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Numerical Simulation of Geothermal Heat Exchanger Equipped with Turbulator Containing a Two-phased Hybrid Nanofluid

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Abstract: This study simulated a geothermal heat exchanger numerically using computational fluid dynamics (CFD). The geothermal heat exchanger is equipped with a turbulator and a simultaneous combination of a turbulator and a vortex generator filled with a two-phased MWCNT-Cu/water hybrid nanofluid. Geothermal heat exchanger geometry is analyzed 3D using Ansys Fluent version 2022 software. In order to model viscosity and two-phased flow, K-Epsilon Realizable turbulence model and mixture model are used respectively. This climate study was carried out assuming a warm semi-arid climate for Isfahan province at a depth of 1 m from the ground. The results obtained from this study showed that by increasing the input speed in the geothermal heat exchanger and the volume fraction of nanoparticles, the thermal performance and pressure drop increased in all stages of the numerical simulation. Also, the maximum thermal performance of the geothermal exchanger, when using the combination of turbulator and vortex generator,was 4% volume fraction and Re = 32000. In addition, the thermal-hydraulic evaluation index was greater than 1 in all cases. Therefore, using a turbulator, a vortex generator, and a combination of a vortex generator and a turbulator simultaneously in a geothermal converter is desirable in terms of the PEC index. In addition, increasing the Reynolds number at the entrance of the geothermal heat exchanger increases the exergy efficiency.

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1. Introduction

Recent estimates by the International Energy Organization have shown that global energy demand will increase by 35% between 2008 and 2035. Considering the limited reserves of fossil energy and the harmful effects of their use on the environmental cycle, it seems necessary to explore renewable energy to deal with this growing demand. According to the International Energy Agency forecasts, more than 13% of the growth of the mentioned energy demand will be provided by renewable energies. Geothermal energy is one of the most available God-given energy sources [1].

Geothermal energy is the thermal energy that exists in the earth's solid crust. This type of energy is often used to produce geothermal electricity, which refers to the cycle of producing electrical energy from geothermal energy. Geothermal energy, unlike other renewable energies, is not limited to seasons, time, and conditions and can be exploited without interruption. Also, the cost of electricity in geothermal power plants is competitive with electricity produced by other conventional (fossil) power plants and is even cheaper than other types of new energy. Also, another important application of geothermal energy is its use in domestic and industrial cooling and heating systems. In other words, the ground is always a suitable source for cooling or heating fluid flows [2].

Zheng et al. [3], using the finite element method, numerically simulated needle turbulators in the turbulent flow regime inside a heat exchanger. In their study, to design the heat exchanger's geometry, they used Solid Works software and Fluent version 15 software for fluid analysis. Their study was done in the turbulent flow regime in the Reynolds number range of 5000 to 25000 while using the K-Epsilon turbulence model. The output results reported by the authors showed that an increase in the number of needle turbulators increased the pressure drop as a negative factor. However, it increased the heat transfer significantly.

Bisoniya et al. [4] Numerical and experimental studies conducted in earth-air heat exchangers (EAHE) were reviewed. According to this study, the main reason for using these converters was the stability of the ground temperature at a depth of 1.5 to 2 m, which did not change much throughout the year. The temperature in the winter season is higher than the earth's surface temperature and vice versa in the summer. EAHE systems are a passive but effective method for cooling and heating buildings.

Rodrigues et al. [5] numerically studied the potential thermal improvement of an EAHE system. They used the available experimental data for a sample city and presented the work results to the distribution of the months of the year. Their proposed method to improve the system's efficiency was to use a multi-pipe system instead of conventional systems. Based on their results, this proposed method could increase the system's efficiency to 73% in summer and 115% in the winter.

Maakoul et al. [6] investigated the effect of using an inner tube with an outer fin in a double-tube heat exchanger using computational fluid dynamics. Their study was based on the limited volume method and the Simple C algorithm. Their output results were reported in the form of velocity, pressure, and temperature contours as well as the graphs of average Nusselt number, pressure drop, and friction coefficient. According to their results, the presence of rotating flow was evident due to the use of external vanes in the speed contour. Therefore, the heat transfer coefficient always increased by adding a blade and increasing the number of its blades.

Chieh Huang et al. [7], through using the laboratory method, investigated the effect of vortex plate generators on fluid flow behavior and displacement heat transfer inside a heat exchanger in the turbulent flow regime. Their study was done in the turbulent flow regime and at Reynolds numbers from 7000 to 34000. Their study showed that vortex ring generators changed the shape of flow lines and increased the number of vortices. Therefore, this factor increased heat transfer. According to the researchers' reports, the maximum heat transfer increased by 56.11% when using vortex ring generators.

Xie et al. [8], by using computational fluid dynamics and Fluent software, simulated rectangular teeth on the channel wall to investigate their effects on fluid flow and heat transfer. Their study was done for different heights of rectangular teeth in the turbulent flow regime. According to their results, after the liquid had collided with the rectangular teeth, the phenomenon of separation occurred, and as the height of the teeth increased, the size of the vortices increased.

Aghaei et al. [9], using the numerical method, they investigated the effect of vortex generators on the thermal efficiency inside a heat exchanger. Their study was done using the limited volume method and Fluent software. This study investigated the behavior and flow of a water-copper nanofluid in the Reynolds number range of 10,000 to 30,000 in the turbulent flow regime. The results obtained from their study showed that the maximum thermal performance of the chamber increased by 42.67% when using triangular vortex generators in the presence of nanofluid.

Saysroy and Eiamsa-ard [10] studied the numerical simulation of the effect of using spiral tape in a duct. The primary purpose of their study was to compare plain spiral tape with perforated spiral tape. This study used Ansys Machining software to discretize the computational area. Also, their numerical simulation was done using Fluent software. They used the Simple C algorithm to couple speed and pressure equations. According to their results, the simple spiral turbulatorhada far better thermal performance in the whole numerical simulation than the hollow spiral strip.

Amanowicz and Wojtkowiak [11] developed a numerical model based on Computational Fluid Dynamics (CFD) to simulate an EAHE system. They also used a multi-tube system in their studies. According to their results, the flow inside the pipes was turbulent, and the presented numerical model was of an excellent ability to simulate the system's performance with relatively high accuracy.

Zhou et al. [12] They investigated experimentally and numerically the effect of using phase change materials (PCM) in EAHE systems to improve the cooling performance. They conducted all their experiments in China. Based on their results, the numerical model has good validity for simulation. They also found that using PCM materials can reduce the temperature of the cooling system to about 0.83 degrees Celsius, equivalent to a 24.20% increase in the cooling capacity of the system.

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Hosseini et al. [13] experimentally and numerically, investigated the effects of adding vortex generators in the channel on thermal performance. In the experimental part, they built the geometry of the channel along with vortex generators and performed experiments for different modes. Then, using the finite volume method and Fluent software, they simulated the geometry of the case and compared the obtained results with the experimental part. According to the results reported by the researchers, the experimental and numerical results matched each other with high precision. Also, the researchers reported the maximum heat transfer when using vortex generators as 56.01%.

Li et al. [14] investigated the performance of an EAHE system in order to provide warm air to the building in cold regions. One of his ideas was to use a preheating system in the device. They also used a multi-tube system. According to their results, the proposed system had a heating capacity of 4665 watts and power consumption of 130 watts, showing high efficiency. Based on the results, their proposed system's average heating performance coefficient was 29.7.

