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Investigation of the effect of magnetic field on the PEC and exergy of heat exchanger filled with two-phase hybrid nanofluid, equipped with an edged twisted tape

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ABSTRACT

In this study, the effect of using hybrid nanofluid and helical twisted tape (HTT) on the exergy efficiency and thermo-hydraulic performance of a heat exchanger is investigated numerically using the finite volume method (FVM). Also, Solidworks is used to sketch the geometry. The study is carried out by assuming the steady state flow using the pressure-based solver. Simulations of Cu-ZnO/water hybrid nanofluids are based on the mixture model. The Reynolds number (Re) changes from 10,000 to 40,000, volume fraction (φ) vary from 1 to 5%, and pitch ratio (PR) is of 1, 2, 3, and 4. The results demonstrate that the average Nusselt number (Nu_{av}) and thermal performance of the heat exchanger are enhanced with Re and φ. At φ = 5% and Re = 40,000, placing a HTT with a PR of 4 causes the pressure drop (ΔP) to enhance by 180.97% In comparison with a collector without a solar panel a turbulator. In addition, in the heat exchanger with a HTT with a PR of 4 and φ = 5%, the exergy efficiency is increased by 38.89% as Re is enhanced from 10,000 to 40,000. The use of a magnetic field causes the PEC in the heat exchanger to become greater than 1 in all cases. Also, the maximum exergy efficiency occurs when a magnetic field is applied at Re = 20,000 and a Hartmann number (Ha) of 150.

1. Introduction

The heat exchanger (HT) is one of the most widely used mechanical equipment in industries, which is used to exchange heat between two or more fluids. Commonly, the fluids have different temperatures comparatively each other. The fluids can be liquid or liquid and gas that can have a heat exchange. For example, in chiller systems, two HTs are used simultaneously, one is used to reduce the temperature of the refrigerant called the condenser, and the other is used to reduce the temperature of the circulating water in the fan coils, which is called the evaporator. There can be a wall between two fluids in HTs. They can be in direct contact with the ambient air, like the heat exchange of water in cooling towers. HTs used in refrigeration systems, air conditioning, heating, and food industries, etc., are mainly designed and manufactured in shell-and-tube, plate, dual tube, and air-conditioning models. Due to the enhancing progress of various industries, an increment in the rate of heat transfer (HT) Researchers have always focused on passive methods. In order to increase HT, turbulators with different configurations are used. Also, the use of nanofluids (NFs) has been of great interest to researchers in recent decades [1,2]. Akar et al. [3] simulated the HT filled with porous materials using CFD. Their study was done using Design Modeler software to design HT geometry. They used ANSYS Machining software to discretize the computational domain. Results indicate obtained from their study, porous materials can improve thermal performance. Meanwhile, the ΔP is enhanced as a negative factor by using porous materials.

Maakoul et al. [4] employed CFD to numerically simulate a dual-tube HT equipped with outer blades. They aimed to evaluate the thermo-hydraulic effects. The SIMPLEC algorithm was used in the turbulent flow regime with the k-ω turbulence model. Results indicate

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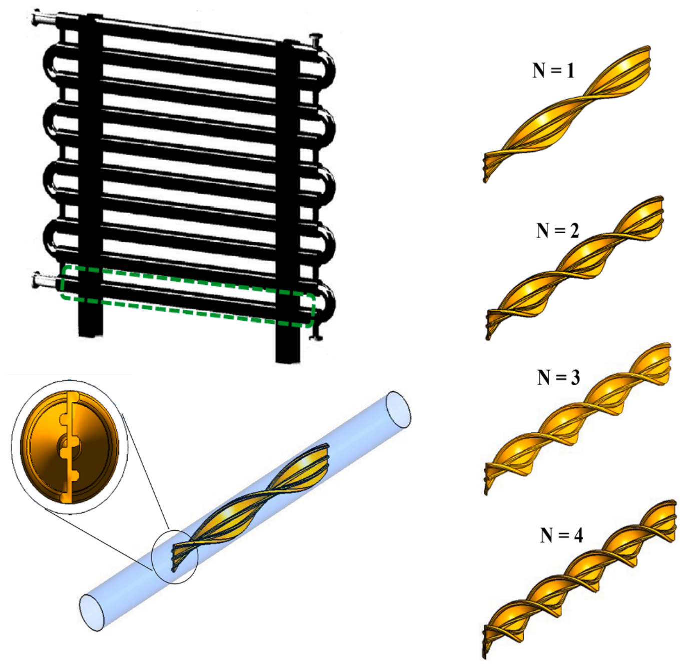


Fig. 1. Schematic of part of the studied HT.

Table 1
The geometry characteristics of the studied HT.

Diemnsion	Value
L	800 mm
D	60 mm
PR	1, 2, 3, and 4

Table 2
NPs and base fluid thermophysical properties [23,24].

Property	water	Cu	ZnO
$\rho(kg.m^{-3})$	998.2	8954	5600
$c_P(J.kg^{-1}.K^{-1})$	4182	383	502.7
$k(W.m^{-1}.K^{-1})$	0.6	400	13
$\mu(kg.m^{-1}.s^{-1})$	0.001003	-	

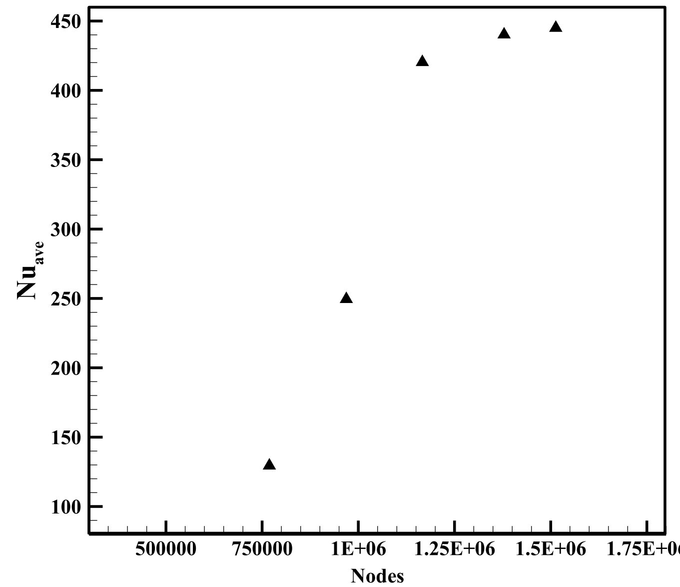


Fig. 2. Nu_{av} is obtained for the TP Cu-ZnO/water HNF inside the HT with a TT with a PR =4 at Re = 40,000 and φ = 5% for the grids with different nodes.

