

# Heat Transfer Enhancement in Single Heat Exchanger 2D Pipe Using Rod with Different Angles Based on Computational Fluid Dynamics Study

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## Abstract

The current numerical study focuses on the statistical investigation of the airflow and the improvement of the heat transfer rate by forced convection of a single pipe in a heat exchanger by the inclusion of a rod. Using the finite volume method by numerical simulation the flow characteristics of the working fluid with enhanced heat transfer are numerically studied. Homogeneous heat flux is applied to the upper and lower walls of the pipe. More for the Reynolds number range (9000-18000) the effect of inserting a rod inside the tube at different oblique angles (40°, 50°, and 60°) was examined. Numerical results revealed that the transfer coefficient rate (Nusselt number) increase in the tube inserted into the rod is higher compared to the normal pipe. In addition, the results also showed that when the angle of inclination of the rod in the single-pipe heat exchanger is gradually increased the Nusselt number increases. The Nusselt number maximum value was shown at the 60° angle of the rod insert. Because of the resistance of a bigger flow, the friction factor was found by using the rod inserts at (60°) and pitch distance (0.04 m). For a minimum slant angle of (40°) and a pitch distance of (0.04 m), the maximum value of the performance evaluation criteria (PEC) was stated. In comparison to the smooth tube, the percentage of fluid velocity distribution rises by (50, 57, and 63%) at the angle of inclination of the rod (40°, 50°, and 60°), respectively.

## 1. Introduction

In a wide range of industrial and engineering applications, for example, power generation, petrochemical industry, air conditioning, etc., shell-and-tube heat exchangers are used. Heat is transferred through the walls of the tube from the hot side to the cold side in these devices. To intensify the heat transfer process, it is necessary additional techniques and methods are used in cases of low heat transfer rate. Significant contributions around the world made by scientists and engineers in technologies for increasing heat transfer [1 and 2]. These techniques are usually divided into two parts, the first passive and the second active. The direct application of external energy is considered the main difference between them is that it is not necessary for passive techniques. And therefore, repeatedly in practical applications, they are adopted. Passive technologies include many types of turbines, such as twisted tape, spiral tape, porous media inserts, etc. [3-6]. Vinous M. Hameed and Bashar Muslem Essa [7] presented an experimental study to verify the properties of heat transfer and airflow as a working fluid in a tube mated in a heat exchanger with a triangular fin. The test section consists of two sections, the first is an insulated pipe made of Perspex material with dimensions of length, internal diameter, and thickness (2, 0.054, 0.003 m),