Dezfulizadeh et al. [15] studied the double-tubed heat exchanger equipped with a turbulator. This study calculated exergy efficiency, the Nusselt number, and friction coefficient in a double-tubed heat exchanger. Also, the nanofluid they studied was a hybrid nanofluid. The flow regime in the study was turbulent, considered in the range of 5000 to 20000. Their results showed that using a turbulator at high Reynolds numbers reduced exergy efficiency and increased the average Nusselt number.

Abdollahi and Shams [16] numerically simulated the rectangular channel equipped with vortex blade generators. The primary purpose of their study was to investigate the effects of vortex generator blades of different lengths and heights on the flow field and heat transfer inside a rectangular channel. Their study was done in the turbulent flow regime and the Reynolds range of 6000 to 24000. They used the K-epsilon turbulence model to model the turbulent flow. Their output results showed that the maximum thermal efficiency at Reynolds number 24000 was 47.13%.

Hong et al. [17] used the experimental method to investigate the effect of the simultaneous use of several twisted strips on thermal hydraulic performance inside a duct. Their study wascarried out in the turbulent flow regime and at Reynolds numbers of 4000 to 17000. Also, their output results were presented as displacement heat transfer coefficient, the average Nusselt number, the pressure drop, and the thermal-hydraulic performance coefficient. The results obtained from their study showed that the use of three twisted strips had the highest thermal performance and the pressure drop inside the duct.

Li et al. [18] investigated the performance of an EAHE system equipped with an irrigation system to regulate soil moisture. This research used a multi-tube system equipped with a preheating system. The results showed that the average heating performance coefficient (COP) of his proposed system was 29.2.

Yang et al. [19] investigated the effect of using PCM materials in EAHE systems experimentally. Their proposed system was a single pipe designed as a flat cylinder. According to their results, using this proposed system could reduce the temperature in the hot season by about 4.5 degrees Celsius.

Aghaei et al. [20], numerically and by using computational fluid dynamics, simulated the effect of using a turbulator and a vortex generator simultaneously. Their study aimed to improve the thermal efficiency using a turbulator and a vortex generator. Their study was done at Reynolds numbers of 10,000 to 100,000 in the turbulent flow regime. The results obtained from their study showed that as the Reynolds number increased, the average Nusselt number and pressure drop increased.

Song et al. [21] simulated grooved pipes in the turbulent flow regime using a numerical method and computational fluid dynamics. The study's primary purpose was to compare grooved and plain pipes. They used a simple algorithm to discretize the governing equations. They also used a second-ordered upwind method for spatial discretization. According to the results presented by the authors, the grooved pipes at the outlet had more improvement in thermal efficiency than the plain pipes. Also, the maximum transmission improvement by grooved pipes was 38.49%.

By examining various research from previous studies in geothermal heat exchangers, it can be seen that many studies have not been done in this field. The studies conducted on the thermal performance and geometric structure of geothermal heat exchangers show that the influencing parameters in the optimization of geothermal heat exchangers are: exergy efficiency, heat transfer coefficient of the working fluid, input heat flux, pipe heat conductivity coefficient, pipe diameter, and system length. Also, previous studies show that the type of pipe system and the working fluid significantly influence the thermal performance of geothermal heat exchangers. Therefore, to design and build a geothermal heat exchanger, all these items must be considered in the geometrical design. Meanwhile, turbulators and vortex

generators have not been given much attention. Therefore, in this study, the effect of using a turbulator and the combination of a vortex generator and a tabulator simultaneously in a geothermal heat exchanger, filled with MWCNT-Cu/water two-phased hybrid nanofluid, are investigated. The study assumes a turbulent flow regime in Reynolds numbers 8000 to 32000. Also, nanoparticles in volume fractions of 1 and 4% are modeled as two-phased in water base fluid.
In other words, the innovations of this study are:

- The numerical simulation of the geothermal heat exchanger, equipped with this model of the geometric shape of the turbulator has yet to receive the attention of researchers.
- The effect of the simultaneous use of turbulator and vortex generators in geothermal heat exchangers has not been investigated by any researcher.
- Most studies conducted in heat exchangers have been conducted using water fluid. The use of hybrid nanofluids has received less attention.
- So far, the hydraulic-thermal effect of MWCNT-Cu/water nanofluid has not been investigated considering the two-phased model in the geothermal heat exchanger.
- Any researcher has yet to investigate the simultaneous investigation of hydraulic-thermal and exergy analyses in a heat exchanger equipped with a combination of turbulator and vortex generator.

2. Geometric Model and Governing Equations

The studied geometry of the geothermal heat exchanger is shown schematically in Figure 1. As it can be seen, the two-phase MWCNT-Cu/water hybrid nanofluid enters the geothermal heat exchanger with a temperature of 16°C. The geothermal heat exchanger is located at a depth of 1 m from the ground. The length of the pipe investigated in this study is 20 m. Also, the simulation has been done at a depth of 1 m from the ground for Isfahan province, which is part of the warm semi-arid climate. The temperature for the depth of 1 m of the ground is considered 21.09°C [22]. The material of the pipe is PVC. The geothermal heat exchanger is investigated in two models equipped with a turbulator and a simultaneous combination of a turbulator and a vortex generator. The results obtained from these modes are compared with the time when the geothermal heat exchanger was simple and without a turbulator and a vortex generator. The schematic of the geometry of the turbulator and the simultaneous combination of the turbulator and the vortex generator are shown in Figure 2 and Figure 3, respectively.

