Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Numerical Investigation of Triangular Y-Shaped Cut Twisted Stripe Insertion on Improving the Performance of Heat Exchangers

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ARTICLE INFO

Article history:
Received 16 August 2024
Received in revised form 7 November 2024
Accepted 15 November 2024
Available online 30 November 2024

Keywords:
Y-shaped twisted tape; heat exchangers; heat transfer increase; energy efficiency; thermal performance; convective heat transfer

ABSTRACT

Passive thermal performance has been the subject of significant study interest lately, with metal inserts being recognized as an effective method for boosting it. Nevertheless, there has been a limited investigation into Y-shaped inserts with diverse geometric configurations. A numerical study was approved to explore the optimization of heat transfer. in a high-temperature circular tube using Y-shaped inserts. The analysis considered two scenarios: one without any twisting, and another with Y-shaped inserts that had an axial twist and a twisted ratio of 2 along the edge. The Ansys 2022-R2 module was utilized to do calculations using the limited volume approach, employing the k-ε turbulence model. The study involved exposing a pipe segment with dimensions of 1.5 m in length and 68 mm in diameter to a steady heat flux of 1000 W/ m^2 applied to the pipe wall. During the analysis, air is used as the fluid used for work, with the Reynolds values (Re) vary from 3000 to 21000., inclusive, in increments of 3000. The findings indicate that the optimal the values of the Nusselt number (Nu), reaching up to 128.14, can be attained at a Reynolds number (Re) of 21000 for Y-shaped designs with a twisted configuration. However, in comparison to a smooth tube, the values of the Nusselt number (Nu) increased by a factor of 5.68, with a coefficient of friction (f) of 0.029 and a Thermal Performance Evaluation (TPE) of 2.147, suggesting higher thermal performance.

1. Introduction

Energy has become a vital element of contemporary life, and it is important for every system to minimize energy consumption during processing procedures [1]. Scientists continuously conduct experiments to enhance the efficiency of equipment. Heat exchangers, often known as HE, are devices designed to transfer thermal energy between two sources and have use across several industries are taken from the previous studies [2,3]. It finds submissions in several productions, such as power generation facilities, cooling systems, air conditioning units, chillers, and others [4,5]. Consequently, optimizing the performance of heat transfer devices. Enhanced heat transfer rates are achieved through increased Surface region and roughness, together with significant alterations in

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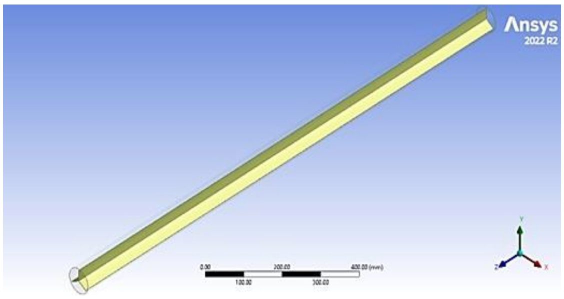
https://doi.org/10.37934/arfmts.124.2.220234

boundary conditions are taken from the previous studies [6,7]. Heat can be transported through three mechanisms: actively, passively, or through a combination of both are taken from the previous studies [8,9]. The passive augmentation of thermal performance techniques has garnered substantial scientific interest over the years. Additional passive methods, including inserts and vortex-generating devices, can induce physical disruptions in fluid flow. These techniques are employed to enhance convection rates and decrease power consumption in external heat exchangers, all while preserving performance. Passive technologies provide several benefits compared to active technology, such as enhanced efficiency and reliability and lower costs for production, repairs and service. The main method for improving heat transmission in passive devices is to increase flow turbulence are taken from the previous studies [10,11]. Multiple inquiries have been conducted to enhance the efficiency of heat transmission in heat exchangers by including different modifications in their geometry, such as wings, vortex power sources, and others [12]. While twisted tape enhances the coefficient of heat transfer, it concurrently induces a pressure decrease are taken from the previous studies [13,14]. Many students have performed tests and analyzed different configurations for twisted tape inserts. Twisted-tape inserts are available in many shapes. Examples encompass a full range of variations, including complete, concise, entirely with different intonations, and uniformly distributed. The subsequent section encompasses the research conducted by different scholars. Eiamsa-Ard and Promvonge [15] conducted research on dual-sided delta-wing tape inserts. The study determined that the delta arms improve heat transfer equally. and performance of high explosives (HE). Eiamsa-Ard and Promvonge [16] conducted additional research, examined the efficiency of heat exchangers by employing a combination of counter-clockwise and clockwise twisted tape configurations while utilizing shorter twisted tapes. The entry experienced a powerful swirling flow, resulting in enhanced performance [17]. Moreover, taking into account the dual delta-winged tape twisted by Eiamsa-Ard *et al.,* [18], twisted tape coupling Eiamsa-Ard *et al.,* [19], rectangular-cut tape with twists utilized by Nakhchi and Esfahani [20], and utilizing perforated coiling tape inserts created by Rahimi *et al.,* [21]. Through their study, they were able to attain a decrease in pressure damage and enhanced liquid mixing as a result of increased vortex production and improved heat transfer properties [22]. The study found that circular disks with rectangular winglets that are solid on the outside and hollow on the inside improve thermal performance compared to plain tubes and circular-ring turbulators [23]. Gautam *et al.,* [24] found that the heat transfer rate in circular rings with twisted tape inserts was enhanced by the generation of eddies. The researchers examined the use of a perforated triple-wing vortex generator and discovered that it improved heat transfer and thermal efficiency compared to a plain tube [25]. A study investigated the heat transmission and thermal mechanical efficiency of heat exchanger tubes by employing twisted tapes in various arrangements. The results indicated that the counter-swirl twisted tape exhibited the highest Nusselt value and the maximum thermal mechanical performance efficiency, with the counter-swirl configuration achieving the highest efficiency of 1.95 at a twist ratio of 0.56 [26]. A study examined the heat transfer properties and thermo-hydraulic efficiency of an exchange tube by employing twisted tape with spherical holes and extensions. The tape with twisted and densely spaced extensions exhibited the highest Nusselt number and largest friction factor at a small Reynolds value. The hydraulic thermal efficiency reached its peak while using twisted tape featuring thick dimples and extensions [27]. Mushatet *et al.,*'s [28] study on heat transfer properties and thermal mechanical efficiency of heat exchanger tubes using perforated triple-twisted tapes revealed enhanced heat transmission and Nusselt values, with the highest thermal hydraulic efficiency at the lowest Reynolds number. The study analyzed the heat transfer and thermo-hydraulic efficiency of an exchange tube with increased conical twisted tape. Results showed a significant improvement in heat transfer, mechanical thermal efficiency, and friction factor are taken from the previous studies [29,30]. later suggested using a variety of perforated guides (PI) to form triangular perforations in a Y-shaped long-term insertion. This research analyzes the current attempts to enhance the heat transfer efficiency of pipe heat exchangers by using different forms of inserts, regardless of whether or not they have holes. Prior research, such as the utilization of twisted tape inserts, generated a vortex at the core of the region, but the vicinity surrounding the outer perimeter exhibited less turbulence in certain instances, leading to inferior heat transfer. Several investigations have observed increased levels of friction in various experiments involving helical rings and other devices that generate vortices. This is mostly caused by a substantial decrease in pressure across the walls, leading to poor thermal efficiency. Based on the researchers' data, there have been only two or three investigations completed on Y-shaped perforation longitudinal insertion. Prior studies have demonstrated that these geometries exhibit significant reductions in pressure [1,6]. To harness the benefits of Y-shaped geometry, a widely-used computational system is used to compare and assess the outcomes of heat exchanger tubes with longitudinal Y-shaped inserts. This study specifically examines characteristics such as the Nusselt value (Nu), the factor of friction (f), and the thermal efficiency factor (TPF) for fluids that are subjected to a constant heat flux. Therefore, the forthcoming alterations to the Y-insert have the capacity to significantly enhance its thermal hydraulic capabilities, therefore making it the main area of concentration in the continuing investigation. The exchanger featuring the proposed Y-shaped twisting is distinct in this investigation. The twisting of the inlet body causes the fluid to follow different routes, resulting in increased turbulence and enhanced heat transmission. This requires additional work to achieve ideal thermal performance. There have been few studies conducted on Y-shaped inserts with varied geometric configurations. When examining previous research, Y-shaped inserts with holes of different geometric shapes were used without any distortion. An investigation was carried out to examine the enhancement of heat transfer in a circular tube operating at high temperatures by the utilization of Y-shaped inserts. Through previous literature, it was noted that there was no focus on tubes twisted in the shape of the letter Y, so we focused on the idea of this type of tube. This study focused on one without any holes or twisting, and the other with Y-shaped inserts that had axial twisting and a twist ratio of 2 along the edge. The computations were conducted using the Ansys 2022-R2 module, employing a finite volume method and the k-ε turbulence model. The numerical calculations involved exposing a tube measuring 1.5 m in length and 68 mm in diameter to a consistent heat flux of 1000 watts per square meter on the tube's wall. The analysis utilized air as the working medium, With the Reynolds number (Re) ranging from 3000 to 21000, increasing in increments of 3000. As seen in Figure 1 and Figure 2.