respectively. The second section consists of a tube made of copper with or without fins with a length of (2.250 m) an internal diameter (0.02 m) and an external diameter (0.022 m). Experimental results showed that by reducing the distance between two fins and increasing the Reynolds number the coefficient of convective heat transfer gradually increases. This is due to the increased surface area. It was found that the value of space (0.022 m) gives a good improvement in heat transfer rate. H.A. Mohammed et al. [8] numerically studied the effect of inserting a strip with holes inside a circular double tube in a heat exchanger using different kinds of nanofluids (Al<sub>2</sub>O<sub>3</sub>, CuO, SiO<sub>2</sub>, and ZnO) with varying volume fraction ratios (1-4 %). Using the finite volume method, the governing equations of flow (the equation of continuity, momentum, and energy) were made. The upper and lower walls of the pipe are highlighted by a uniform constant heat flow. Two different tape insertion arrangements (forward and backward) for how many Reynolds (10000-50000) were used. The results of the numerical analysis showed an increase in heat transfer by about (367-411 %) when the strip with the front openings is arranged at an angle of inclination of (30°) and a distance of (30mm). S.R. Shabanian et al. [9] numerically and experimentally studied computational fluid dynamics (CFD) modeling on heat transfer, friction factor, and thermal performance of an air-cooled heat exchanger equipped with three types of tube inserts including butterfly, classic twisted tape, and toothed. The maximum thermal performance factor was obtained by including the butterfly in the considered range of the Reynolds number at an oblique angle of 90°. Also, the results of the study revealed that the difference between the heat transfer rates obtained from the use of classical and coarse inserts was reduced by lowering the twist ratio. In terms of the severity of the disorder, the expected results of computational fluid dynamics were used to explain the observed results. In addition, good agreements were obtained between the Nusselt number with the values of the friction factor. Mahdi Pourramezan and Hossein Ajam [10] presented a numerical investigation to improve the hydraulic properties of heat transfer by convoluted conical inclusions inside a circular tube with a single-phase turbulent flow using the CFD method to simulate three-dimensional situations. The K-epsilon model was used for the computational domain. The results of the study showed that by increasing the number of Reynolds the friction factor gradually decreases and the Nusselt number increases. S.K. Saha et al. [11 and 12] conducted experiments to investigate the laminar flow's heat transfer characteristics and friction factor in a circular pipe fitted with regularly spaced twisted tape components, which inhibit fluid flow less than continuous twisted tape. According to their experimental findings, the flow in the pipe inserted with segmented twisted tape elements has a 40% lower pressure drop than the flow in the pipe placed with continuous twisted tape, and the former exhibits superior thermo-hydraulic performance. Bodius Salam et al. [13] presented an experimental analysis to improve the heat transfer efficiency of a circular pipe in which water flows equipped with a rectangular twisted strip to measure the heat transfer coefficient and the friction factor. A tube made of copper with a length (0.9 m) and an inner and outer diameter (0.0266 and 0.03 m), respectively, was used. The test section is heated by a wire, which is also thermally insulated with fiberglass. The experimental results showed that by inserting the rectangular twisted tape, the Nusselt numbers in the tube were enhanced by (2.3-2.9) with an increase in the friction factor by (1.4-1.8) times compared to the empty tube. Paisarn Naphon and Tanapon Suchana [14] experimentally analyzed the enhancement of heat transfer in a horizontal concentric tube to study the effect of inserting a twisted wire brush from a turbulent water flow. It was observed that the heat transfer rate and friction factor of the smooth tube with 300 twisted wire brush inserts were higher than those of the ordinary tube with (100 and 200) twisted wire brush inserts are therefore higher than those of the empty tube without enhanced method. Smith Eiamsa-ard et al. [15] presented an experimental study of enhancing the heat transfer of vortex generation in a tube on the Nusselt number and friction factor by blocking the fluid flow by inserting single twisted strip, full-length and regularly spaced double twisted strips. The experimental results showed a percentage increase (12-29 %) in the heat transfer rate and friction factor of double-twisted tapes compared to single tape. A.R. Anvari et al. [16] numerically and experimentally studied the effect of the role of conical rings to improve the flow characteristics, heat transfer, and pressure drop variation of a pipe with a uniform constant thermal overflow. The conical rings were placed in two different orders, the first convergent and the second divergent. The CFD method was used in numerical simulations and the results indicated a remarkable agreement with the experimental data of the Nusselt numbers. According to the expectations and the experimental findings, conical ring inserts have a negative impact on the heat exchanger pipe enhanced heat-transfer efficiency when water is used as the working fluid (even when air is used as well). Wenbin Tu et al. [17 and 18] reviewed a numerical and experimental study to improve the heat transfer coefficient and analyzed the addition of a small tube inside a circular tube to obstruct the flow. The pipe is inserted with different dimensions and diameters with a laminar flow of the working fluid (water). The results showed an increase in the Nusselt number and the friction factor with a decrease in the length of the separator, also, a decrease in the diameter of the inserted pipe increases the amount of the Nusselt number and the friction factor. Eflita Yohana et al. [19] introduced numerical simulations to enhance heat transfer by inserting a rod inside the vortex tube and obstructing the flow of fluid, which contributes to an increase in the heat transfer rate represented by the Nusselt number. The results of the numerical analysis showed about (13 and 22%) increase in assembly efficiency and heat rate, respectively. The findings also demonstrate that the location of the vortex source has a significant impact on the tornado's performance. S. A. Marzouk et al. [20] numerically and experimentally studied the improvement of the heat

transfer rate of a double heat exchanger by inserting a rod with a bolt configuration with a length (1000 mm) made of steel with a turbulent single-phase flow with a Reynolds number ranging (3200-5700). Three steps of insertion of the rod are studied with values of (25, 50, 100 mm). The results of the study indicated that the introduction of rods inside the tube improves the heat transfer rate represented by the number of Nusselt in addition, so the increase can be achieved more by the distance between the rods. Sarmad Ahmed Ali et al. [21] the heat transfer rate improved by (12.808, 17.989, and 20.978%) as a result of the inclusion of three different configurations (square, circular, and triangular) on the surface of the three-dimensional horizontal pipe with turbulent water flow within the ranges of single-phase Reynolds numbers (3500-7000). The governing equations of the flow were solved using the (Ansys Fluent) program. The numerical results also indicated that the use of dimples has disadvantages by increasing the friction factor due to the obstruction of the fluid to flow compared to the smooth pipe.

The current numerical analysis focuses on improving the thermal performance of a single pipe in a working fluid flow (air) heat exchanger of the Reynolds number range (9000-18000) with a turbulent single-phase flow exposed on the upper and lower walls a constant heat flux of (80kW/m<sup>2</sup>). A rod with three different angles (40°, 50°, and 60°) is used to obstruct the flow inside the pipe to study the effect on the heat transfer rate and the friction factor. Analysis and discussion of the velocity and temperature distribution as well as the change of the Nusselt number and the friction factor with Reynolds number ranges are studied numerically.