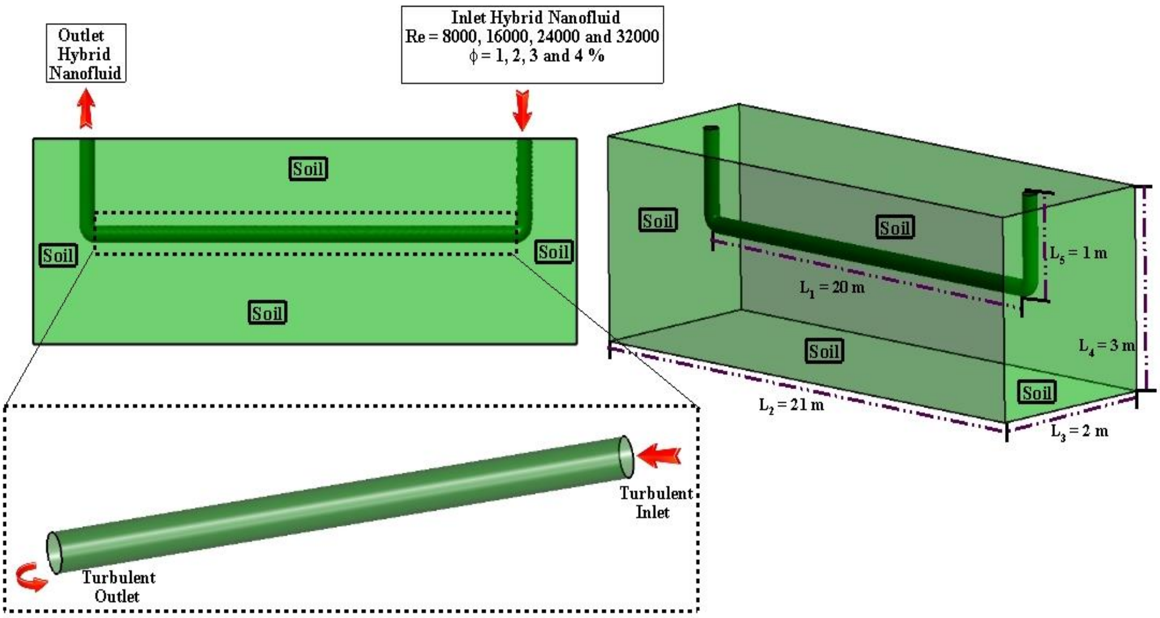


Fig. 1: Geothermal heat exchanger geometry schematic

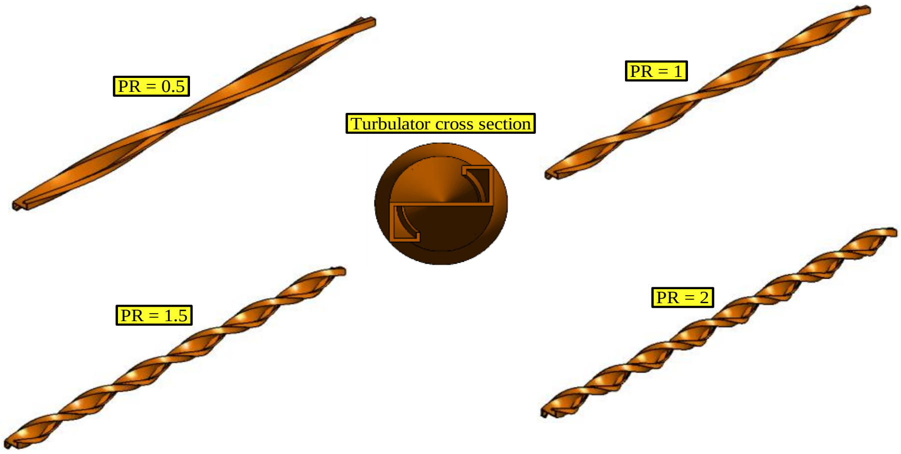


Fig. 2: Schematic of turbulator geometry with different pitch ratios

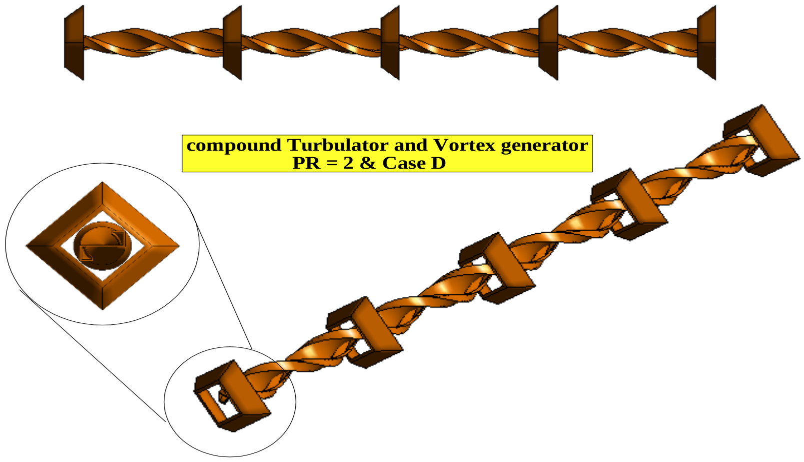


Fig. 3: Schematic of turbulator and vortex generator combination

In this study, MWCNT-Cu/water two-phased hybrid nanofluid has been used as the working fluid in the geothermal heat exchanger. The thermophysical properties of the materials used in this study are presented in Table 1. In addition, this study was carried out assuming a warm semi-arid climate for Isfahan province. Geographical characteristics and annual climatic averages of the studied station are reported in Table 2. In this table, T is air temperature; Rs is solar radiation; R is rainfall; RH is relative humidity; P is air pressure; e_a is air vapor pressure, and U_{10} is the wind speed at 10 m.

Table 1: Thermophysical properties of materials [23, 24]

Properties	Water	Cu	MWCNT	Soil	PVC
$\rho\left(kg.m^{-3}\right)$	998/2	8954	2100	2050	1380
$c_P\left(J.kg^{-1}.K^{-1}\right)$	4182	383	519	1840	900
$k\left(W.m^{-1}.K^{-1}\right)$	0.6	400	3000	0.52	0.16
$\mu\left(kg.m^{-1}.s^{-1}\right)$	0.001003	-	-	-	-

Table 2: Geographical characteristics and annual climatic averages of Isfahan province [22]

Position	U_{10} (m. s^{-1})	e_a (kpa)	P (kpa)	RH (%)	R (mm $year^{-1}$)	R_s (Mjm^{-2})	T (°C)	Height above sea level (m)	Latitude (N)	Longitude (E)	Climate type
Isfahan province	1.56	0.6	84.4	36	122.8	16.80	16.8	1550	32-37	40-51	Warm semi-dry

This study uses a mixed two-phased model to model the flow of two-phased MWCNT-Cu/water hybrid nanofluid in a geothermal heat exchanger. The mixed two-phased method consists of two primary and secondary phases. The primary phase is usually the same as the base fluid, and the second phase includes nanoparticles. In this study, two-phased hybrid nanofluid is MWCNT-Cu/water. Therefore, water should be modeled as the primary phase, and copper nanoparticles and carbon nanotubes as the second phase in the settings section of the base fluid. In addition, each of these phases can have specific boundary conditions. For example, each phase can have a different speed and volume fraction. Based on the results of the studies, a mixed two-phased model has very high accuracy. It should be noted that the continuity, momentum, and energy equations for MWCNT-Cu/water two-phased hybrid nanofluid are calculated separately for each primary and secondary phase. The governing equations of the problem are:
Continuity equation [25-27]:

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

The following equation is used to calculate the mass-average velocity relationship.

$$\vec{U}_m = \frac{\rho_s \phi_s \vec{U}_s + \rho_{bf} \phi_{bf} \vec{U}_{bf}}{\rho_m} \tag{2}$$

In the above equation, $\vec{U}_m$, $\vec{U}_s$, and $\vec{U}_{bf}$ are the mixture's average velocity, nanoparticle, and base fluid velocity, respectively. The mixture density relationship is as follows:

$$\rho_m = \rho_s \phi_s + \rho_{bf} \phi_{bf} \tag{3}$$

ρ_m is the density of the two-phase mixture. The momentum equation for the geothermal heat exchanger is written as follows

$$\rho_m\left(\vec{U}_m \nabla \vec{U}_m\right) = -\nabla \vec{P} + \mu_m\left(\nabla \vec{U}_m + \left(\nabla \vec{U}_m\right)^T\right) + \nabla\left(\rho_{bf} \phi_{bf} \vec{U}_{dr,bf} \vec{U}_{dr,bf} + \rho_s \phi_s \vec{U}_{dr,s} \vec{U}_{dr,s}\right) + \rho_m \vec{g} \tag{4}$$

Eqs.(5) and (6) are used to calculate the base fluid's velocity and nanoparticles' velocity, respectively [28].

$$\vec{U}_{dr,bf} = \vec{U}_{bf} - \vec{U}_m \tag{5}$$

$$\vec{U}_{dr,s} = \vec{U}_s - \vec{U}_m \tag{6}$$

μ_m is the mixture's viscosity, and $\vec{U}_{dr,bf}$ and $\vec{U}_{dr,s}$ are the sliding and relative velocities, respectively. The energy equation for the geothermal heat exchanger is rewritten below:

$$\nabla\left(\rho_{bf} \phi_{bf} \vec{U}_{bf} h_{bf} + \rho_s \phi_s \vec{U}_s h_s\right) = \nabla\left(\left(\phi_{bf} k_{bf} + \phi_s k_s\right) \nabla \vec{T}\right) \tag{7}$$

h_{bf} and h_s are the enthalpy of base fluid (water) and enthalpy of nanoparticles (copper and multi-walled carbon nanotube), respectively. The volume fraction of the two-phase mixture and the sliding speed is calculated using Eqs.(8) and (9), respectively [29].