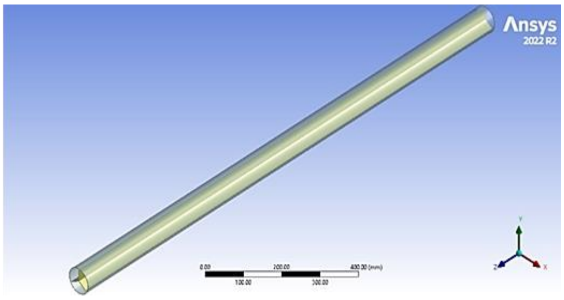


Fig. 1. Y-shaped addition linked within a tube

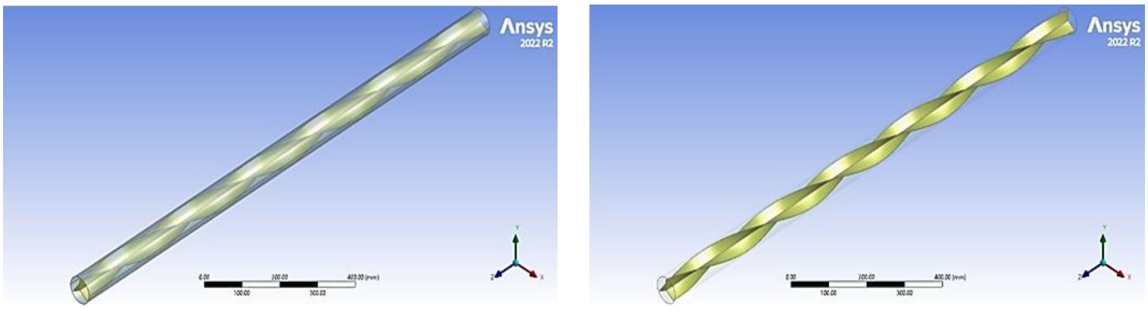


Fig. 2. Y-shape with twisted addition linked within a tube

2. Methodology

2.1 Mathematics Calculations

The terminology utilized in this investigation is outlined as follows [6]:

Reynolds number: $Re = \frac{\rho v Dh}{\mu}$ (1)

The Nusselt number: $Nu = \frac{h.D}{k}$ (2)

The Heat transfer coefficient:

$$h = \left(\frac{\mathbf{Q}}{(\mathbf{T}wm - \mathbf{T}f\,m)A}\right) \quad (3)$$

$$h = \left(\frac{(\mathbf{T}o - \mathbf{T}i)mcp}{(\mathbf{T}wm - \mathbf{T}f\,m)A}\right) \quad (4)$$

where

$$\mathbf{T}wm = (1/A)\int_0^A (T)dA \quad (5)$$

And $\mathbf{T}fm = \frac{To - Ti}{2}$ (6)

Calculate the friction factor [1]: $f = \left(\frac{\Delta\mathbf{P}}{(\frac{1}{2}\,\rho\, v^2 * \frac{L}{Dh}}\right)$ (7)

A thermal performance factor (TPF) is used to evaluate the performance of HE [1].

$TPF = \frac{Nu}{Nus} \,/\, \left(\frac{f}{fs}\right)^{1/3}$ (8)

2.2 Grid Independence and Modeling Testing

2.2.1 Governing equations

The conservation equations for continuity, momentum, and energy can be mathematically represented [1].

i. The continuity equation (mass conservation)

$$\frac{\partial(\rho ui)}{\partial xi} = 0 \tag{9}$$

The variable ρ indicates the density of air, whereas ui denotes the average velocity component in the xi direction.

ii. Momentum equation

$$\frac{\partial(\rho uiuj)}{\partial xj} = -\frac{\partial p}{\partial xi} + \frac{\partial}{\partial xi}\left(\mu \frac{\partial(ui)}{\partial xj} - \overline{\rho ui'uj'}\right) \tag{10}$$