## 2. Description of Numerical Model

### 2.1 Assumptions of the Computational Model

The schematic of the physical model representation of the two-dimensional pipe that the group of rods is placed into is shown in Figure (1). The length of the rod insert is approximately (0.015 m). The impact of varied combinations of the pitch of ( $S= 0.04$  m) and slant angle of ( $\alpha= 40^\circ, 50^\circ,$  and  $60^\circ$ ) is also examined in the numerical simulation current study. The pipe of ( $L= 0.3$  m) in length and has an inner diameter of ( $D= 0.05$ m). The thickness of the solid wall is not taken into consideration in this investigation. Also, the heat transfer by conduction in the rods and the tube surface is neglected. The rod is fixed on the surface of the inner tube of the heat exchanger by inserting rods with a number (7) in the upper part and the lower part contains rods with a number (7), thus the total number of rods enhanced heat transfer ( $n=14$ ).

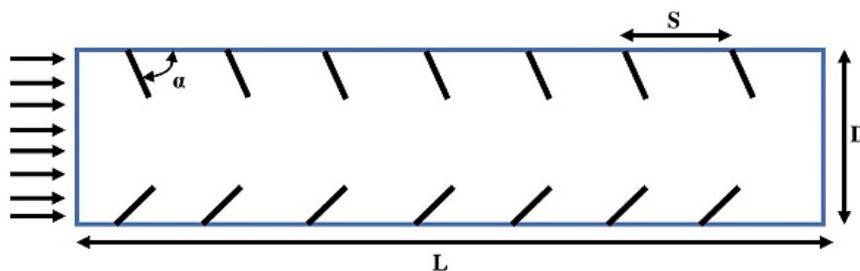


Fig. 1 Representation of schematic 2D pipe with inserted rod

### 2.2 Governing Equations of Fluid Flow

Using the Ansys CFD analysis method in a single-pipe heat exchanger with a rod inside, the flow-governing equations involving continuity, energy, and Momentum were solved. When investigating the current study of the phenomenon subjected to equations that include incompressible and two-dimensional energy Navier-Stokes equations are as follows [22-25]:

Continuity equation:

$$\frac{\partial}{\partial x}(\rho u_i) = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial(\rho u_i u_i)}{\partial x(u_i)} = -\frac{\partial p}{\partial x_j} + \left[ \frac{\partial}{\partial x_i} \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{2\mu \delta_{ij}}{3} \frac{\partial u_k}{\partial x_k} \quad (2)$$

Energy equation:

$$\left(\frac{\rho u_i C_p T \partial}{\partial x_i} - \frac{\partial}{\partial x_i} \frac{k \partial T}{\partial x_j}\right) = \frac{u_i \partial p}{\partial x_j} + \left[\left(\frac{\mu \partial u_i}{\partial x_j} + \frac{\mu \partial u_j}{\partial x_i}\right)\right] - \frac{2\mu}{3} \frac{\delta_{ij} \partial u_k}{\partial x_k} \quad (3)$$

This work has taken into consideration the  $k$ - $\varepsilon$  technique since it has several applications in heat transfer and can be addressed by CFD for both recirculating flows and planar shear layers [26]. A lot of researchers mention that this model is widely used and validates the turbulence model with several applications ranging from engineering industrial flows to environmental [27 and 28]. The following equations represent the approach of ( $k$ - $\varepsilon$ ):

$$\frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{u_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon \quad (4)$$

$$\frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{u_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (5)$$

$$G_k = \left( -\overline{\rho u_i u_j} \right) \frac{\partial u_j}{\partial x_i} \quad (6)$$

To determine the heat transfer optimization of the heat exchanger pipe by the following performance evaluation criteria (PEC) as follows:

$$PEC = (Nu / Nu_o) / (f / f_o)^{1/3} \quad (7)$$

This mathematical equation is used in fluid flow to determine the extent of the impact of various technologies to enhance heat transfer and improve flow characteristics in most engineering or industrial applications, for example, fluid flow in automobiles radiator or heat exchangers in oil and energy plants or channels, etc., where the change of the coefficient of thermal performance against the ranges of Reynolds numbers is explained and discussed.

Where  $Nu$  and  $Nu_o$  are represented Nusselt numbers for rod pipe and plain pipe, respectively. The friction factor of plain and rod pipe are denoted by  $f_o$  and  $f$ , respectively.

### 2.3 Boundary Condition of Physical Model

Figure (2) presents the current numerical analysis; the boundary conditions of the apparent computational domain are simplified. The figure shows the two-dimensional pipe of a heat exchanger with a steady-state single-phase turbulent flow with the rod inserted side by side. The upper and lower walls of the pipe have a uniform heat flux applied to them, while the fluid velocity inlet and outlet are exposed to the left and right sides of the pipe, respectively. On the lower and upper walls of the heat exchanger heat flux of (80 kW/m<sup>2</sup>) is applied. To achieve forecast accuracy in the circular pipe, the (RNG)  $k$ - $\varepsilon$  turbulence and conventional  $k$ - $\varepsilon$  turbulence models were selected. In the evaluation of the pressure field, the finite volume model was used. Also, a semi-implicit method was used for the pressure-velocity coupling algorithm for (SIMPLE) pressure-related equations. To perform the analysis of the perturbation model and to solve the independent incompressible Navier-Stokes time equations. By 1% at the entrance, a fully developed speed profile was used while maintaining the severity of the disturbance. The results of the study in terms of the influence of the oblique angle of the rod insert on the Nusselt number, the PEC, and the friction factor are presented. In the simulations carried out in this study, air was used as a working fluid for the numerical investigation carried out in heat exchangers containing rod inserts. The test pipe with slant angles of (40°, 50°, and 60°) with a linear direction was used to position the inclined rod inserts.