$$\nabla\left(\rho_s \phi_s \vec{U}_m\right) = -\nabla\left(\rho_s \phi_s \vec{U}_{dr,s}\right) \tag{8}$$

$$\vec{U}_{bf,s} = \vec{U}_{bf} - \vec{U}_s \tag{9}$$

As mentioned before, in this study, the K-epsilon turbulence model was used to model the turbulent flow. The equations of this model are [30, 31]:

$$\nabla\left(\rho_m \vec{U}_m k\right) = \nabla\left[\left(\mu_m + \frac{\mu_{t,m}}{\sigma_k}\right) \nabla k\right] + G_{k,m} - \rho_m \varepsilon \tag{10}$$

$$\nabla\left(\rho_m \vec{U}_m \varepsilon\right) = \nabla\left[\left(\mu_m + \frac{\mu_{t,m}}{\sigma_\varepsilon}\right) \nabla \varepsilon\right] + \frac{\varepsilon}{k}\left(c_1 G_{k,m} - c_2 \rho_m \varepsilon\right) \tag{11}$$

Turbulence viscosity and production rate can be calculated from Eqs.(12) and (13) [31]:

$$\mu_{t,m} = C_\mu \rho_m \frac{k^2}{\varepsilon} \tag{12}$$

$$G_{k,m} = \mu_{t,m}\left(\nabla \vec{U}_m + \left(\nabla \vec{U}_m\right)^T\right) \tag{13}$$

The inlet velocity in the geothermal heat exchanger is calculated from the following equation [28].

$$\mathrm{Re} = \frac{\rho_{bf} \cdot u_m \cdot d_a}{\mu_{bf}} \tag{14}$$

$\vec{U}_m$, d_p, ρ_m, andμ_m are the nanoparticles' average velocity, diameter, density, and viscosity, respectively. The average Nusselt number can be calculated using the following equation [29, 30]:

$$\mathrm{Nu} = \frac{h_{bf} \cdot d_a}{k_{bf}} \tag{15}$$

Eq.(16) calculates the pressure drop in the geothermal heat exchanger [29, 30].

$$P = P_{av,inlet} - P_{av,outlet} \tag{16}$$

Thermal–hydraulic performance evaluation criteria and exergy efficiency are calculated from Eqs.(17) and (18) [24].

$$PEC = \left(\frac{Nu_{TT\ and\ WG}}{Nu_S}\right) \cdot \left(\frac{\Delta P_{TT\ and\ WG}}{\Delta P_S}\right)^{-1/3} \tag{17}$$

$$\eta_{ex} = \frac{\dot{Q}_{HTF} - \dot{m}_{HTF} c_{p,HTF} \ln\left(\frac{T_\infty}{T_{i,HTF}}\right)}{\dot{Q}_{HTF} - \dot{m}_{CF} c_{p,CF} \ln\left(\frac{T_{o,CF}}{T_{i,CF}}\right) + VI\eta_P} \tag{18}$$

3. Numerical modeling

In this study, a geothermal heat exchanger equipped with a turbulator and the simultaneous combination of a turbulator and a vortex generator filled with a hybrid nanofluid and a two-phased MWCNT-Cu/water hybrid nanofluid have been numerically simulated using computational fluid dynamics. The geothermal heat exchanger's geometry is analyzed 3D using Ansys Fluent version 2022 software. The study is carried out under the assumption of constant, stable, and turbulent flow. In order to model the viscosity, K-Epsilon Realizable turbulence model is used. Also, considering two-phased flow, a mixed model is used for numerical simulation. In order to couple speed and pressure, a simple algorithm is used to spatially discretize the gradients from the Least Squares Cell Based model. Also, the PRESTO model is used to discretize the pressure, and the First-Order Upwind model is used for the equations of momentum, volume fraction, and turbulent kinetic energy. The geothermal heat exchanger at a depth of 1 m from the ground in two models equipped with a turbulator and a combination of a vortex generator and a turbulator is investigated simultaneously. In addition, the results obtained from the average Nusselt number, pressure drop, thermal-hydraulic index, and exergy efficiency for these three cases are compared with the case where the geothermal heat exchanger is simple and without a vortex generator turbulator. According to the investigations conducted by Al-Ajami et al. [30] and the results obtained from their study, the thermal effect of the soil around the pipe after the distance between the briar and the outer radius of the pipe is insignificant. Therefore, the temperature of the tube can be considered constant. This study was carried out assuming a warm semi-arid climate for Isfahan province. Geographical characteristics and annual climatic averages of the studied station are reported in Table 2. In this study, the soil temperature at a depth of 1 m for Isfahan province is considered 21.09°C [22]. This is considered a constant temperature as an initial condition for the entire computational domain in the pipe wall. Also, the thermophysical properties of soil and other materials are reported in Table 1. The material of the pipe is PVC. The study is carried out for volume fraction of 1 to 4% of nanoparticles, pitch ratio of 0.5, 1, 1.5, and 2 of turbulator, and simultaneous combination of turbulator and vortex generator (PR = 2 & Case D) in the Reynolds range of 8000 to 32000.

The mixture model in Anasys Fluent is designed for two or more phases. In a mixture model like the Eulerian model, phases can be intertwined. In the mixture model, the momentum equation is solved for both phases, and relative velocities are used to describe the behavior of the second phase. Among the applications of the mixture model, we can mention the simulation of flow-carrying particles with a low charge, bubbly flows, evaporation in Ensys fluent, and simulation of cavitation. When a nanofluid is used, there are liquid and solid phases. When the two-phased mixture model is used, it is possible to select each of these phases separately and enter the properties of each phase separately into the Fluent software. This makes the physics of the problem closer to reality. Also, in terms of computational costs, using the two-phased mixture model is more appropriate than the other models.

4. Grid Configuration

In this study, to check the independence test from the results of the grid, the geometry of the geothermal heat exchanger, along with the combination of turbulator and vortex generator filled with MWCNT-Cu/water two-phased hybrid nanofluid in a volume fraction of 4% for the gird with a different number of points has been investigated. The average Nusselt number is reported for each. The results obtained from the grid independence test are schematically shown in Fig. 4.

As it can be seen, with an increase in the number of the grid elements, the average Nusselt number changes significantly. Although after several repetitions with increasing the number of the grid points, the average Nusselt number does not show significant changes. In this study, from the number of elements 2143157 onwards, the average Nusselt number changes are minimal. Therefore, the number of elements 2132044 is chosen as the optimal grid and is used in numerical simulation.

