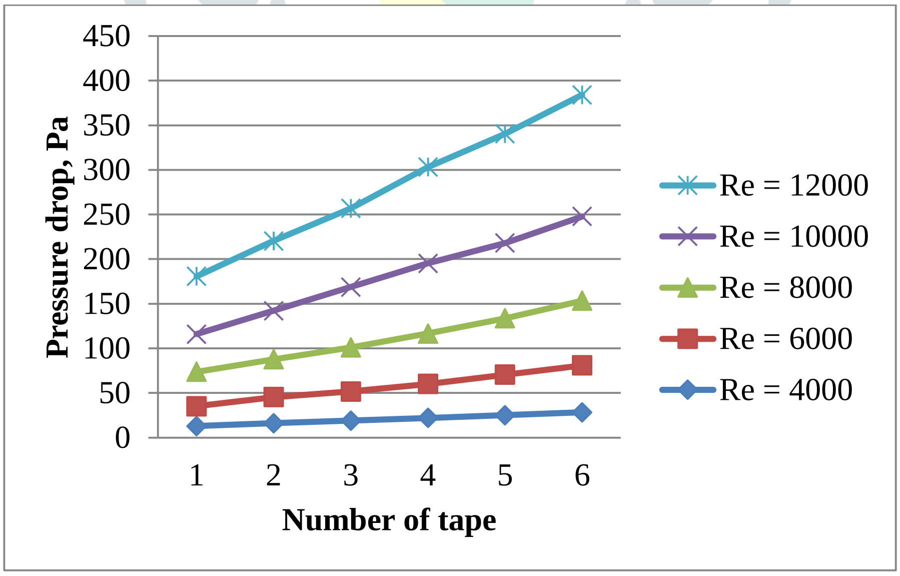


Fig. 17: Simulation of pressure drop with unilateral twisted tapes (n)

Fig. 17 shows that the more the number of inserted twisted tapes, the larger is pressure drop. This is because the friction between the twisted tapes and fluid increases. The increasing number of twisted tapes also strengthens the disturbance caused by the swirls in the region near the wall since more swirls appear.

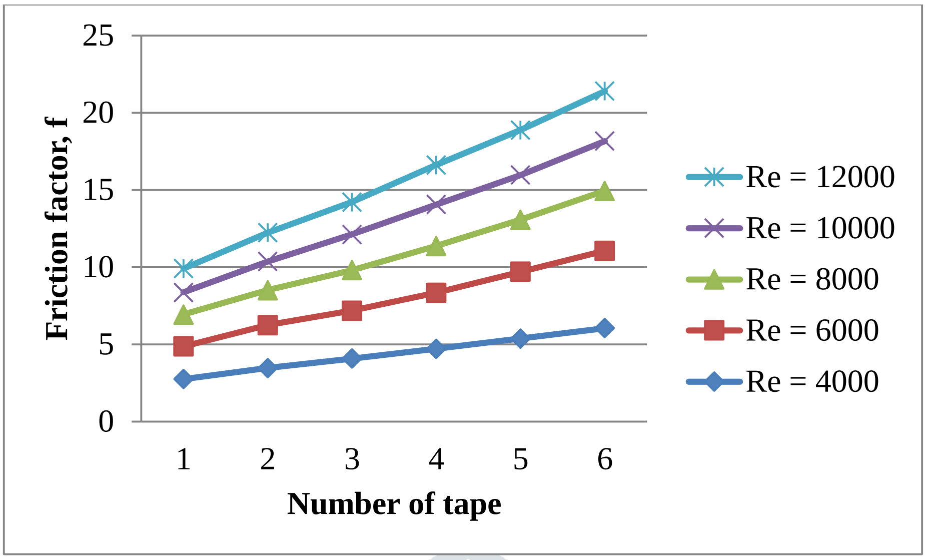


Fig. 18: Variation of friction factor (f) with the number of unilateral twisted tapes (n) fitted in a tube

Fig. 18 shows that the more the number of inserted twisted tapes, the larger is the friction factor. This is because the friction between the twisted tapes and fluid increases. The increasing number of twisted tapes also strengthens the disturbance caused by the swirls in the region near the wall since more swirls appear.