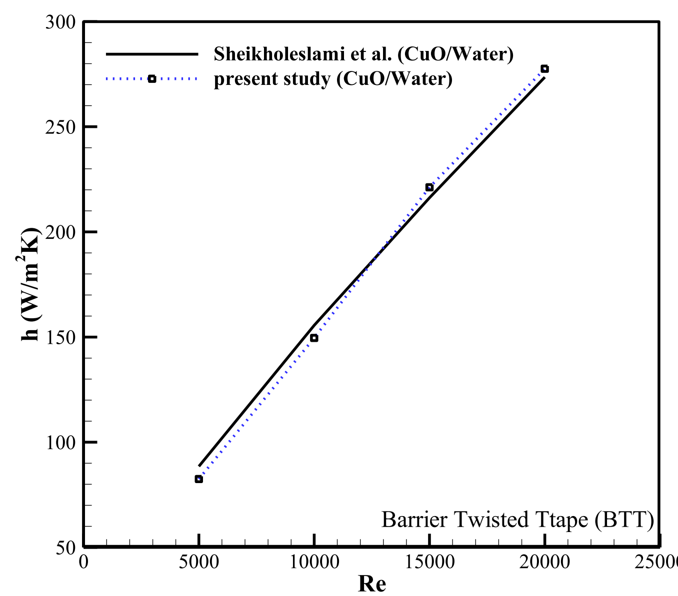


Fig. 3. Numerical simulation validation Comparatively the study of Sheikholeslami et al. [28].

presented by the authors, the outer blade disrupts the shape of the streamlines near the walls and enhances HT.

MeyaryDovom et al. [5] Utilizing CFD, we numerically simulated the effect of spherical vortex generators on the thermohydraulic performance of a HT. They used the SIMPLEC algorithm to couple velocity and pressure equations. The results revealed that the thermo-hydraulic performance is enhanced in all stages of the study.

Rashidi et al. [6] numerically simulated the twisted tape (TT) inside a HT During turbulent flow. Its primary goal was to improve HT using TT. Their study was done at 5000 < Re < 12,000 using the SST k-ω turbulence model. They showed that the TT can increase thermal performance by 50.11% at Re = 12,000 and a PR of 0.75.

Nazir et al. [7] reviewed the research done on improving the performance of parabolic trough solar collectors using turbulators. They found that the most effective turbulator types are the ribbed absorber tube and the concentric rod insert.

Bhuiya et al. [8] experimentally made a helical tape and examined its effect inside a HT to improve the thermal performance of the HT at different inlet velocities. At turbulent flow regimes, they conducted their study 7400 < Re < 54,000. Thermal performance was improved by 38.12% using helical tape. Also, the use of helical tape caused a significant ΔP at the outlet of the HT.

Kareem et al. [9] experimentally and numerically assessed Twisted effects tape on HT and the flow field. They first experimentally made the tube with different PR s. Following that, Nu_{av}, friction coefficient, and ΔP were studied for different PR values. There was excellent agreement between experimental and numerical data.

Aghaei et al. [10] simulated the effect of using TT s and a vortex generator simultaneously in the turbulent flow regime. Their study aimed to improve thermal efficiency by assuming steady-state flow and a pressure-based algorithm. Researchers found that tape disrupted the viscous layer and enhanced HT.

Tanachai and Boonloi [11] numerically simulated the zigzag vortex generators inside in turbulent flow, a tube has three dimensions. As a result of turbulent flows, the standard K-ε turbulence model was used. Their results were presented in the form of V, T, and P contours and the graphs of Nu_{av}, HT coefficient, and friction coefficient. It was stated that the zigzag vortex generators enhance the HT due to the chaotic flow that

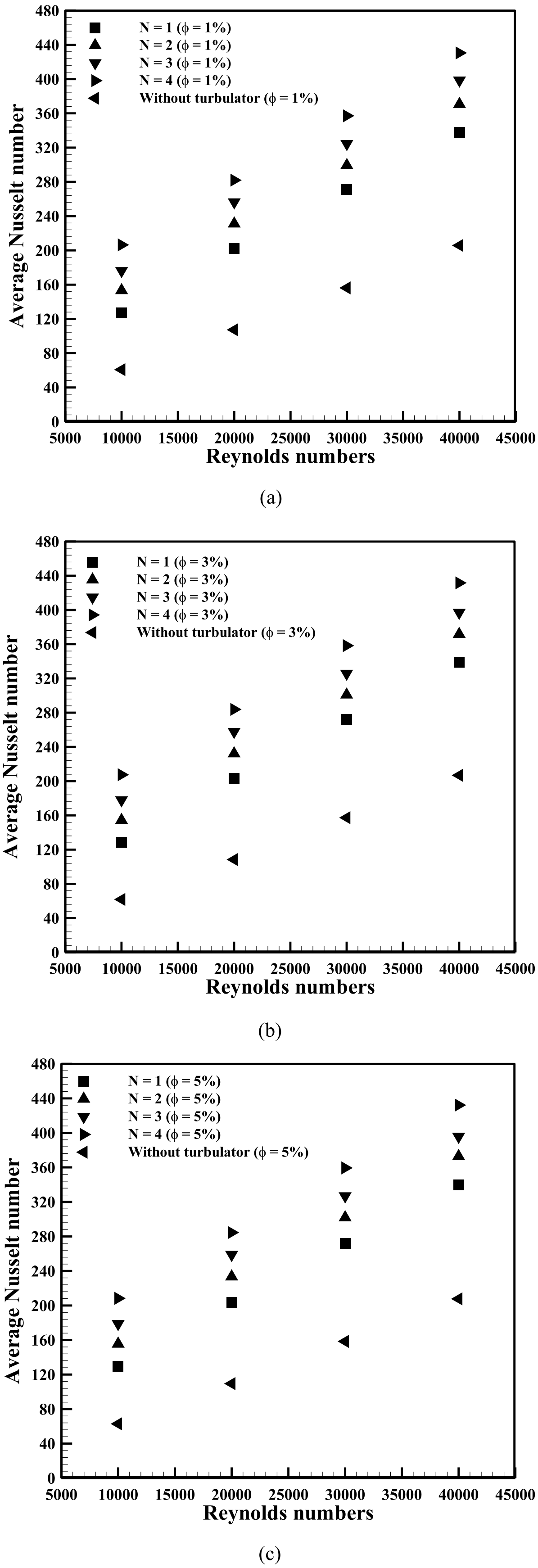


Fig. 4. Variations of the Nu_{av} as far as Re is concerned in a HT With different PRs on the TT for different φ.

they create in the tube.

Aghaei et al. [12] Calculation of the energy and exergy efficiency of a parabolic solar collector (ST) using numerical simulation of nanoparticle morphology. In this study, they used the single-phase method to model the NF flow and examine the morphology of NPs. It was demonstrated that the energy and exergy efficiency in the ST is enhanced with φ.

Xiangtao et al. [13] examined the effect of cylindrical fins on the thermo-hydraulic performance of a ST using CFD. Their study was done based on the FVM. They used the SIMPLE algorithm to couple velocity and pressure equations. They also used the RNG k-ε turbulence model to model the turbulent flow. The results showed that the convection HT coefficient in the ST is strongly influenced by the height of the cylindrical fins.

Dizaji et al. [14] An evaluation of the effect of using helical spirals inner tube with different pitches in a thermal model experimentally. During turbulent flow, their study was conducted 5000 < Re < 25,000. The results showed that the maximum thermal performance of the HT is enhanced by 67.11% at Re = 25,000 and a PR = 3.