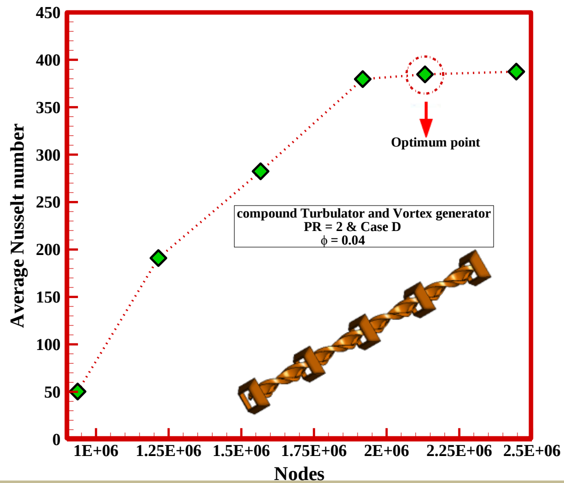


Fig. 4: Independence of grid results in the geothermal heat exchanger

The gridded geometry schematic of the geothermal heat exchanger, along with the combination of turbulator and vortex generator, is shown in Fig. 5. As it can be seen, the grid has been reduced to a very acceptable level to be more accurate in the numerical calculations. Also, in the areas close to the wall, the boundary layer mesh has been used for high accuracy in solving the equations.

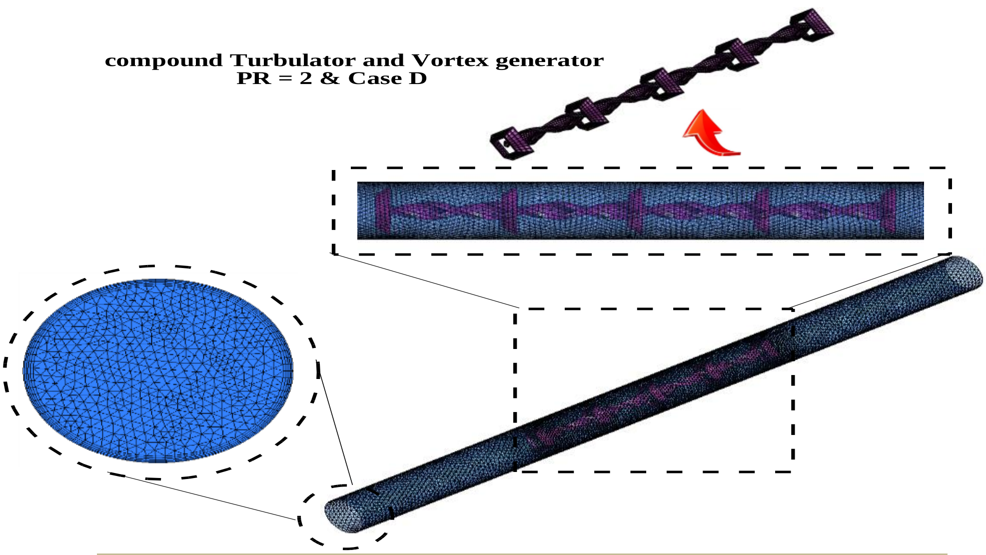
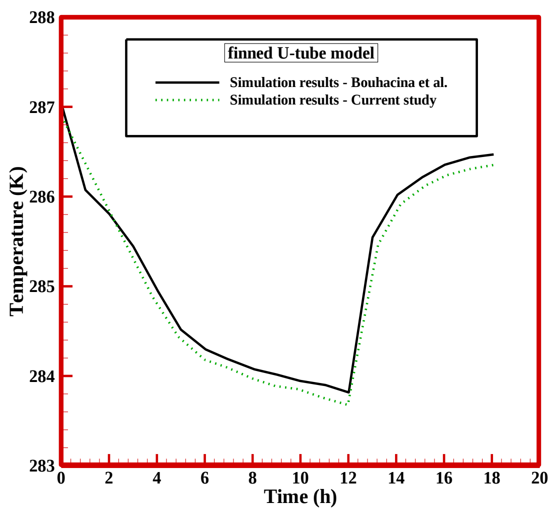


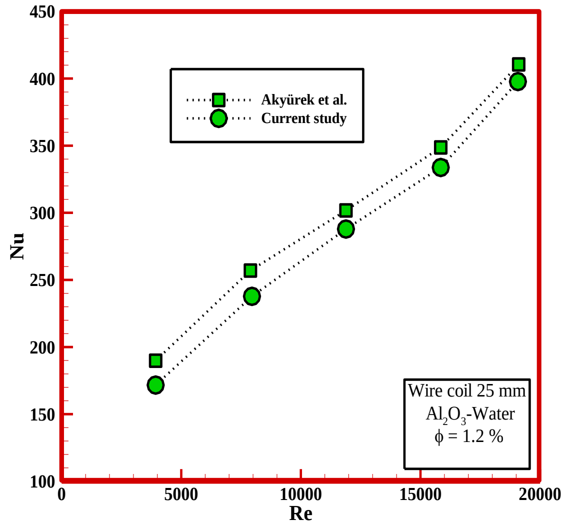
Fig. 5: Schematic of gridded geometry of the geothermal heat exchanger

5. Validation

In this study, the numerical results were validated with the studies of Bouhacina et al. [32] and Akyürek et al. [33]. Buhachina et al. [32] numerically investigated the effect of using rectangular fins on the thermal performance of a geothermal heat exchanger. The geometry of the geothermal thermal model of Bohachina et al. has been modeled in three dimensions and transiently using Ansys Fluent software. Their study considered polyethylene pipe at a depth of 25 m. Validation of the numerical results based on the geometry and boundary conditions of the study of Buhachina et al. [32] was investigated and the results obtained from the outlet temperature at a depth of 25 m are presented in Fig. 6-(a). As can be seen, the results obtained from the temperature study of Buhachina et al. [32] are insignificant, and the maximum difference is 3.67%. In order to further ensure the accuracy of the calculations, the validation of the numerical results based on the geometry and boundary conditions of the study by Akyürek et al. [33] has also been investigated. Akyürek et al. [33] experimentally investigated the thermal performance of a heat exchanger equipped with a spring turbulator and nanofluid. Its study has been investigated in the turbulent flow regime and the range of Reynolds 4000 to 19000. The results related to the Nusselt number with the study of Akyürek et al. [33] are presented in Fig. 6-(b). As can be seen, the values obtained from the Nusselt number are not much different from its study. Also, the maximum error with the study results is 4.84%. According to the performed validations and minimal error with numerical and experimental results, the correctness of the obtained results can be ensured.



(a)



(b)

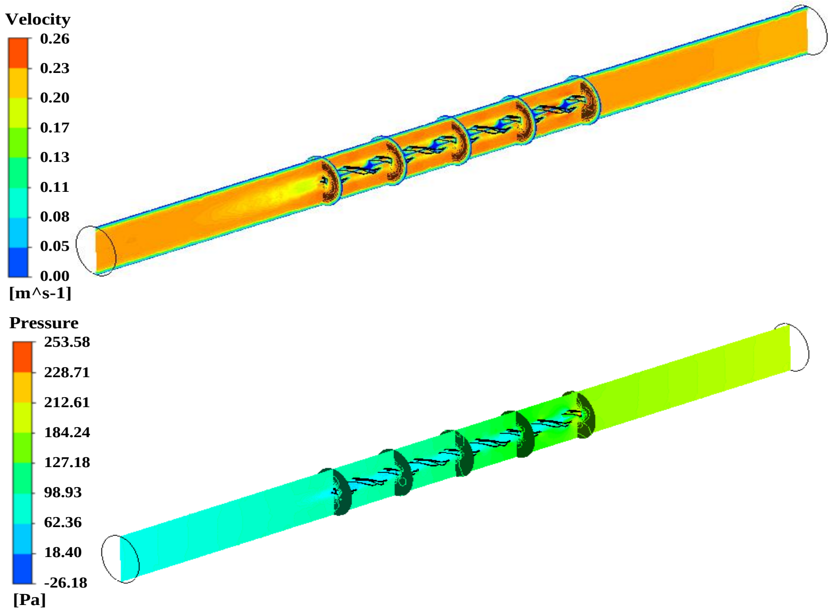
Fig. 6: Validation of numerical results with the studies of (a) Buhachina et al. [31] and (b) Akyürek et al. [32]