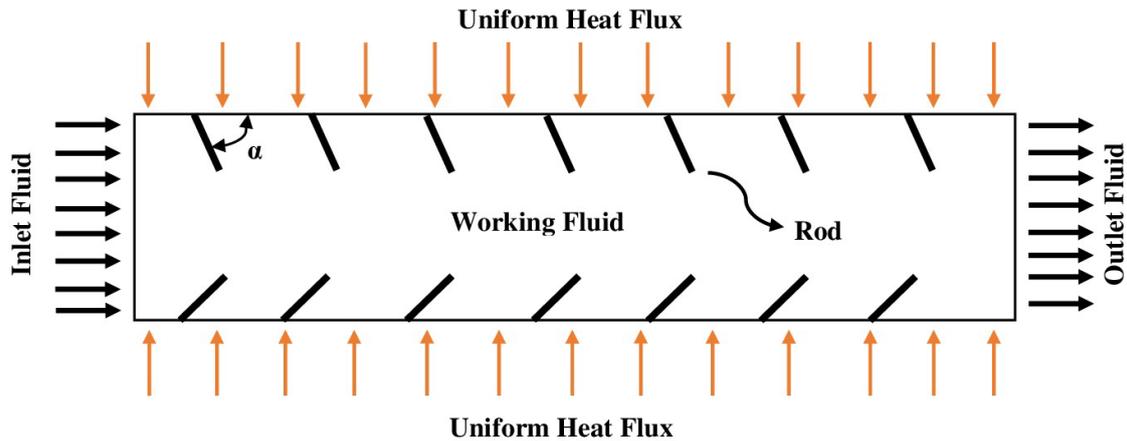


Fig. 2 Boundary conditions applied to the computational model

## 2.4 Technique of Numerical Simulation

Using one of the programs (Ansys Flint V2023 R2) CFD trading, which works by the finite volume method, all the governing equations of the flow are estimated with the boundary conditions of the physical matter. According to the study by the researcher Ravikanth S. Vajjha et al. [29] three different types of algorithms (COUPLED and PLSO) contradict the SIMPLE algorithm, although all algorithms have the same accuracy, the SIMPLE algorithm is characterized by giving the fastest numerical convergence rate. So, using the simple algorithm the velocity and pressure fields are also numerically coupled to cope with the convection conditions a second-order downwind system is used. To achieve a balance between computational economics and the level of development, the perturbation model ( $k-\epsilon$ ) is the most widely used criterion. Due to its efficiency, robustness, and reasonable accuracy across a wide range of turbulent flows, it is commonly used in industrial flow and heat transfer simulations. For this reason, the standard  $k-\epsilon$  turbulent model is employed, with the diffusion term in the momentum and energy equations being approximated by second-order upwind. The continuity, momentum, and turbulence equations converge with residues of ( $10^{-4}$ ), but the energy equation converges with residues of ( $10^{-8}$ ) as shown in Figure (3). A numerical model is convergent by approaching a set of model solutions with continuously repeating domains to a constant value. Moreover, if the sequence converges during the solution of the equations governing the flow and the physical state, the numerical mathematical model is consistent.