The variables p, u', The variables μ, pressure, turbulent changes, and viscosity change relate to the characteristics of the air, respectively. The Reynolds stress, represented by the word $\overline{\rho ui'uj'}$, The expression for $\overline{\rho ui'uj'}$ can be formulated as:

$$\rho ui'uj' = \mu t\left[\frac{\partial(ui)}{\partial xj} + \frac{\partial(uj)}{\partial xi}\right] - \frac{2}{3}\rho k\delta ij - \frac{2}{3}\mu t\frac{\partial(uk)}{\partial xk}\delta ij \tag{11}$$

iii. Energy equation

$$\frac{\partial}{\partial xi}(\rho uiT) = \frac{\partial}{\partial xi}\left[\left(\frac{\mu}{Pr} + \frac{\mu_t}{P_{rt}}\right)\frac{\partial T}{\partial xi}\right] \tag{12}$$

$$\frac{\partial}{\partial xi}(\rho kui) = \frac{\partial}{\partial xi}\left(\frac{\mu}{\sigma k}\frac{\partial K}{\partial xi}\right) + \mu_t\left(\frac{\mu eff}{\sigma k}\frac{\partial K}{\partial xi}\right) + \mu_t\left(\frac{\partial(ui)}{\partial xj} + \frac{\partial(uj)}{\partial xi}\right)\frac{\partial(ui)}{\partial xj} - \rho\varepsilon \tag{13}$$

$$\frac{\partial}{\partial xi}(\rho\varepsilon ui) = \frac{\partial}{\partial xi}\left(\frac{\mu}{\sigma k}\frac{\partial\varepsilon}{\partial xi}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}\mu_t\left(\frac{\partial(ui)}{\partial uj}\frac{\partial(uj)}{\partial xi}\right)\frac{\partial(ui)}{\partial uj} - C_{2\varepsilon}\frac{\varepsilon^2}{k} - ap\frac{\varepsilon^2}{k} \tag{14}$$

In Eq. (12), T represents the temperature, Pr represents the Prandtl number, P_{rt} represents the turbulent Prandtl number, and μt represents the turbulent viscosity.

2.2.2 Numerical model

An investigation was conducted to analyze the enhancement of heat transfer in a circular tube operating at high temperatures through the utilization of Y-shaped inserts. The analysis considered two scenarios: one without rotation and another with axial rotation along the edge of the inserts. The "Ansys 2022-R2" module was utilized for computation utilizing the finite volume method, employing the k-ε turbulence model. The numerical involved subjecting a pipe wall with a diameter of 68 millimeters and a length of 1.5 meters to a constant heat flow 1000W/m^2. The equations were solved using a pressure-centric methodology to analyze high Reynolds values, ranging from 3000 to 21,000. Table 1 presents the boundaries and physical parameters of the air that were investigated in the test.

Table 1
Boundary parameters and test section characteristics

Name	Conditions
Inlet	The inlet velocity (v) is related to the Reynolds number (Re) values of 3000, 6000, 9000, 12000, 15000, 18000, and 21000
The temperature at the inlet, Tin	300 kelvins
The canal's hydraulic diameter, designated as Dh,	68 mm
Y-shaped insertion	The adiabatic condition, denoted by Δ q = 0
Heat exchanger consisting of a tube	There is no slide
The heat flux	1000 Wm^{-2}
Y-shaped insertion	The adiabatic condition, denoted by Δ q = 0
Outlet Parameters	Pressure = zero
The Turbulence Model	RNG model (k-ε)
Coolant material: the density of air (ρ Air)	1.225 kg/m^3
(Cp)	1006.43 J/kg-K
(λ)	0.0242 W/m-K
(µ Air)	1.7894 × 10-5 kg/m-s
Thermal conductivity of Aluminum (K Al)	202.4 W/m - K
(ρ Al) is	2719 kg/m^3

2.2.3 Grid independence test

It was employed to assess the influence of the element's numerical value on the resulting outcomes. This study used structured meshing to analyses and compare the temperature at the exit and the pressure decrease. Table 2 displays the grid independence values for a smooth pipe with a Reynolds value (Re) of 3000. The selection of the "fine" grid consisting of 2295624 computational cells was based on careful consideration of factors such as time, cost, and accuracy. As seen in Figure 3 and Figure 4.

Table 2
The element numbers for several geometries that were used to validate grid independence

Elements No.	Nusselt number	$\frac{\mathrm{Nu\,i+1-Nu\,i}}{\mathrm{Nu\,i+1}}$	Pressure drop	$\frac{\mathrm{f\,i+1-f\,i}}{\mathrm{f\,i+1}}$
753811	22.206	-----	1.147	-----
1016344	21.221	0.0443	1.140	0.0061
2295624	20.75	0.0221	1.2	0.05
3046946	20.718	0.0015	1.19	0.0083
4059858	20.704	0.0006	1.18	0.0084