Abdolbaqi et al. [15] fabricated rotating turbulators and investigated their effect on thermo-hydraulic performance inside an elliptical channel experimentally. Their study was carried out to increase the improvement of thermal performance in the elliptical channel by adding rotating turbulators at different inlet velocities when 7000 < Re < 34, 000. Their results demonstrated that the maximum increase in HT using rotating turbulators is about 40.98% at Re = 34,000.

Rashidi et al. [16] Examined numerically the effects of wavy vortex generators on the channel wall on HT and fluid flow using the FVM. They studied turbulent flow using the standard k-ε turbulence model. It was found that the use of vortex generators and increasing their height significantly affect the convection HT coefficient and Nu_{av}. Also, enhancing the height in the vortex generators increased the ΔP to a high extent Comparatively the simple channel.

Zheng et al. [17] An analysis of the effects of using a magnetic field and NF on convective and radiation HT of water/aluminum oxide NF using FVM using QUICK algorithm In order to couple equations of velocity and pressure. The results demonstrated that the use of a magnetic field is effective in the improvement of thermal performance.

Balla [18] employed CFD to numerically simulate a spiral tube in the turbulent flow regime to compare the HT in a spiral tube and a simple tube, SIMPLEC algorithm and second-order upwind spatial discretization. The results demonstrated that the spiral tube has a much higher thermal performance than the simple tube.

Wu et al. [19] utilized the FVM to assess influence of using absorber different directions for tubes inside the parabolic ST. To discretize the equations, they used the SIMPLE algorithm. Thermal performance in the parabolic ST is maximized when absorber tubes with a 3-degree inclination angle are used.

Dezfulizadeh et al. [20] evaluated the effect of a combined turbulator on the exergy efficiency of triple hybrid nanofluid (HNF) in a HT under the influence of a magnetism. Study findings was done for 5000 < Re < 20,000 and 1% < φ < 3%. The results showed that adding a hybrid turbulator enhances the exergy efficiency at high values of Re.

Ebrahimpour and Sheikholeslami [21] The single-phase method and FVM for modeling were used to examine the effect of different angles of an ST mirror filled with nanofluid. The results demonstrated that enhancing the angle of the ST mirror and increasing the Re improve ST's thermal performance. Furthermore, the maximum enhancement should be achieved in the ST was 69.46% by adjusting the mirror angle.

Akbarzadeh [22] Efficacy and energy efficiency of ST can be quantified numerically by evaluating the effects of helical turbulators. Its study was based on the FVM. Studying the energy and energy efficiency of STs in different pitches of the helical turbulator was the main objective. In comparison to the simple ST, the spiral turbulator significantly increases the energy and efficiency. Moreover, the PR in ST reduced exergy efficiency.

In accordance with the studies that have been conducted so far,

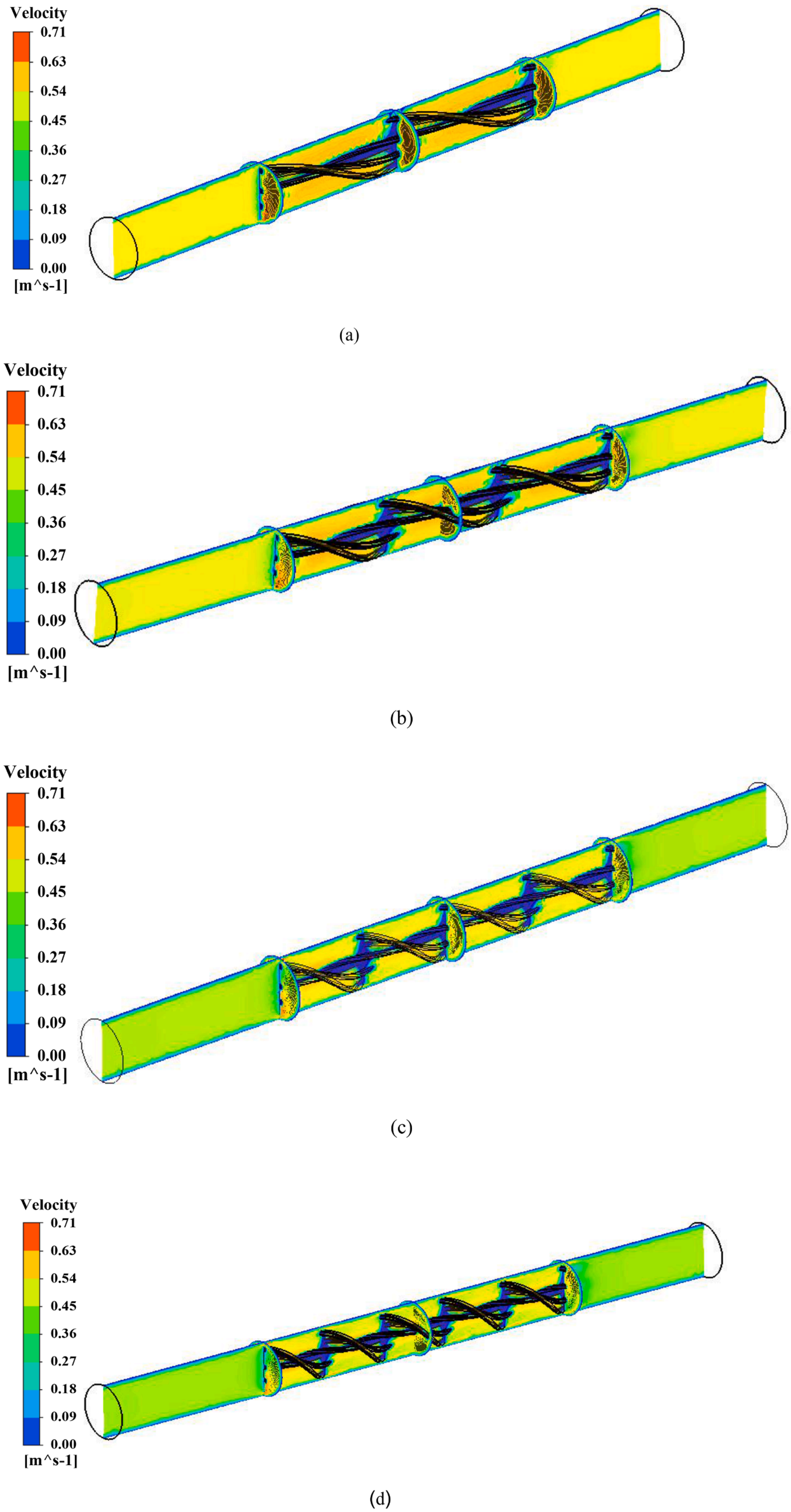


Fig. 5. Velocity contours for TP Cu-ZnO/water HNF inside the HT at $\varphi = 5\%$ fraction and Re = 40,000 for different PRs.