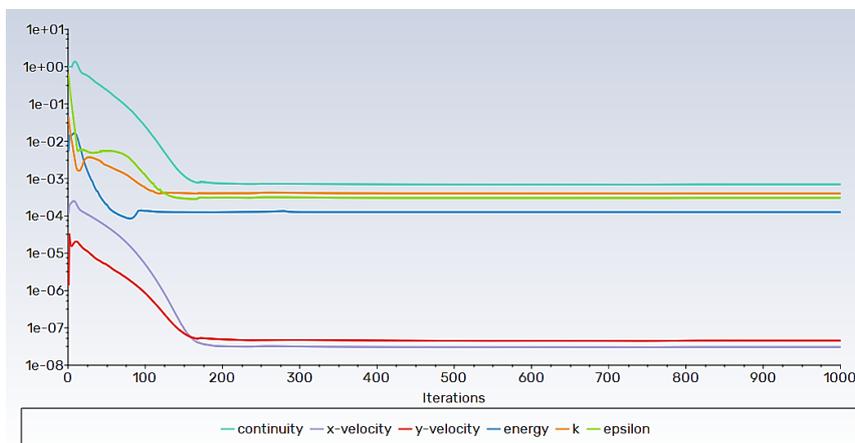
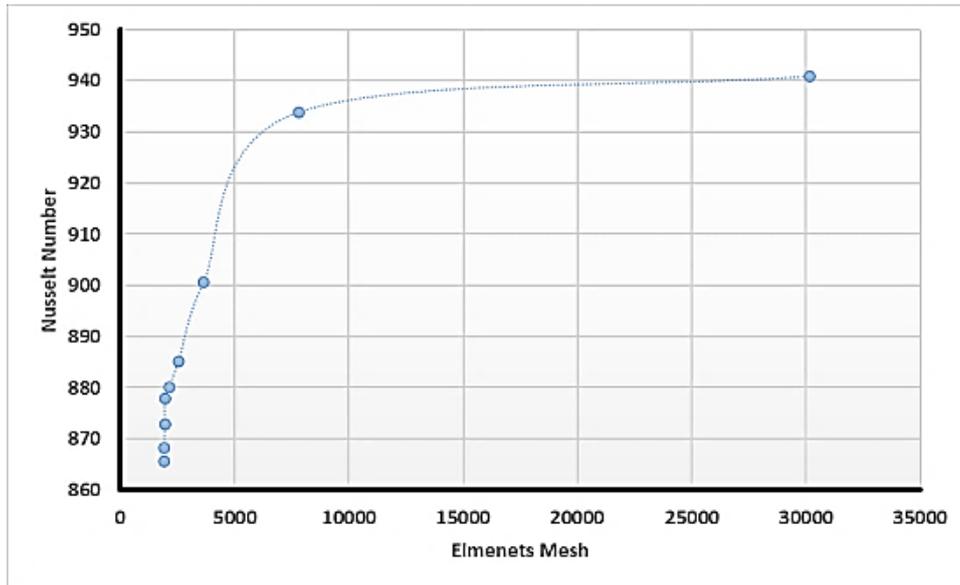


Fig. 3 Numerical convergence criteria for the conservation and turbulence equations

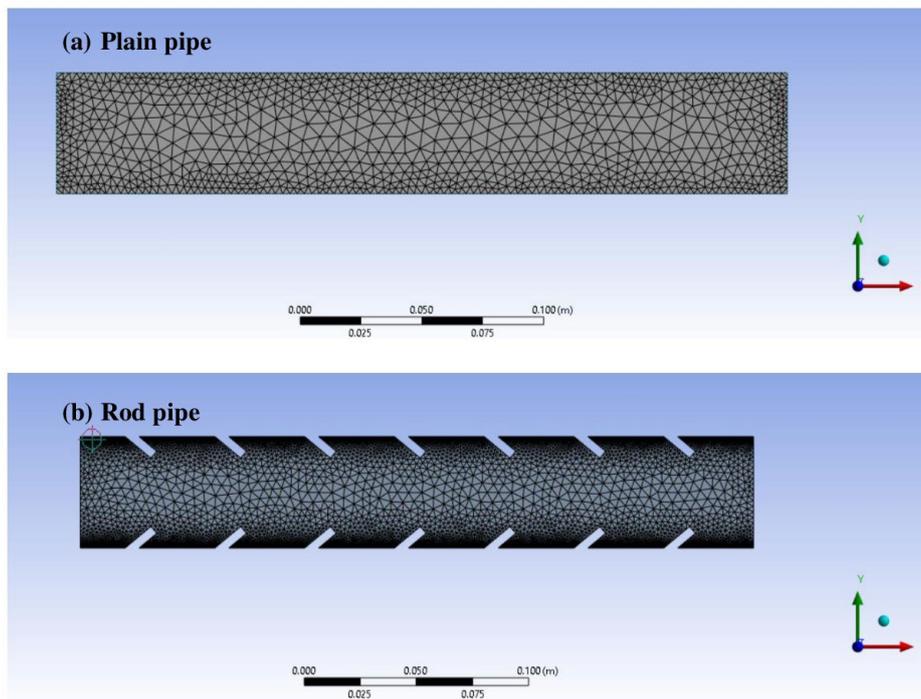
## 2.5 Test of Grid Independence

In this work, a set mesh of  $S/D = 0.8$  has been determined for a Reynolds number of (9000). The results demonstrate that the Nusselt number is related to the number of faces; at thirty thousand faces, the Nusselt number was nine forty. Furthermore, as Figure (4) illustrates, the Nusselt number remains unchanged as the number of faces increases to 30000 and beyond. As a result, 30000 faces were set up to run the simulation. Figure (5) shows the choice of the type of mesh to generate it around the walls and edges of the tube in two cases, the

first is a smooth normal tube, and the second is when the rod is inserted at various angles of (40°, 50°, and 60°) inside pipe. The softer grid division can be observed in the second case to achieve numerical convergence and accuracy of the results, where smoothing the edges for small numbers is extremely important.