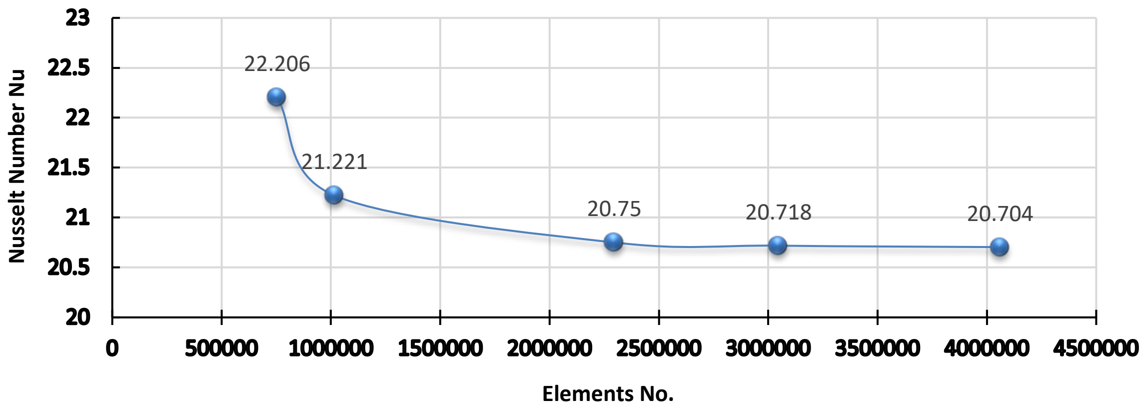


Fig. 3. The effect of elements number on Nusselt number

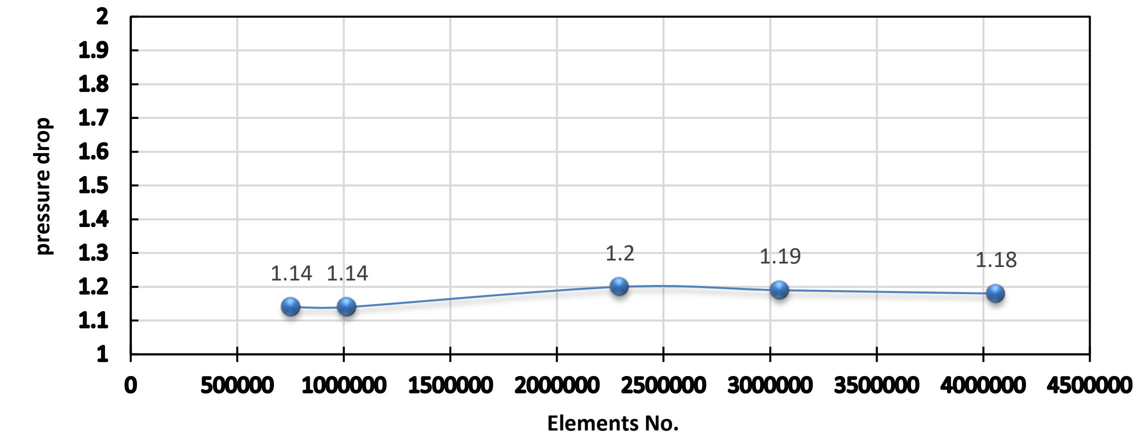


Fig. 4. The effect of elements number on pressure drop

2.4 Validation

To validate the precision of the fluid simulation in a seamless tube, the findings were compared to those acquired by Ifraj *et al.,* [1]. The experimental results are presented for the variables Nu and f. This model relies on computational techniques. The numerical simulations in Figure 5 and Figure 6 also investigated the Dittus-Boelter and Blasius empirical correlations in connection to the Nusselt number (Nu) and friction factor (f). The mean absolute deviations were calculated as follows: 4.7%, 3.4%, 3.4%, 3.4%, 3.2%, 3.1%, 1.2%, and 0.05%, respectively.

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.4} \tag{15}$$

$$f = 0.316\ Re^{-0.25} \tag{16}$$

Nu and f were validated at Re values ranging from 3000 to 21000.

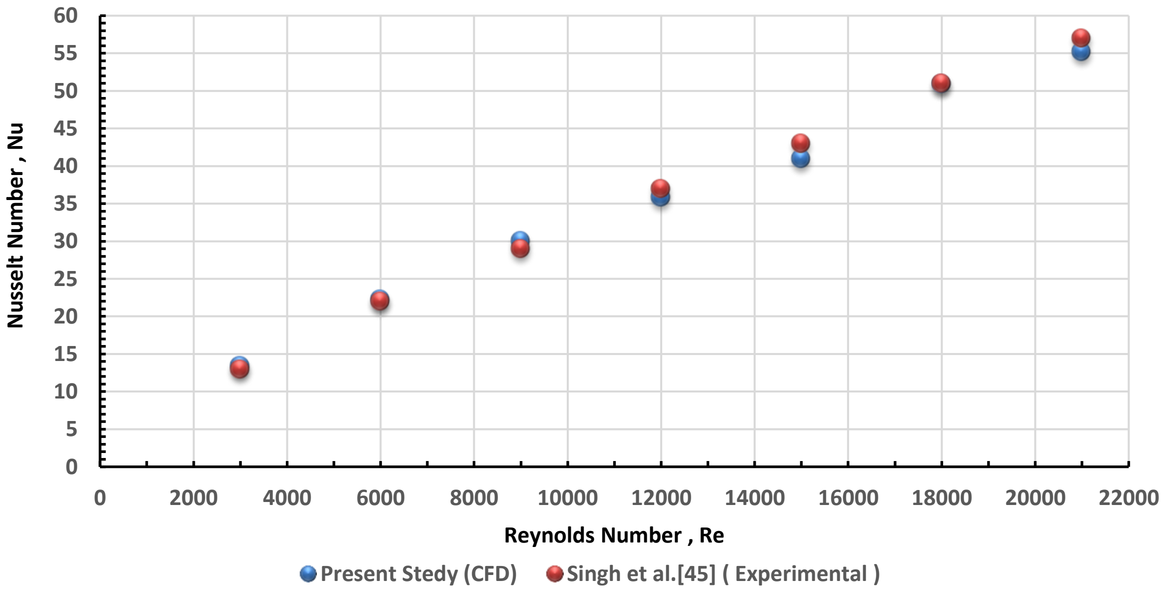


Fig. 5. The effect of the Reynolds number on the Nusselt number

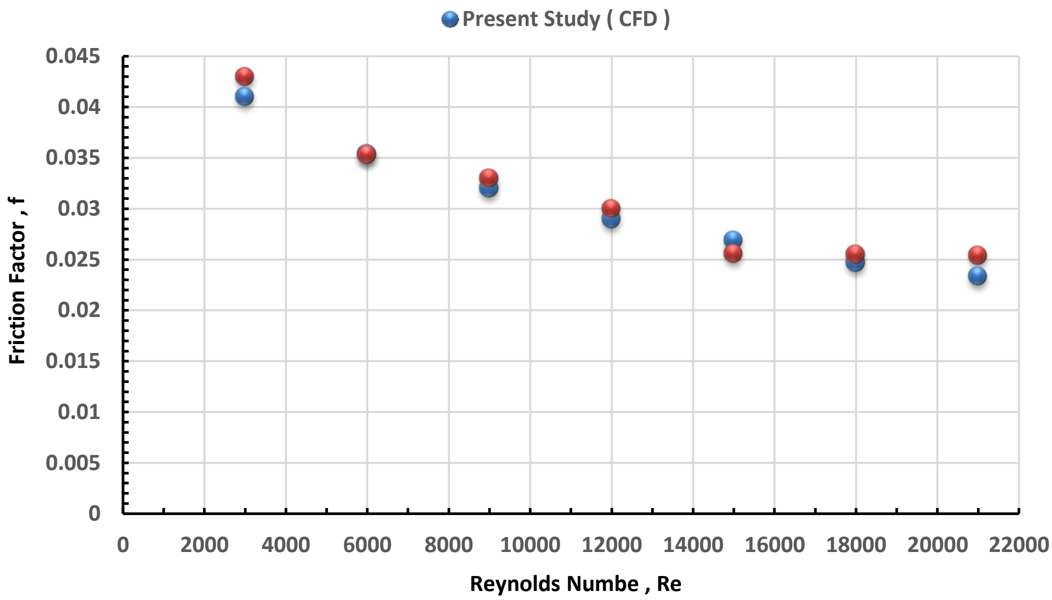


Fig. 6. The effect of Reynolds number on friction factor

3. Results and Discussion

Figure 7 displays the Nu values associated with different combinations of pipe geometry and flow velocity. The Nu values are used to compare the heat transfer between a heat exchanger and a smooth circular tube. Raising the flow rate results in an increase in the Nusselt number (Nu) in all tube configurations. By increasing the flow rate, the heat created on the surface of the tube may be efficiently removed. When the external heat flow is held constant, the overall heat transfer rate (h) increases, and there is a noticeable fluctuation in the temperature difference between the tube and the liquid. Among all the simulated scenarios, the Nu value that has been recorded as the highest is approximately 128.14. The value is linked to the Y configuration with the highest Reynolds number (Re) of 21,000. Unlike an empty tube, the maximum recorded Nu value was 55.23. The higher Nu value is due to the accelerated heat transfer rate. Figure 7 illustrates efficient fluid blending, as seen by the concentration of streamlines in the central area of each container in the fluid field, which occurs due to the introduction of a Y-shaped insert under rotational circumstances. With an increase in the Reynolds number, both the velocity of the fluid and the rate at which heat is dissipated also increase. Eddy currents are produced in close proximity to the tube wall.