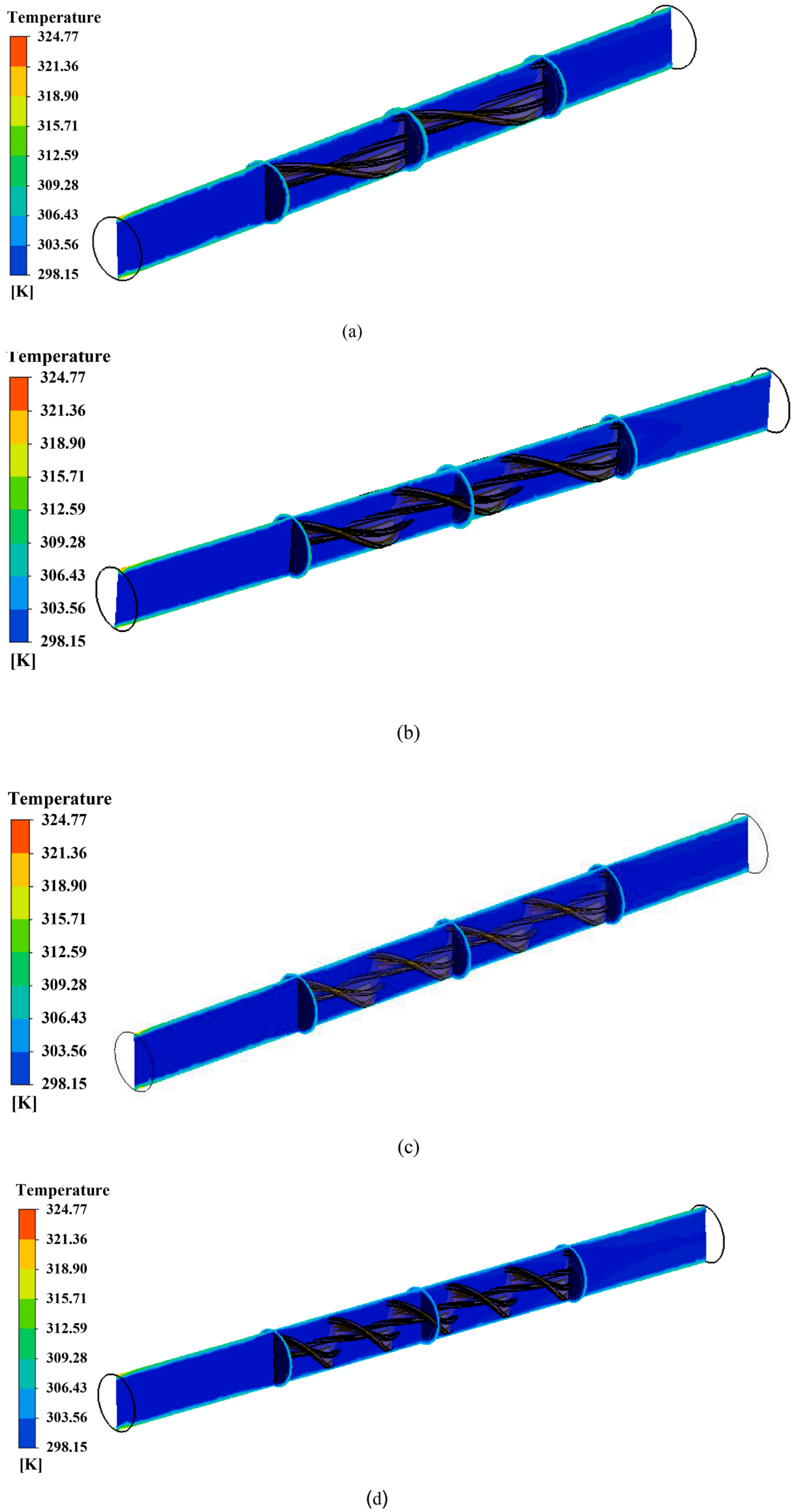


Fig. 6. Temperature contours for TP Cu-ZnO/water HNF at φ = 5% fraction and Re = 40,000 for different PRs.

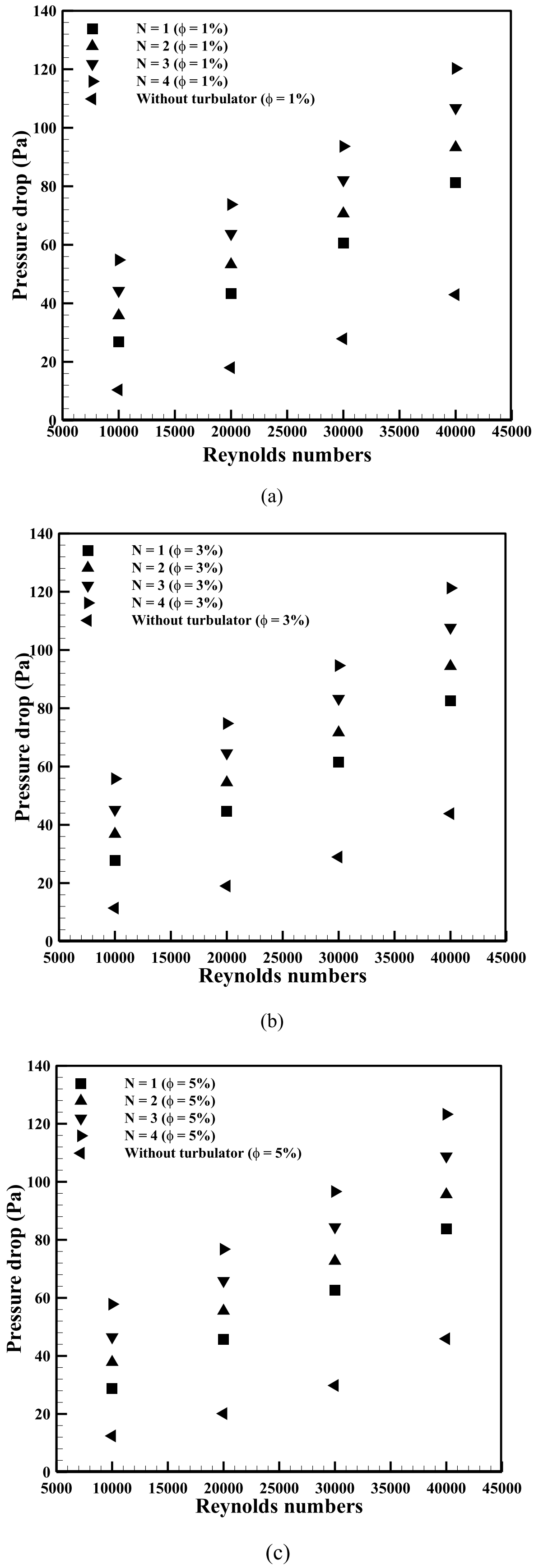


Fig. 7. Changes in ΔP in terms of Re in a HT equipped with a TT with different PRs for different φ.

Performance and efficiency of thermohydraulic systems of two-phase (TP) Cu-ZnO/water HNF in a HT equipped with an edged TT have not been studied. Therefore, in this study, the flow of TP Cu-ZnO/water HNF with $1\% < \varphi < 5\%$, $10{,}000 < Re < 40{,}000$, and PR = 1, 2, 3, and 4 was examined for Flow regimes that are turbulent.