**Fig. 4** Analysis of grid independence test



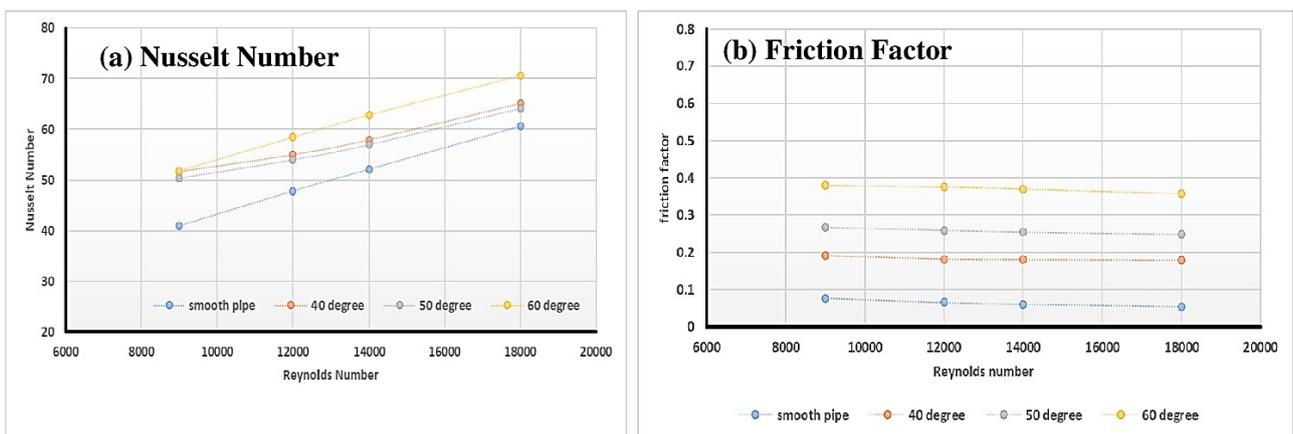
**Fig. 5** Mesh generation for (a) plain pipe; and (b) rod pipe at an angle of 40°

### 3. Results and Discussion

#### 3.1 Influence of Geometric Parameters

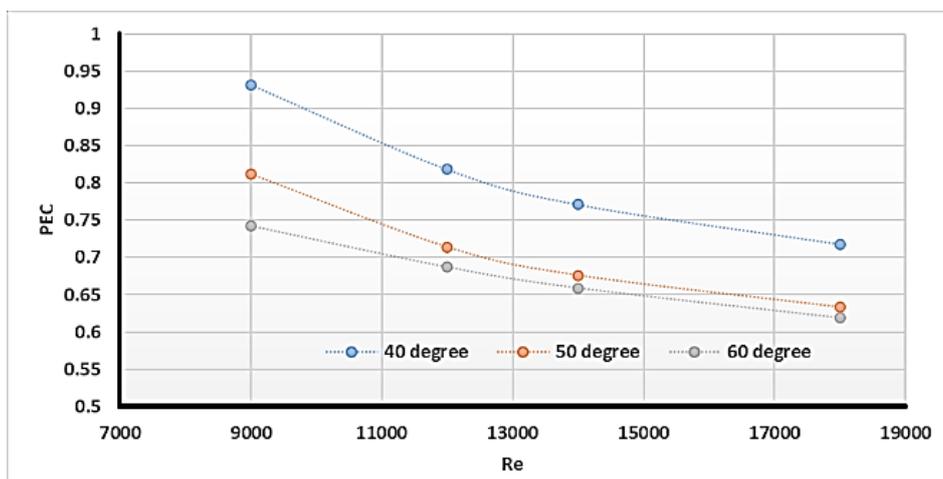
Figure (6a) shows the variation of the Nusselt number against the Reynolds number for the smooth pipe and the pipe inside which the rod is inserted at different angles. Based on the numerical results of all the angles of inclination of the inserted rod the Nusselt number is gradually increased by increasing the Reynolds number. It is

also observed that the number of Nusselt increases gradually with increasing angle inclination, with the highest value achieved at the angle (60°). In addition, it was also found by penis inserts a strong intensity of perturbation was produced. This in turn especially at high oblique angles caused the flow to mix rapidly. The findings indicate that using inserts with a 40° angle improves the heat transfer rate (Nusselt number) of heat exchangers by 38% as compared to normal pipe. Additionally, using inserts with an angle of 50° increased the heat exchanger's enhancement by 37% when compared to the smooth pipe, and using inserts with an angle of 60° increased the enhancement by 43% when compared to the normal pipe. Increasing the angle of insertion causes an obstruction in the flow of liquid, which leads to an increase in the percentage in the rate of heat transfer by forced convection compared to the empty pipe. Figure (6b) diagnoses the difference in the values of the friction factor with the Reynolds number and with the change of the angles of the rolled rod and the smooth pipe. It can be noted that with an increase in the Reynolds number and an increase in the angles of inclination of the pipe compared to the empty pipe, the friction factor gradually decreases. Additionally, because of the resistance of greater flow, which was seen at the biggest angle, an increase in the slant angle of the rod inserts causes an increase in the friction factor, with a maximum value attained at the angle of 60°. The findings displayed in Figure (6b) indicate that as the slang angle increases, so does the friction factor. At an angle of 40°, the friction factor increases by 57% compared to a smooth pipe; at an angle of 50°, it increases by 70%, and at an angle of 60°, it increases by 79%.