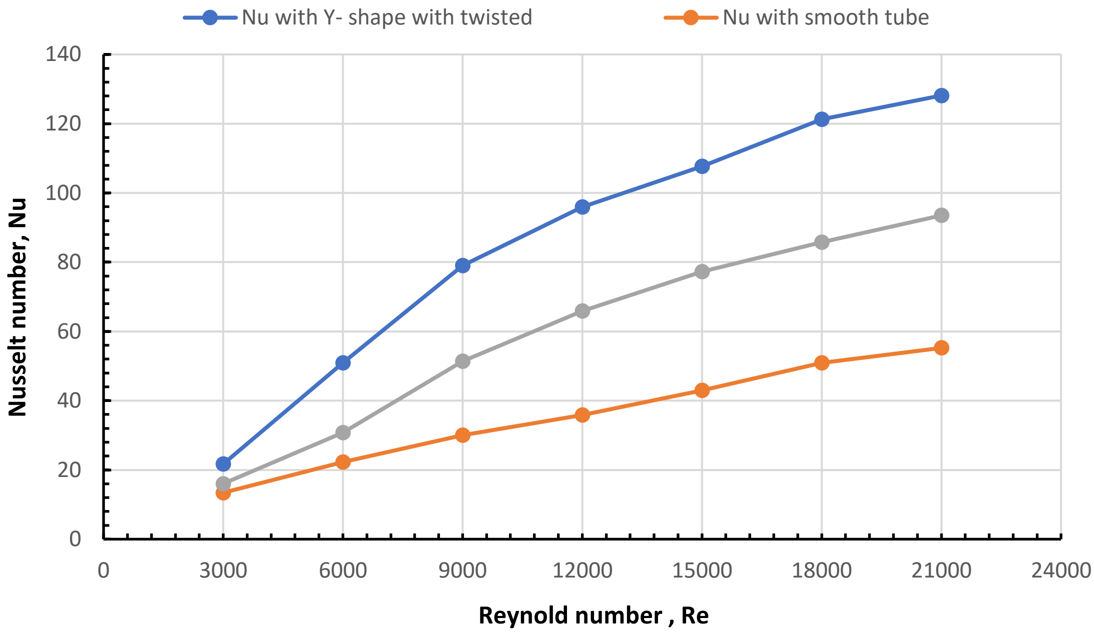


Fig. 7. The effect of the Reynolds number on the Nusselt number

3.1 The Reynolds Number Affects the Friction Factor

Figure 8 displays the relationship between the friction factor, f, and the composition and Reynolds number (Re) values. The f parameter is employed to compare the thermal outcome of each test case with that of the smooth tube. The increase in f with each modification in tube design is influenced by countercurrents, flow obstruction, and the ongoing contact area between the fluid and the tube surface. Based on Figure 5, the maximum value of f occurs when inserting a Y-shaped strip without twisting. At the lowest Re value of 3000, the f value is approximately 0.093, indicating that this configuration is the least favorable in terms of fluid performance. However, when inserting a Y-shaped strip with twisting, the minimum f value of 0.029 occurs at Re = 21000, suggesting that this configuration is more effective in reducing the friction factor.

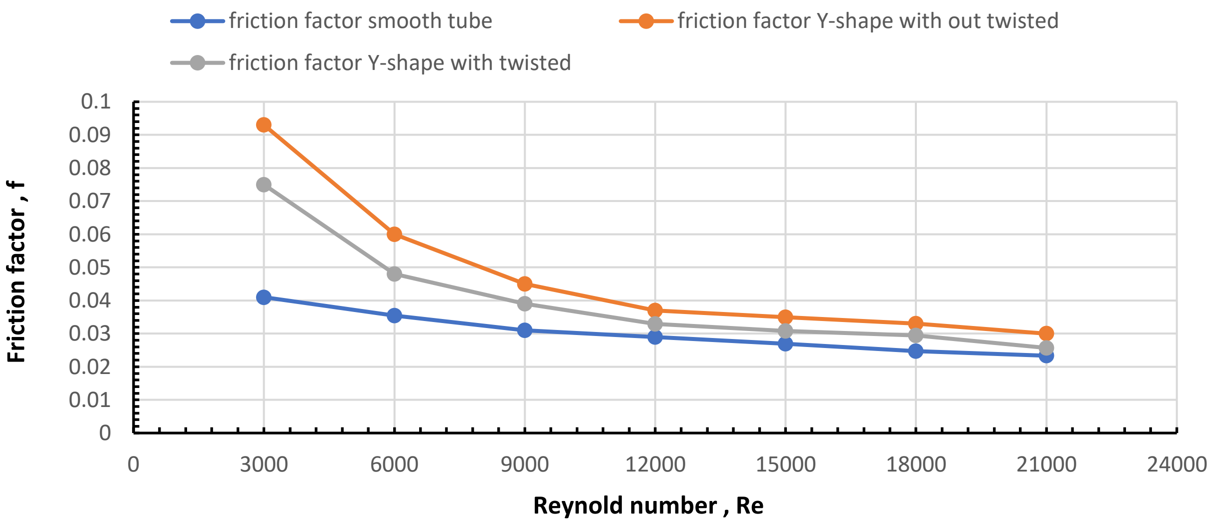


Fig. 8. The effect of Reynolds number on friction factor

3.2 The Reynolds Number has an Impact on the Thermal Performance Factor

The Y-shaped insert, twisted at a Reynolds number of 3000, achieved a thermal performance (TPF) of 3.099, which is the highest recorded. Figure 9 demonstrates that as the Reynolds number decreases, there is an improvement in heat transfer performance. This occurs due to the test section experiencing a higher pressure drop at higher velocities, resulting in an increase in the friction factor and a decrease in thermal performance.