2. Modeling and equations governing the geometry

Fig. 1 shows a schematic diagram of the HT studied with TT. Geometry studied by an HT is one of its outputs. Outlet tube length is 800 mm, curved tape length is 400 mm. A diameter of 800 mm is used for the outlet tube, 400 mm for the curved tape, and 200 mm for the TT at the inlet and outlet. In this study, the aim is to improve the heat transfer rate in a heat exchanger that is widely used in industries, by using turbulator and magnetic field. This heat exchanger can be used in various industries such as metal smelting, food related industries, and the production of water pipes.

Table 1 presents the characteristics of the geometry of the HT with TT.

In Table 2, the thermophysical properties of the base fluid (water) and NPs are presented for TP Cu-ZnO/water HNF.

The TP mixture model is used to Analyze numerically the TP Cu-ZnO/water HNF inside the HT. The governing equations of the problem are as follows.

The equations of continuity, momentum, and energy can be written as [25–27]:

$$\nabla\left(\rho_m \vec{U}_m\right) = 0 \tag{1}$$

$$\rho_m\left(\vec{U}_m \nabla \vec{U}_m\right) = -\nabla\vec{P} + \mu_m\left(\nabla\vec{U}_m + \left(\nabla\vec{U}_m\right)^T\right) + \nabla\left(\rho_{bf}\phi_{bf}\vec{U}_{dr,bf}\vec{U}_{dr,bf} + \rho_s\phi_s\vec{U}_{dr,s}\vec{U}_{dr,s}\right) + \rho_m\vec{g} + F_B \tag{2}$$

F_B is the Lorentz force is caused by the application of a magnetic field. According to Mustafa et al. [26], the energy equation can be written as follows;

$$\nabla\left(\rho_{bf}\phi_{bf}\vec{U}_{bf}h_{bf} + \rho_s\phi_s\vec{U}_s h_s\right) = \nabla\left(\left(\phi_{bf}k_{bf} + \phi_s k_s\right)\nabla\vec{T}\right) \tag{3}$$

where $\vec{U}_m$ is the mean velocity of NPs and base fluid:

$$\vec{U}_m = \frac{\rho_s\phi_s\vec{U}_s + \rho_{bf}\phi_{bf}\vec{U}_{bf}}{\rho_m} \tag{4}$$

where ρ_m is calculated as follows.:

$$\rho_m = \rho_s\phi_s + \rho_{bf}\phi_{bf} \tag{5}$$

The following relations are used to calculate the velocity, Nu_{av}, performance evaluation criteria (PEC) and exergy efficiency, respectively:

$$Re = \frac{\vec{U}_m d_p \rho_m}{\mu_m} \tag{6}$$

$$Nu = \frac{h_f \cdot D_i}{k_f} \tag{7}$$

$$PEC = \left(\frac{Nu_{av,nf}}{Nu_{av,f}}\right)\cdot\left(\frac{\Delta P_{nf}}{\Delta P_f}\right)^{-1/3} \tag{8}$$

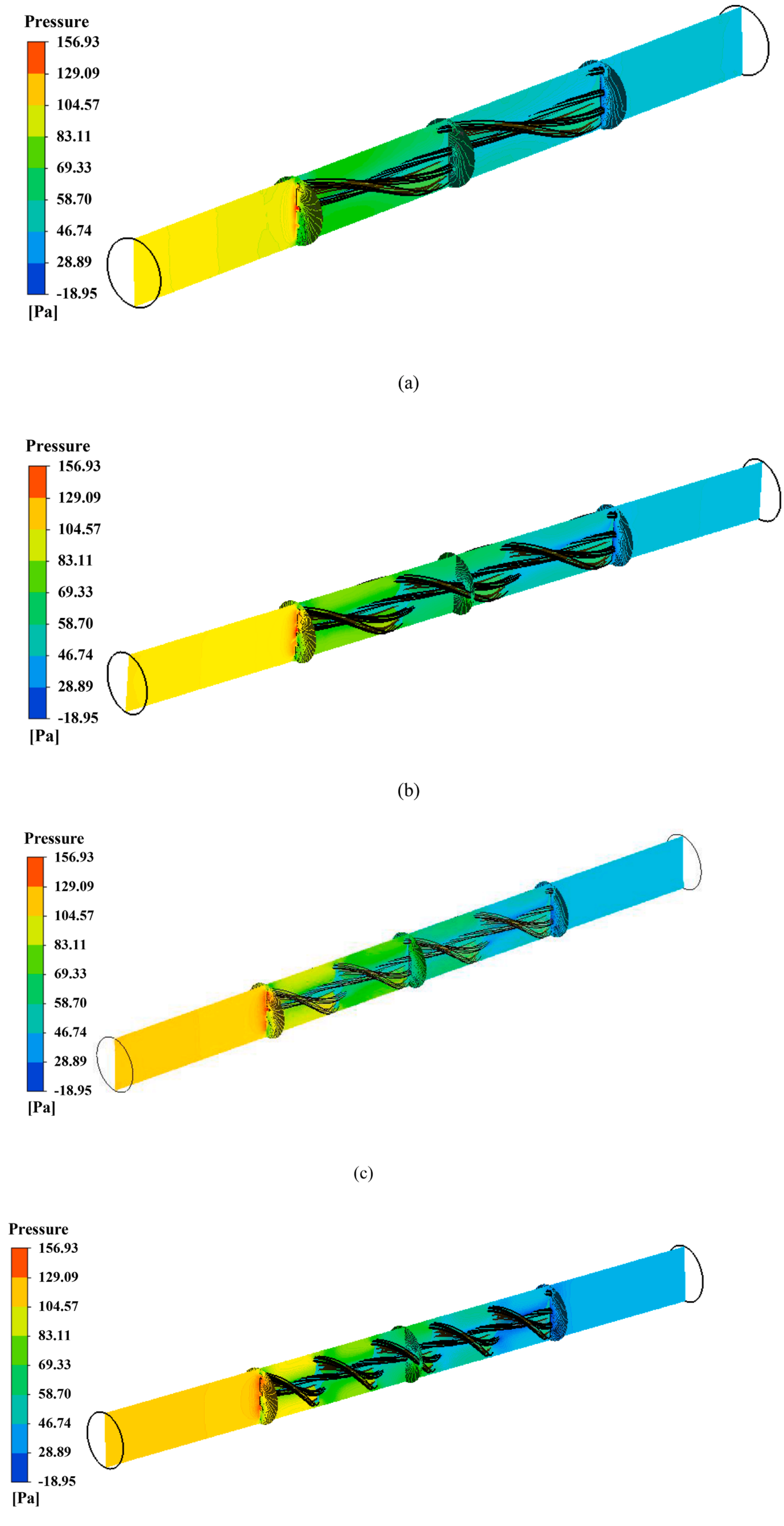


Fig. 8. Contours of pressure for TP Cu-ZnO/water HNF at φ = 5% fraction and Re = 40,000 for different PR.