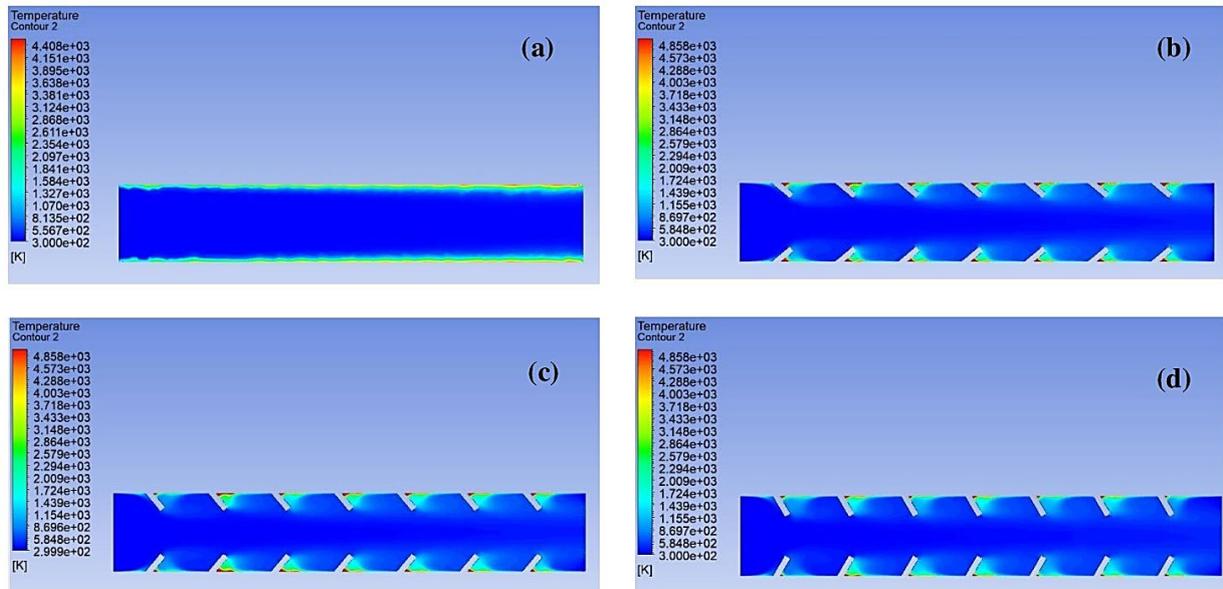
**Fig. 6** Variation of Reynolds number at different rod angles inserted in a smooth pipe with (a) Nusselt number; and (b) friction factor

Figure (7) shows the change in the performance evaluation criterion with the Reynolds number. It can be seen from the figure that as the Reynolds number increases, the performance evaluation criterion gradually decreases. The large angle of inclination (60°) of the rod gave the best criterion for evaluating performance compared to other angles (40° and 50°). All values of the thermal performance factor can also be observed using the rod inserted inside the pipe causing the obstruction of the flow, being less than one, so it improves the hydraulic and thermal performance compared to the ordinary smooth pipe.