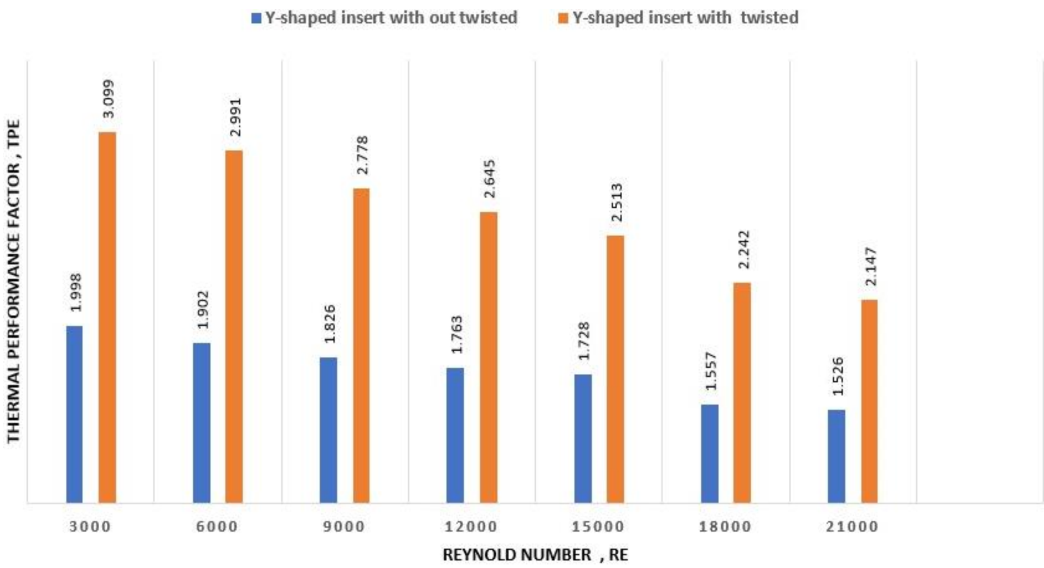


Fig. 9. The effect of Reynolds number on thermal performance factor

4. Properties Related to the Movement of Fluids and the Transfer of Heat

Figure 10 and Figure 11 illustrate the disparity in the air flow patterns at the Y-shaped junction without any twisting, compared to the altered flow patterns resulting from twisting. These flow patterns were observed in the X-Y plane, which was consistent across all cases, with a Reynolds number (Re) of 3000. Torsion-induced vortices enhance the process of fluid mixing. The dimensions of the vortices promote accelerated fluid blending by encouraging the neighboring fluids to generate further vortices. This enhances the stability of flow acceleration and thermal performance by facilitating the rapid dissipation of heat from the volatile fluid. Increasing the size of the vortex amplifies the possibility of heat transmission, hence improving the overall thermal-hydraulic efficiency.

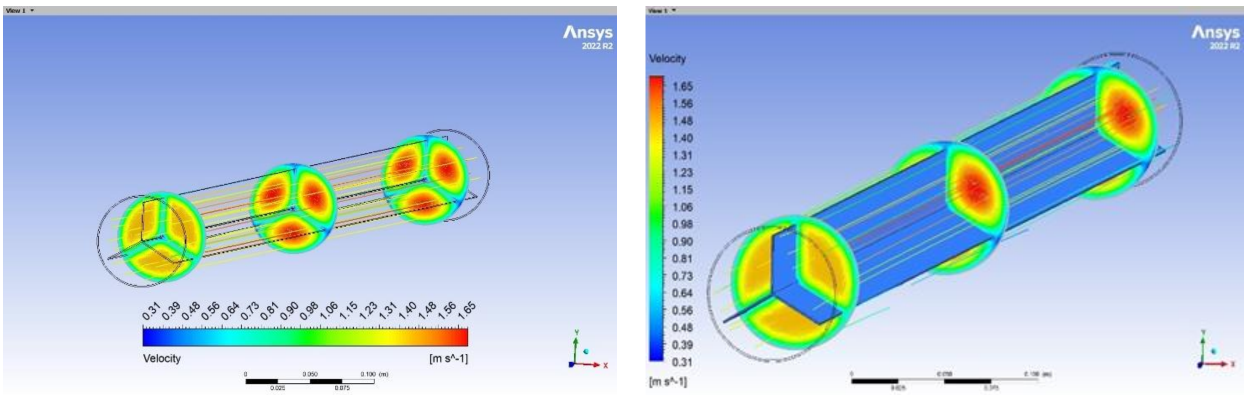


Fig. 10. Streamlines at Y- Shaped addition without twisted at Re = 3000

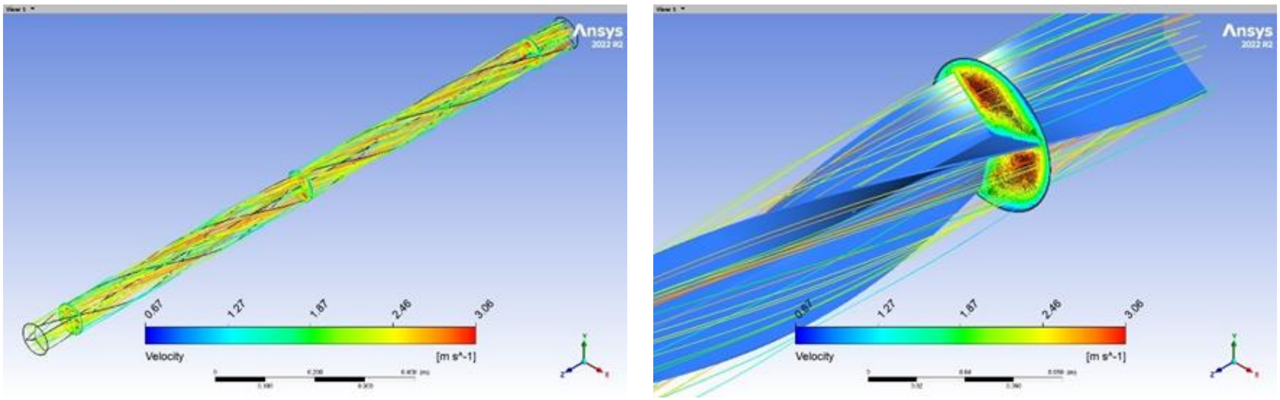


Fig. 11. Streamlines at Y- Shaped addition with twisted at Re = 3000

Figure 12 and Figure 13 depict the velocity patterns at a Reynolds number (Re) of 3000. The influence of the Y's form on the fluid's velocity distribution is evident. When the insert is not twisted, the velocity increases from 0.31 to 1.65. However, when the insert is twisted, there is even more mixing happening along the walls of the inlet Y. Vortices induce circumferential currents that enhance the fluid velocity, as shown in Figure 13.