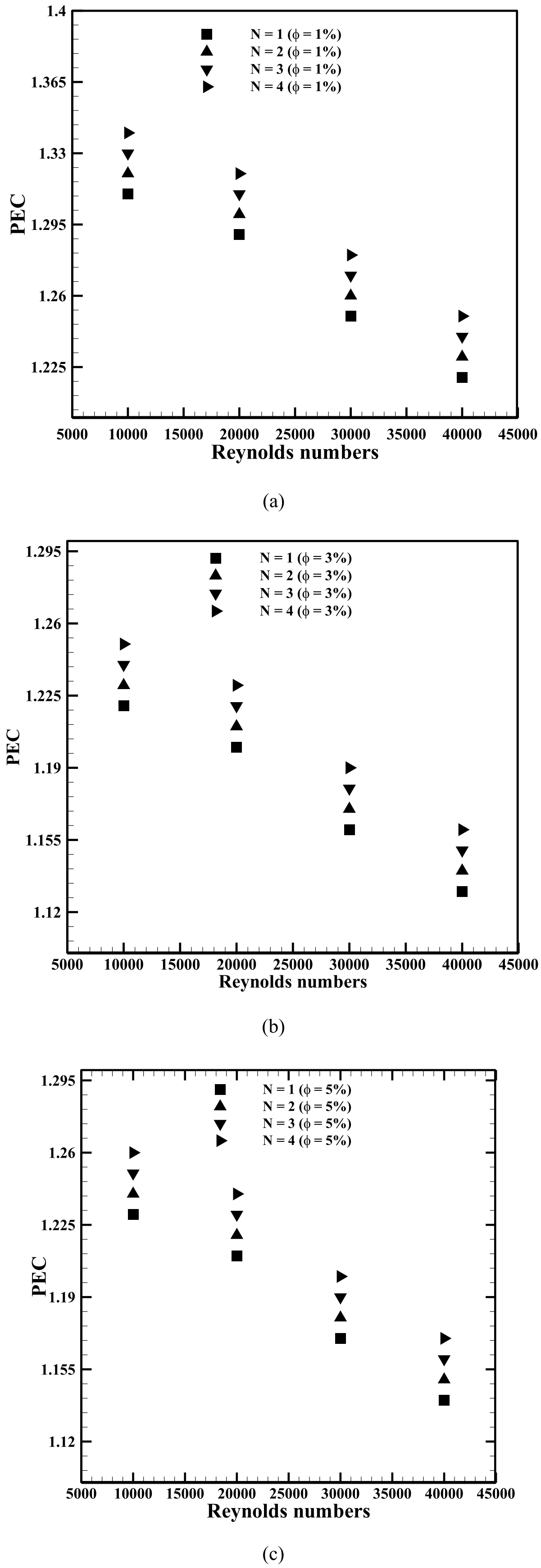


Fig. 9. Variations of PEC relative to in a HT a TT with different PRs is equipped for different φ.

$$\eta_{ex} = \frac{\dot{Q}_{HTF} - \dot{m}_{HTF} c_{p,HTF} \ln\left(\frac{T_\infty}{T_{i,HTF}}\right)}{\dot{Q}_{HTF} - \dot{m}_{CF} c_{p,CF} \ln\left(\frac{T_{o,CF}}{T_{i,CF}}\right) + VI\eta_P} \tag{9}$$

Boundary conditions follow as:

$$\begin{aligned} &\text{Inletcondition, velocityinletfrom } \vec{U}_m = \frac{\mathrm{Re}\ \mu_m}{d_p \rho_m} \\ &\text{Inletcondition, pressureoutlet}(\mathrm{P} = \mathrm{P_{atm}}) \\ &\text{Temperatureforallthewalls, } \mathrm{T} = 350\ \mathrm{K} \end{aligned} \tag{10}$$

3. Numerical modeling

In the present study, Solidwork software is used to sketch the geometry of the HT and FVM is utilized for computational analysis. The study is carried out by assuming the steady state flow using the pressure-based solver. The TP Cu-ZnO/water HNF flow is Utilizing a simulation the mixture model. This model is based on a of realizable turbulence theorem which is used to model turbulent flow. The Re changes from 10,000 to 40,000, φ varies from 1 to 5%, and PR = 1, 2, 3, and 4. Additionally, pressure is discretized using the standard model, and momentum, kinetic energy, and turbulent kinetic energy are discretized using the power law model.

4. Grid independence test

In order to achieve independent results, a suitable grid must be found, the average Nu_{av} is obtained for the TP Cu-ZnO/water HNF inside the HT with a TT with a PR of 4 at Re = 40,000 for the grids with different nodes (Fig. 2). According to the figure, the grid with 1,378,749 nodes is suitable for the HT with a TT.

5. Verification

By utilizing the geometry and boundary conditions that have been described by Sheikholeslami et al. [28], the numerical results are validated. Comparing the convective HT coefficient with their data is shown in Fig. 3. In this numerical simulation, the difference between the convective HT coefficient values can be ignored (the maximum error is 3.08%) Comparatively Sheikholeslami et al. [28].

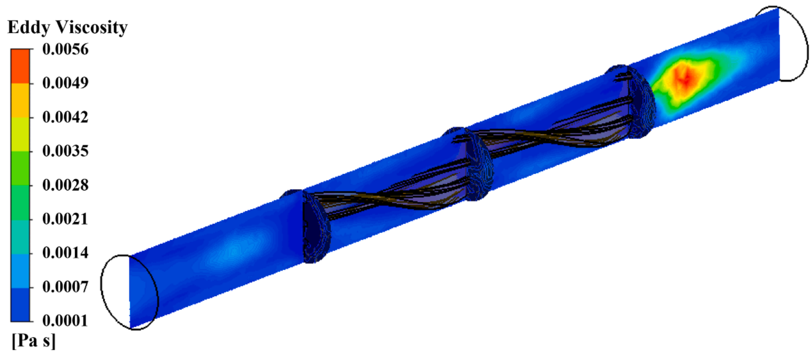
6. Results and discussion

In this section, numerical results are presented. A comparison of the effects of different factors PR of the TT inside the HT on Nu_{av}, ΔP, PEC, and Examines energy efficiency. Also presented are the contours of V, T, P, and EV inside the HT with TT with PR of 1, 2, 3, and 4.