6. Results and Discussion

This section presents the numerical simulation results of the geothermal heat exchanger filled with MWCNT-Cu/water two-phased hybrid nanofluid equipped with a turbulator and a combination of a turbulator and a vortex generator simultaneously. First, the contours of velocity, pressure, and temperature are presented respectively for the time when the geothermal heat exchanger is equipped with a turbulator and a combination of a turbulator and a vortex generator in a volume fraction of 4% of the two-phased MWCNT-Cu/water hybrid nanofluid and a Reynolds number of 32000. In order to investigate the form of the turbulent flow lines of two-phased MWCNT-Cu/water hybrid nanofluid, the contour of the flow lines is also presented. Finally, the output results are presented in water base fluid in form of graphs of average Nusselt number, pressure drop, coefficient of thermal-hydraulic performance, and exergy efficiency for the time when the geothermal heat exchanger is equipped with a turbulator, and a combination of a turbulator and a vortex generator in Reynolds numbers 8000 to 32000 and volume fraction 1 to 4% of Copper nanoparticles and multi-walled carbon nanotubes.

6.1. Output Contour of the Geothermal Heat Exchanger

flow lines for two-phased MWCNT-Cu/water hybrid nanofluid at 4% share rate and 32000 Reynolds number in a geothermal heat exchanger equipped with turbulator step ratio two and the combination of a turbulator and a vortex generator are shown respectively in figures 7 and 8. According to the results obtained from the output of the velocity contours from the geothermal heat exchanger equipped with a turbulator, it can be seen that the use of the turbulator has increased the speed and created mixing in the middle part of the geothermal heat exchanger. Meanwhile, in the areas close to the wall, due to the non-slip condition, the speed of MWCNT-Cu/water two-phase hybrid nanofluid is almost equal to the speed of the wall, i.e., zero. Also, as evident from the speed contours, the simultaneous combination of the turbulator and vortex generator caused the density of flow lines to increase. Because the simultaneous use of the turbulator and the vortex generator increases the mixing, this increases the speed and, thus, increases the heat transfer of the displacement heat. In addition, the simultaneous use of a turbulator and a vortex generator has caused the pressure drop in the geothermal heat exchanger to increase. Because, in this case, the rate of hybrid nanofluid contact with the turbulator surface will be higher, and the pressure drop will be higher. Increasing the pitch ratio increases the velocity of MWCNT-Cu/water two-phased hybrid nanofluid. Also, the output results of the temperature contours in the case of simultaneous use of the turbulator and Rotex generator show that, in this case, the surface temperature is much higher than the time when only the turbulator was used.



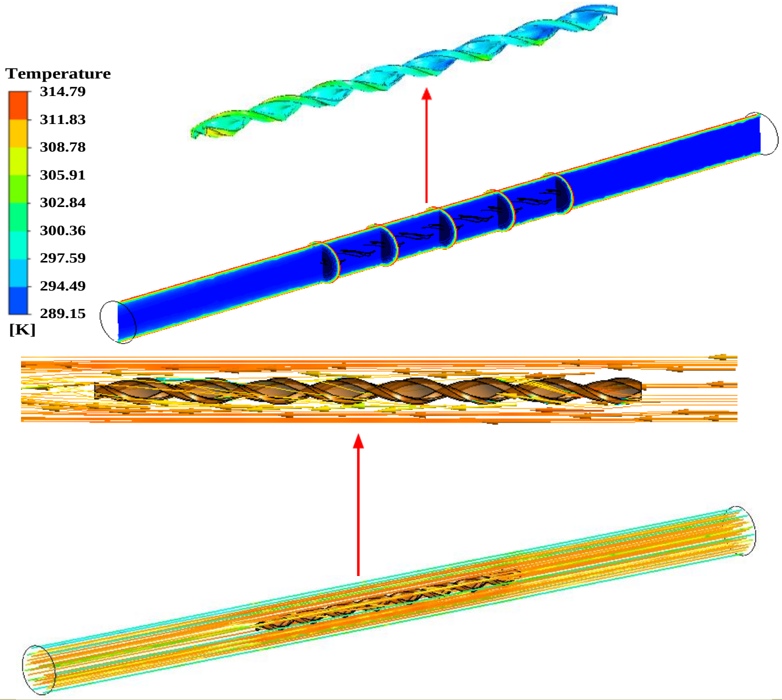
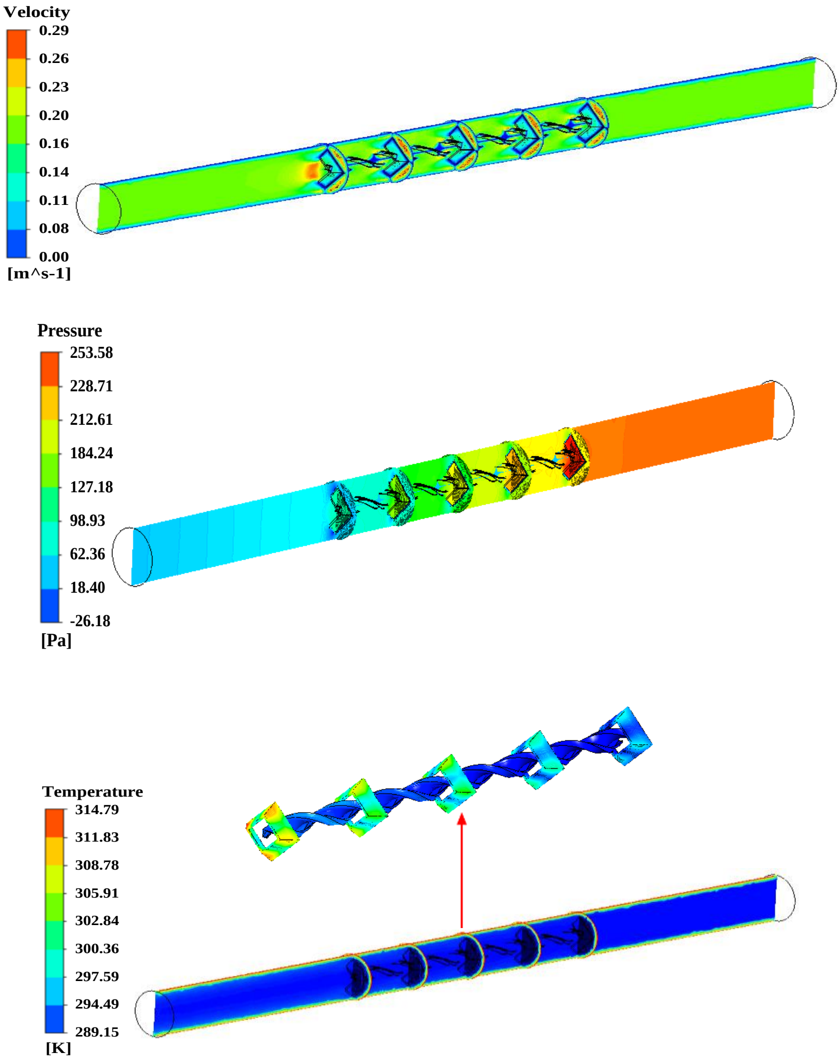


Fig. 7: Contours of the geothermal heat exchanger equipped with turbulator at Reynolds number 3200 and volume fraction 4%