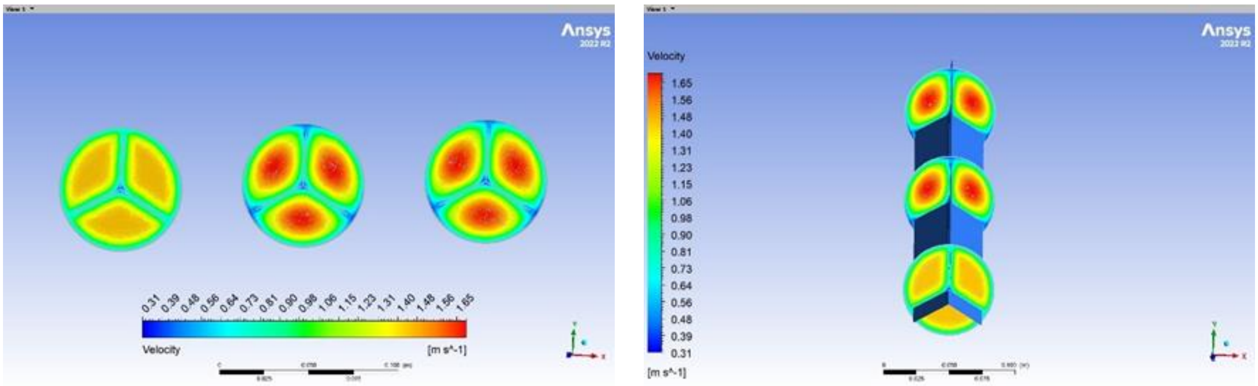


Fig. 12. Velocity contours at Y-shaped addition without twisting at Re = 3000

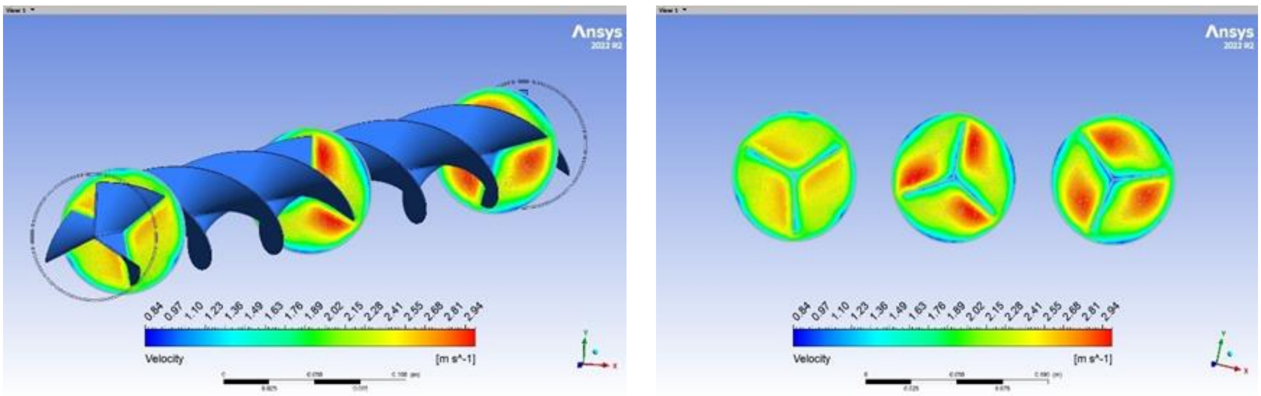
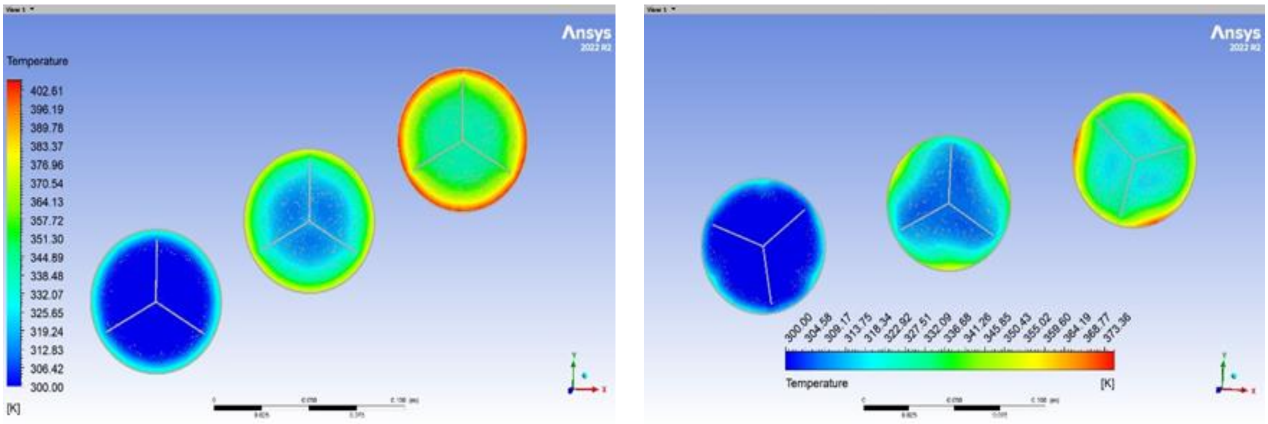


Fig. 13. Velocity contours at Y-shaped addition with twisted at Re = 3000

Turbulence occurs when there is a rise in airflow velocity. Turbulent flow is distinguished by increased internal mixing of the air, leading to more effective heat transmission compared to laminar or transitional flow. The efficiency of heat transfer in turbulent flow is increased as a result of intensified particle mixing. Consequently, the air has the capacity to more effectively take in heat from the pipe walls, leading to a quicker cooling of the area that is exposed to the heat flow. The heat transfer coefficient, h, increases as the air velocity rises because of enhanced molecule mixing in turbulent flow. Consequently, the air can more effectively dissipate heat from the tube. The decrease in temperature from 402.61 K in the Y shape without twist to 373.36 K in the Y shape with twist is a consequence of the enhanced heat transfer efficiency due to the increased air velocity and turbulent flow. This leads to a higher rate of heat extraction from the surface of the tube. As seen in Figure 14(a) and Figure 14(b).



(a) (b)

Fig. 14. (a) Temperature contours at a Y-shaped addition without twisting at Re = 3000, (b) Temperature contours at Y-shaped addition with twisted at Re = 3000

A Y-shaped addition signifies the division of flow into multiple branches, leading to intricate flow patterns. Torsion introduces further intricacy by progressively altering the direction of the flow, resulting in heightened interactions among distinct flow layers. The vector lines depicted in Figure 15 and Figure 16 illustrate both the direction and magnitude of the velocity at every point within the analyzed domain. Upon analyzing these lines, one can see alterations in velocity and changes in the direction of flow as a result of the intricate structure of the Y-shaped addition and torsion .This overlapping can result in areas with distinct velocities and occasionally give rise to the formation of minor whirlpools due to abrupt shifts in direction.