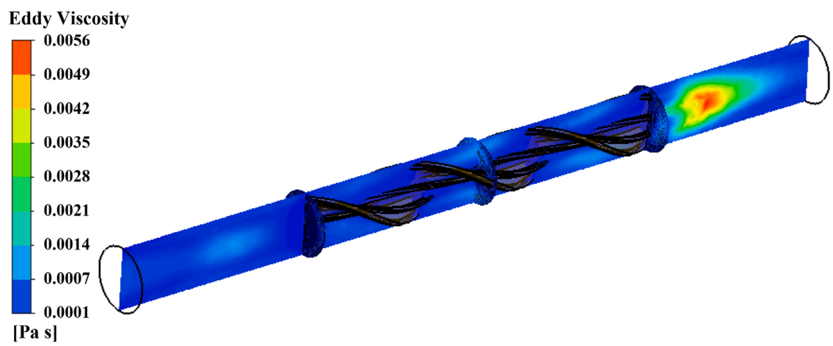
6.1. Effect of the PR of the TT on the average Nu_{av}

Fig. 4 Graphs the variations of Nuav in terms of Re in a HT with a TT with different PRs for (a) φ = 1%, (b) φ = 3%, and (c) φ = 5%. As can be seen, as Re is enhanced, Nu_{av} is increased. By increasing Re, the flow velocity is intensified and as a result, the convection HT coefficient is enhanced, leading to an increment in the Nu_{av}. At φ = 1% and Re = 40,000, placing a TT with a PR of 4 inside the HT enhances the Nu_{av} by 109.20% Comparatively the HT without a TT. At φ = 3% and Re = 40,000, placing a TT with a PR of 4 inside the HT enhances the Nu_{av} by 109.73% Comparatively the HT without a TT. At φ = 5% and Re = 40,000, placing a TT with a PR of 4 inside the HT enhances the Nu_{av} by 110.11% Comparatively the HT without a TT.

Velocity contours for TP Cu-ZnO/water HNF inside the HT at φ = 5% fraction and Re = 40,000 are shown in Fig. 5. Due to the no-slip boundary condition, the TP Cu-ZnO/water HNF is attached to the wall and has the same velocity as the wall. As a result, there is little velocity near the wall. In the tube's center, velocity reaches its maximum value.

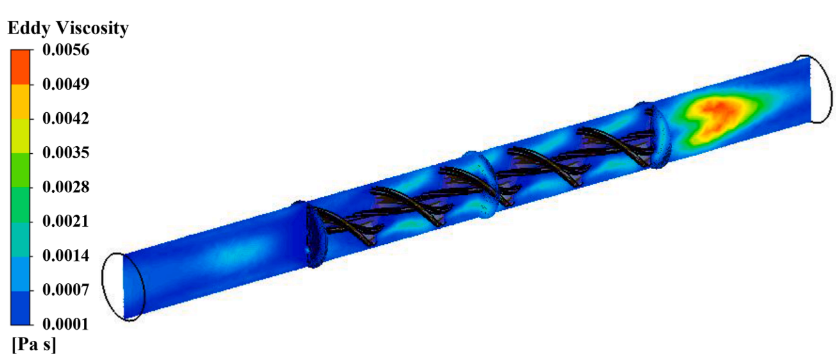


(a)



(b)

(c)



(d)

Fig. 10. Eddy viscosity contours for TP Cu-ZnO/water HNF at $\varphi = 5\%$ fraction and Re = = 40,000 for different PR.

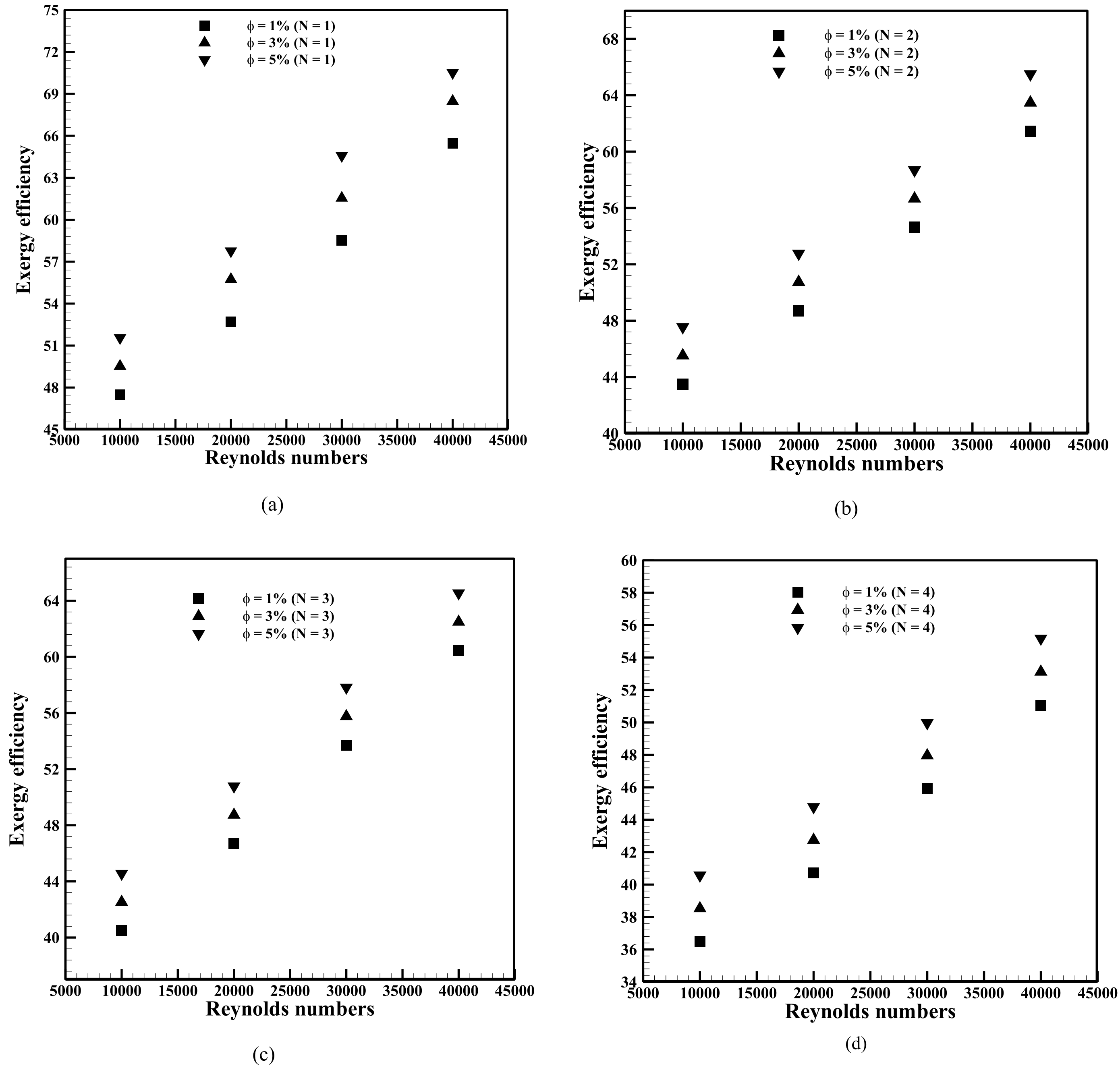


Fig. 11. Variations of exergy efficiency in terms of Re in a HT equipped with a TT with different values of φ and for different PR.

Fig. 6 This graph shows the contours of temperature for TP Cu-ZnO/water HNF at φ = 5% fraction and Re = 40,000 for different PRs.