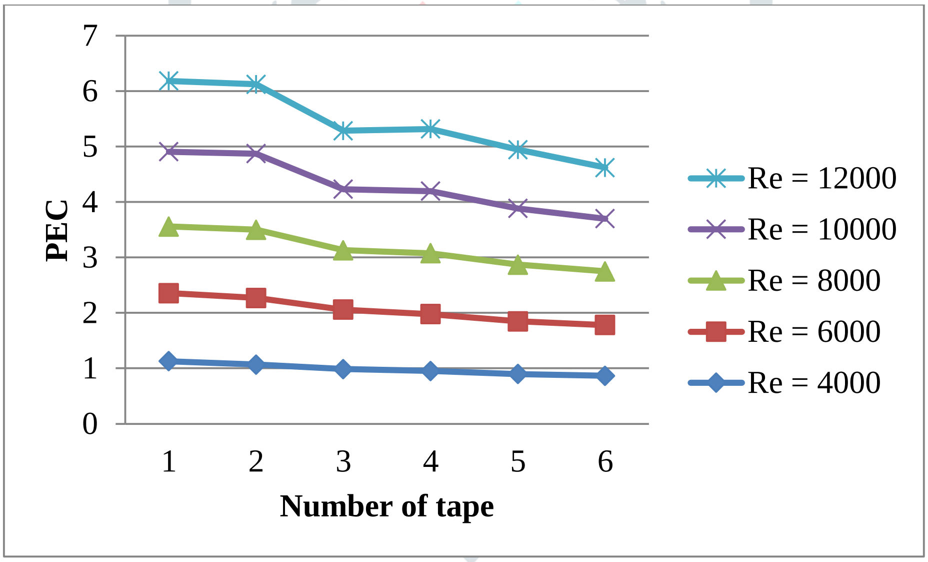


Fig. 19: Variation of PEC with unilateral twisted tapes (n)

Fig. 19 shows the results of PEC variation with the number of unilateral twisted tapes. The tube with two or three unilateral twisted tapes shows good overall performance at higher Reynolds numbers. When the Reynolds number increases over 4000, the number of twisted tapes should increase excessively and after Reynolds number 12000, performance decreases. The best overall performance is achieved when the number of twisted tapes is 3.

7. CONCLUSION

In this study, first, the effect of the hollow width and clearance on the heat transfer and resistance characteristics of a tube with cross hollow twisted tape inserts is analyzed. Then, the effect of the number of unilateral twisted tapes on the heat transfer and resistance performance is examined.

1. The results indicate that the tube with a cross hollow twisted tape shows good overall performance. There is a value of hollow width to obtain the best overall heat transfer performance.
2. Nu initially increases and then decreases as the number of unilateral twisted tapes increases. The number of swirls increases as the number of twisted tapes increases from 1 to 4. High-intensity swirls will produce more disturbance in the fluid near the wall, resulting in more heat being transferred. However, when n continues to increase, Nu deceases. The more the number of inserted unilateral twisted tapes, the smaller is the gap between two twisted tapes in the central region. This hinders the mixing of the fluid in the near-wall and central zones. Therefore, the heat transfer performance is weakened if there are too many unilateral twisted tapes.
3. When the clearance increases to 1 mm, more fluid flows through the clearance and the dead flow zone disappears. As we know, throttling will increase the pressure drop and enhance the irregular disturbance. Because of larger zone of disturbance on boundary layer and the irregular disturbance caused by the clearance, pressure drop suddenly increases when the fluid flows through the clearance, and hence, the friction factor increases. When the clearance continues to increase, swirls are located far away from the tube wall and the velocity gradient near the wall becomes smaller.
4. It is observed that the more the number of inserted twisted tapes, the larger is the friction factor. This is because the friction between the twisted tapes and fluid increases. The increasing number of twisted tapes also strengthens the disturbance caused by the swirls in the region near the wall since more swirls appear.
5. The tube with two or three unilateral twisted tapes shows good overall performance at higher Reynolds numbers. When the Reynolds number increases over 4000, the number of twisted tapes should increase excessively and after Reynolds number 12000, performance decreases.
6. In summary, under turbulent flow conditions, the cross hollow twisted tape provides better heat transfer performance than the centre-cleared twisted tape. In addition, the effect of hollow on drag reduction is clearly observed. Therefore, the cross hollow twisted tape is a good tube insert for enhancing heat transfer performance in numerous applications.

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