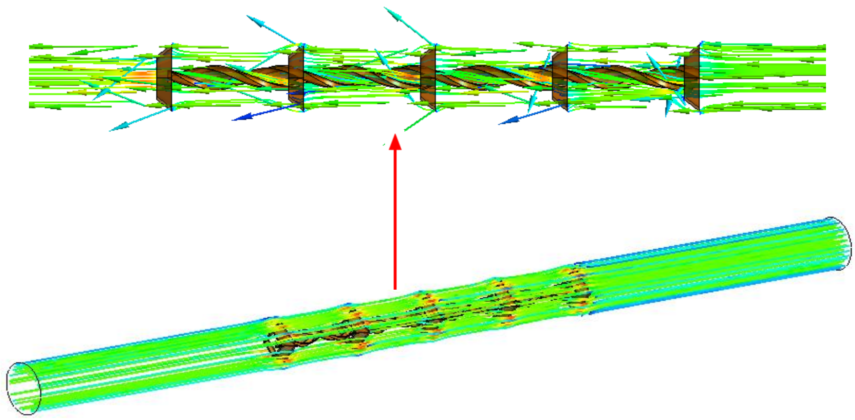


Fig. 8: The contours related to the geothermal heat exchanger equipped with a combination of turbulator and vortex generator at 32000 Reynolds number and 4% volume fraction

6.2. Effect of Turbulator Pitch Ratio on the Thermal Performance of Geothermal Heat Exchanger

Fig. 9 shows the changes of the average Nusselt number in terms of Reynolds number in a geothermal heat exchanger equipped with a turbulator with different pitch ratios in (a) ϕ = 1% and (b) ϕ = 4% of MWCNT-Cu/water two-phase hybrid nanofluid. As can be seen from the obtained results, as the input speed increases in the geothermal heat exchanger, the output thermal performance increases. In fact, as the Reynolds number increases, the displacement heat transfer coefficient increases. It is considered that the displacement heat transfer coefficient strongly influences the average Nusselt number. Therefore, with its increase, this parameter increases. To put it better, physically, at a constant Reynolds number, increasing the pitch ratio of the turbulator causes more mixing and irregularity in the two-phase MWCNT-Cu/water hybrid nanofluid flow. Therefore, this increases the heat transfer and, as a result, increases the thermal performance of the geothermal heat exchanger. In the volume fraction of 1% of MWCNT-Cu/water two-phase hybrid nanofluid and Re = 32000, the use of turbulator with a pitch ratio (PR = 2) in the geothermal heat exchanger has caused the average Nusselt number to be 68.90% compared to the case where the Geothermal converter heat without a turbulator will increase. In addition, in the ϕ = 4% of MWCNT-Cu/water two-phase hybrid nanofluid and Re = 32000, the use of turbulator with pitch ratio (PR = 2) in the geothermal heat exchanger caused the average Nusselt number to increase by 71.67% compared to the case where the geothermal heat exchanger is without turbulator, increase.

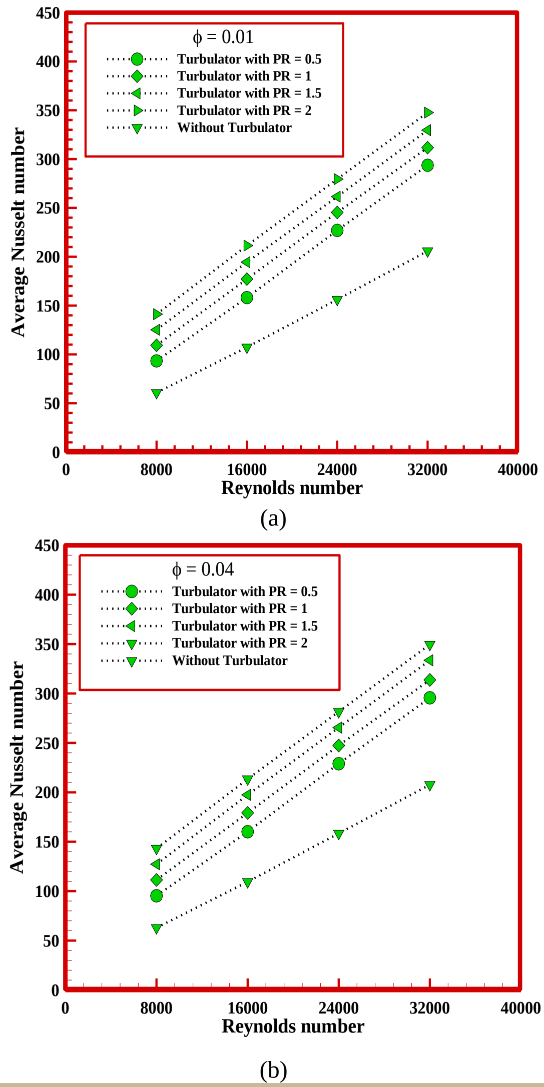


Fig. 9: Average Nusselt number changes in geothermal heat exchanger equipped with turbulator

6.3. The Effect of Simultaneous Use of Turbulator and Vortex Generator on the Thermal Performance of Geothermal Heat Exchanger

Since the main objective of this study is to improve the thermal performance of the geothermal heat exchanger, the effects of the simultaneous use of turbulator and vortex generator in the heat exchanger have also been investigated. Fig. 10 shows the changes of the average Nusselt number in terms of the Reynolds number in a geothermal heat exchanger equipped with a combination of a turbulator with a pitch ratio of 2 and a vortex generator with a Case D geometric shape in different volume fractions of MWCNT-Cu/water two-phase hybrid nanofluid. As can be seen, in the combined system, as before, they are increasing the input speed of MWCNT-Cu/water two-phase hybrid nanofluid has caused a significant increase in the average Nusselt number in the geothermal heat exchanger. In addition, by increasing the volume fraction of copper nanoparticles and multi-walled carbon nanotubes, the thermal performance has increased. Meanwhile, the simultaneous use of a turbulator and vortex generator is much more than when the heat exchanger is only equipped with a turbulator. Therefore, it can be concluded that the simultaneous use of a turbulator and vortex generator is more desirable in improving thermal performance.

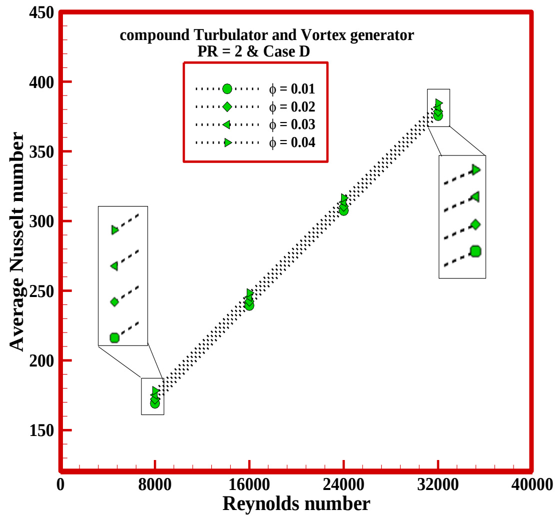


Fig. 10: Average Nusselt number changes in geothermal heat exchanger equipped with turbulator and vortex generator combination

6.4. Effect of Turbulator Pitch Ratio on the Geothermal Heat Exchanger Pressure Drop

Figure 11 shows the changes in pressure drop in terms of Reynolds number in a geothermal heat exchanger equipped with a turbulator with different pitch ratios in (a) 1% volume fraction and (b) 4% volume fraction of MWCNT-Cu/water two-phased hybrid nanofluid. According to the results obtained from the pressure drop, it can be concluded that using a turbulator in the geothermal heat exchanger caused the pressure drop to increase significantly compared to the case where the geothermal heat exchanger had been without a turbulator. Also, according to the obtained results, with an increase in the Reynolds number and an increase in the pitch ratio of the turbulator, the flux loss shows a significant increase. It can be seen that the density of the two-phase MWCNT-Cu/water hybrid nanofluid flow lines due to the collision with the turbulator is very high and results in a pressure drop.