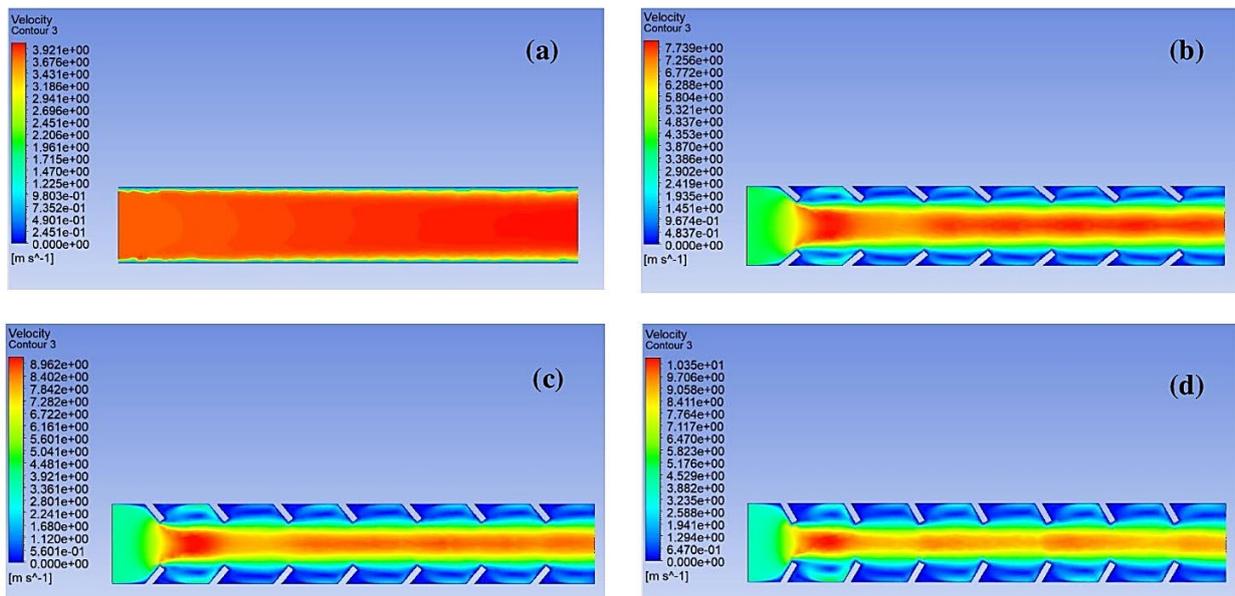


**Fig. 7** Variation of PEC against Re at different angles of inserted rod in the pipe

Figures (8 and 9) show the impact of different rod insert slant angles on temperature contours and velocity at a Reynolds number of (12000) in the computational domain. The illustrations demonstrate how many vortices are created as the slant angle increases due to the high turbulence flow or active mixing at the rear of the rod inserts. At the maximum angle of (60°), the greatest vortices and mixing flow were attained. It was discovered that the lowest flow occurred at the shortest angle of (40°), leading to an excessively weak convective current that had no impact on the rate of heat transfer.



**Fig. 8** Temperature contour at Reynolds number of (12000) of 2D pipe (a) smooth; (b) rod with 40°; (c) rod with 50°; and (d) rod with 60°



**Fig. 9** Velocity contour at Reynolds number of (12000) of 2D pipe (a) smooth; (b) rod with 40°; (c) rod with 50°; and (d) rod with 60°

#### 4. Conclusions

In the current numerical simulation, the heat transfer is improved by forced convection of heat with a two-dimensional steady-state single-phase turbulent flow of a single pipe in a heat exchanger by inserting a rod at different angles subjected to a uniform constant heat flux along the upper and lower wall. The Ansys Fluent

program was used to obtain the Nusselt number, the friction factor, and the performance evaluation criterion. Conclusions were drawn based on numerical analysis as follows:

- The number of Nusselt increases in the single-tube heat exchanger gradually as a result of the inclusion of the rod.
- The heat transfer rate (represented by the Nusselt number) increases when an increase in the changing angles of the inclined rod occurs. It was found that the maximum value of the average Nusselt number was achieved with an oblique angle of (60°) from the inclusion of the rod.
- Finding the maximum friction factor involved inserting a rod into a 2D pipe at a pitch of 40 mm and an angle of 60°. The reason for this is that the larger slant angle was where the resistance of a larger flow with rod inserts was noticed.
- At the value of the minimum angle of inclination of the rod (40°), the highest value of the performance evaluation criterion was obtained for the heat exchanger pipe compared with other angles (50° and 60°) with a pitch distance of (0.04 m).
- Along the axis of the fluid flow, the temperature distribution gradually increases as the length of the pipe increases.
- The percentage of fluid velocity distribution increases by (50, 57, and 63%) at the angle of inclination of the rod (40°, 50°, and 60°) respectively compared to the smooth pipe.
- The gradual decrease of the hydraulic thermal performance factor by increasing the range of Reynolds numbers.

### Nomenclature List

Cp	Heat capacity at constant pressure (kJ/kg.K)
D	Diameter of single pipe heat exchanger (m)
f	Friction factor (dimensionless)
k	Turbulence of kinematic energy (m <sup>2</sup> /s <sup>2</sup> )
L	Length of single pipe heat exchanger (m)
n	Total number of inserted rods (dimensionless)
Nu	Nusselt number (dimensionless)
PEC	Performance Evaluation Criterion (dimensionless)
Re	Reynolds number (dimensionless)
S	Pitch between two angles (m)
T	Temperature of fluid (K)
u	Velocity of fluid (m/s)
μ	Dynamic viscosity of fluid (N.s/m <sup>2</sup> )
ε	Turbulence of dissipation rate (m <sup>2</sup> /s <sup>2</sup> )
ρ	Density of fluid (kg/m <sup>3</sup> )

### Subscript List

i and j	The direction of flow in x and y respectively
o	Without enhancing
t	Turbulent

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### Conflict of Interest

Regarding the paper's publication, the authors state that they have no conflicts of interest.

### Author Contribution

*The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.*

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