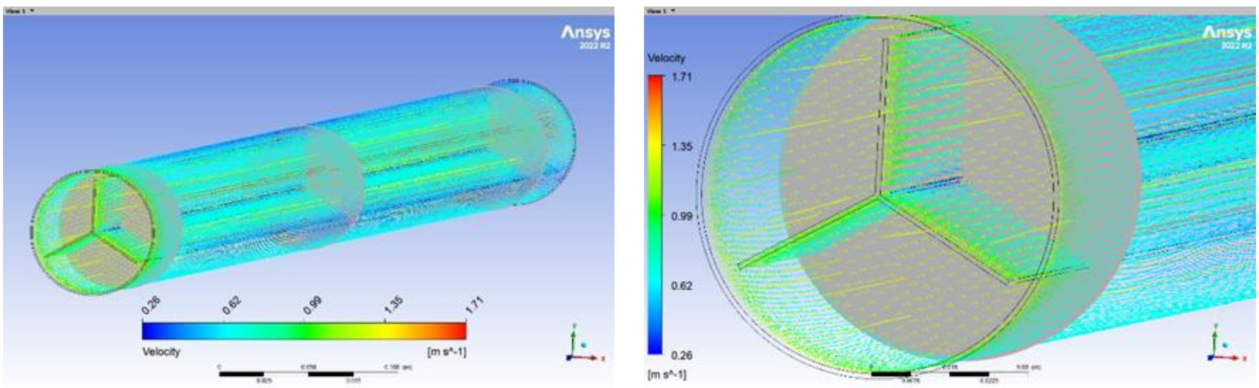


Fig. 15. Vector contours at Y-Shaped addition without twisted at Re = 3000

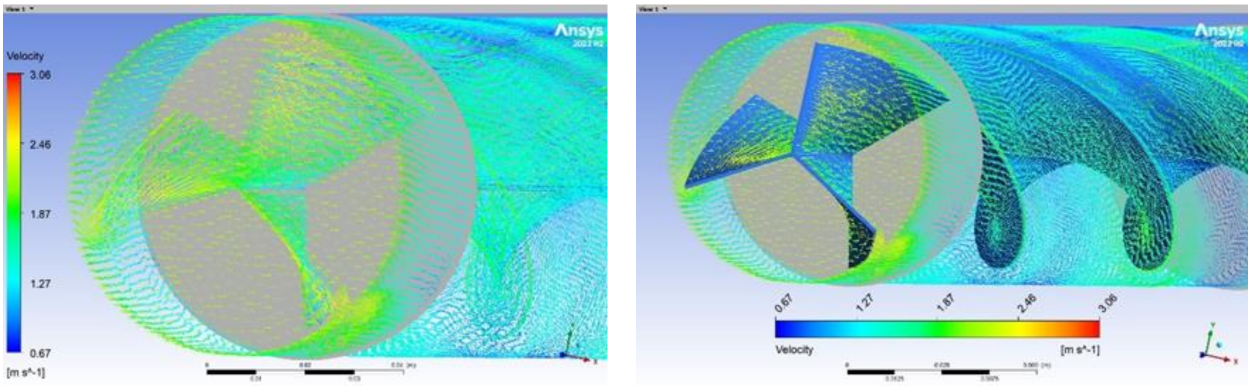
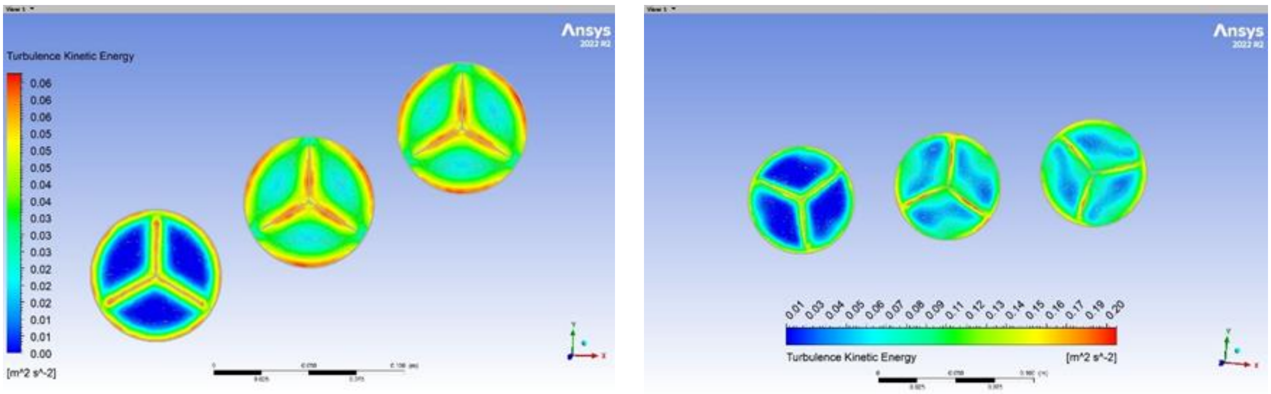


Fig. 16. Vector contours at Y- Shaped addition with twisted at Re = 3000

In order to comprehend the impact of Figure 17(a) and Figure 17(b), depicting the turbulent kinetic energy lines when combined with a Y-shaped structure subjected to torsion at a Reynolds number of 3000, it is necessary to elucidate certain fundamental concepts.

Turbulence refers to the irregular and chaotic flow of a fluid, such as air or water, that is characterized by rapid changes in velocity and pressure. Kinetic Energy: Turbulent kinetic energy quantifies the level of energy contained in the turbulent movements occurring within a liquid. It serves as a measure of the level of turbulence in the flow and highlights regions with significant turbulent movement. Turbulent kinetic energy is anticipated to be concentrated at the locations where the Y-shaped structure splits and at the regions where torsion occurs. The zones can be easily observed in the isobars (contours) that represent turbulent kinetic energy. Increased turbulent kinetic energy results in enhanced fluid mixing and greater heat transfer. This phenomenon can be utilized in engineering applications to enhance the efficiency of systems that depend on the movement of fluids.



(a) (b)

Fig. 17. (a) Turbulence Kinetic Energy contours at a Y-shaped addition without twisting at Re = 3000, (b) Turbulence Kinetic Energy Contours at Y-Shaped Addition with Twisted at Re = 3000

5. Conclusion

This study involved a numerical analysis of the installation of a Y-cut triangular twisted strip into a circular tube with HE shapes. The results indicate that Y-shaped inserts have a significant influence on Nu, f, and TPF. The primary findings of the investigation are as follows:

i. Growing the Y-twisted triangular laminate inserts are enhanced to improve heat transmission properties and simultaneously decrease friction. Moreover, there is a positive correlation between a narrower range of Reynolds numbers and a higher value of TPF.

ii. The Y-cut triangular twisted configuration exhibits a Nu range of 21.7 to 128.14, covering Reynolds values from 3000 to 21000. The coefficient of friction varies between 0.075 and 0.0257.
iii. The Y-shaped insert with a twisted configuration and Reynolds number (Re) of 3000 had the highest convective heat transfer coefficient, measuring 3.099.
iv. The study indicates that this type of input could enhance industrial applications by enhancing heat transmission and thermal performance. The present study shows enhanced heat transfer capacities associated with prior research conducted within the same Reynolds number range.

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