6.2. Effect of the PR of the TT on the ΔP

Here Fig. 7 is an example of the changes in DP in a HT equipped with a TT with different PRs for (a) φ = 1%, (b) φ = 3%, and (c) φ = 5%. As can be seen, the ΔP has an upward trend in all cases by enhancing Re and PR. At φ = 1% and Re = 40,000, placing a TT with a PR of 4 inside the HT causes the ΔP to enhance by 179.93% Comparatively the HT Turbulator-less. At φ = 3% and Re = 40,000, placing a TT with a PR of 4 inside the HT causes the ΔP to enhance by 180.42% Comparatively the HT Turbulator-less. At φ = 5% and Re = 40,000, placing a TT with a PR of 4 inside the HT causes the ΔP to enhance by 180.97% Comparatively the HT without a turbulator.

Contours of pressure for TP Cu-ZnO/water HNF are shown in Fig. 8 at φ = 5% fraction and Re = 40,000 for different PR. This PR enhances the density of the streamlines in the HT, as can be seen.

6.3. Effect of the PR of the TT on PEC

Fig. 9 depicts the variations of PEC in terms of Re in a HT A TT with different features PRs for different φ. As can be seen, in all cases, the PEC is greater than 1. Thus, adding TT and increasing its PR is desirable from a PEC perspective.

Fig. 10 shows the eddy viscosity contours for TP Cu-ZnO/water HNF at φ = 5% fraction and Re = 40,000 for different PR. Clearly, the amount of vortices created increases with the increase of the PR in the curved rotating tape.

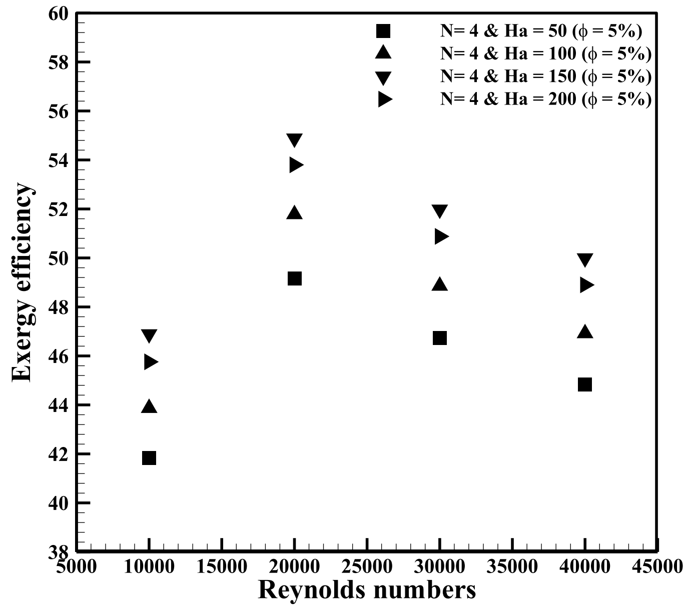


Fig. 12. Variations of exergy efficiency Re in HTs with rotating tapes with a PR = 4 and φ = 5% for different amounts of Ha.

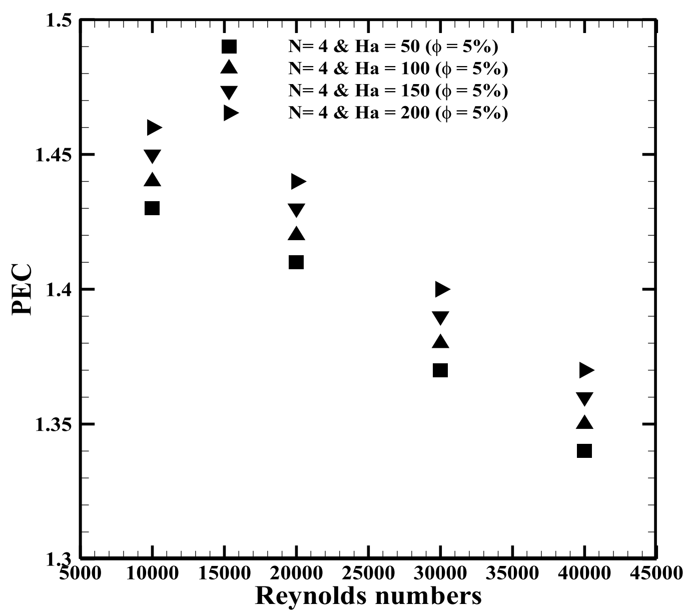


Fig. 13. Variations of the PEC in terms of Re in the HT equipped with a TT with a PR = 4 and φ = 5% for different amounts of Ha.

6.4. *Effect of the PR of the TT on exergy efficiency*

Fig. 11 This diagram illustrates how the energy efficiency of a HT equipped with a TT changes with different values of φ for different PR. There is an upward trend in the exergy efficiency with increasing Re and φ of NPs, and a downward trend with PR. A HT with a TT and a PR of 1 enhances exergy efficiency by 36.78% when φ = 5% and Re increases from 10,000 to 40,000. A HT with a TT and PR = 2 enhances exergy efficiency by 37.72% when φ = 5% and Re increases from 10,000 to 40,000. A HT with a TT and PR = 3 increases energy efficiency by 38.19% when φ = 5% and Re increases from 10,000 to 40,000. The exergy efficiency of HT in TT with PR = 4 is improved by 38.89% when φ = 5% and Re increases from 10,000 to 40,000.

6.5. *Effect of magnetic field on exergy efficiency of HT*

Fig. 12 demonstrates the changes of exergy efficiency of a HT with rotating tape in terms of Re with a PR of 4 and φ = % for different amounts of Ha. As can be seen, the exergy efficiency is enhanced as Ha is increased from 50 to 150. Also, by increasing the Re up to 20,000, the exergy efficiency is enhanced and then reduced. It can be concluded that the use of a magnetic field leads to the maximum exergy efficiency at Re = 20,000 and Ha = 150.

6.6. *Effect of magnetic field on PEC*

Fig. 13 shows how the PEC varies with Re in HTs equipped with TTs with PR = 4 and φ = 5% for different amounts of Ha. As can be seen, PEC is enhanced by reducing Re and increasing Ha, while the PEC index is greater than 1 in all cases. Therefore, it can be concluded that the use of a magnetic field in a HT is desirable in terms of PEC.

7. Conclusions

In this study, the effect of using HNF and TT on the exergy efficiency and thermo-hydraulic performance of a HT is assessed numerically using FVM. The study is based on simulations a mixture model.

- The average Nu_{av} and PEC are enhanced by increasing the inlet velocity and volume concentration of NPs.
- The amount of PEC is greater than 1 in all cases. Therefore, it can be concluded that the use of TT and HNF in the HT is desirable.
- By placing a TT with PR = 4 inside the HT, the Nuav increases by 110.11% compared to the HT without a twisted tape.
- Adding a helical twisted tape at Re = 40,000 increases the ΔP by 180.97% compared to the STe without one.
- A HT with a twisted tape with a PR = 4 improves the efficiency of exergy by 38.89% when φ = 5% and Re increases from 10,000 to 40,000.
- The maximum exergy efficiency occurs at Re = 20,000 and Ha = 150 when a magnetic field is applied.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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