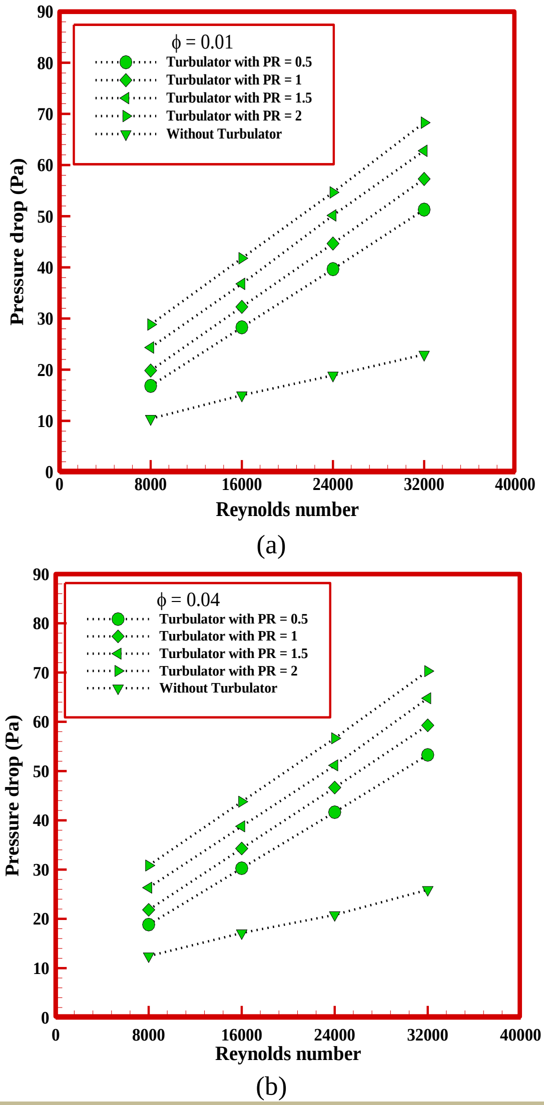


Fig. 11: Changes in pressure drop in a heat exchanger equipped with a turbulator

In the volume fraction of 1% of MWCNT-Cu/water two-phased hybrid nanofluid and the Reynolds number of 32000, the use of a turbulator with a pitch ratio of 2 (PR = 2) in the geothermal heat exchanger caused the pressure drop to be 197.29% compared to the case where the heat exchanger Geothermal had been without turbulator, increase. In volume fraction of 4% of MWCNT-Cu/water two-phased hybrid nanofluid and the Reynolds number of 32000, the use of a turbulator with pitch ratio 2 (PR = 2) inside the geothermal heat exchanger caused the pressure drop to be 200.31% compared to the case where the heat exchanger Geothermal had been without turbulator, increase.

6.5. The Effect of Simultaneous Use of Turbulator and Vortex Generator on Pressure Drop of Geothermal Heat Exchanger

Fig. 12 shows the changes in pressure drop in terms of Reynolds number in a geothermal heat exchanger equipped with a combination of turbulator and vortex generator with different volume fractions of two-phase MWCNT-Cu/water hybrid nanofluid. As can be seen, in the combined system, as before, increasing the input speed of MWCNT-Cu/water two-phase hybrid nanofluid has caused a significant increase in the pressure drop in the geothermal heat exchanger. In addition, with the increase in the volume fraction of copper nanoparticles and multi-walled carbon nanotubes, the pressure drop has increased.

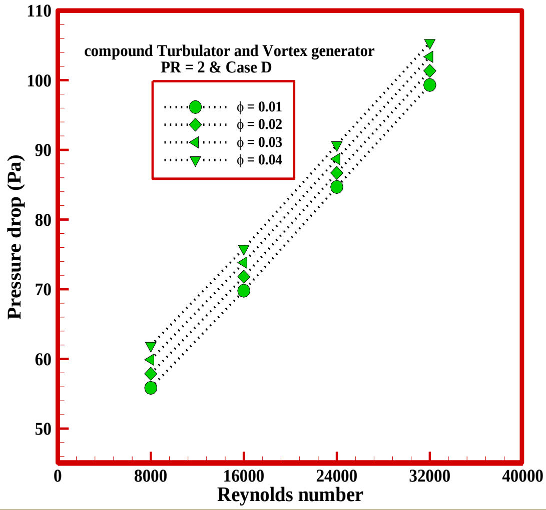
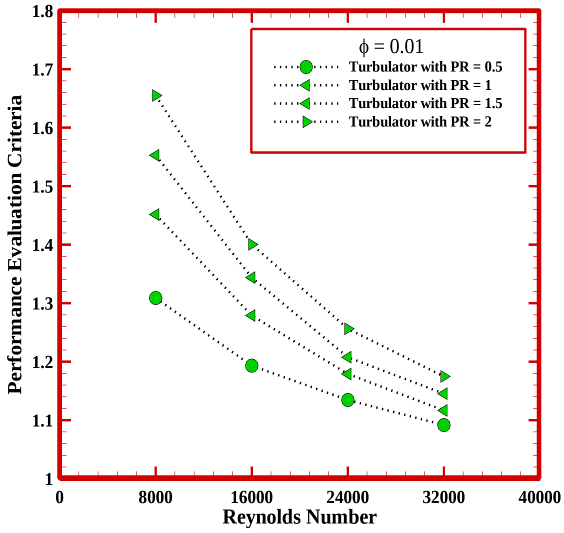


Fig. 12: Pressure drop changes in geothermal heat exchanger equipped with turbulator and vortex generator

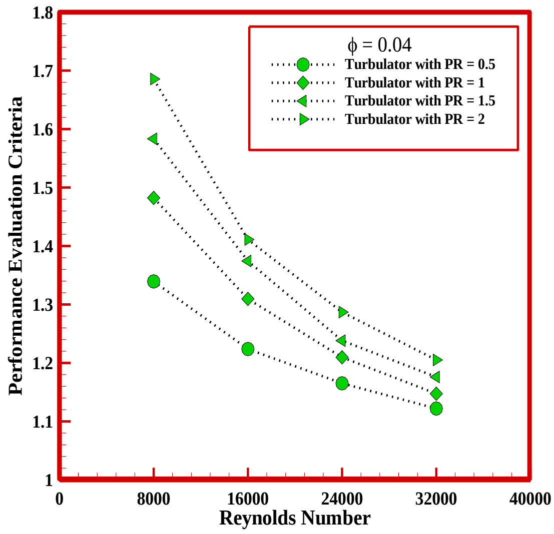
By examining the obtained results, it can be seen that the pressure drop in the geothermal heat exchanger with the combination of turbulator and vortex generator always has the most significant pressure drop changes since the main objective of this study is to improve the thermal performance of the geothermal heat exchanger. Therefore, the effects of the simultaneous turbulator and vortex generator in the heat exchanger on the loss have also been investigated. In addition to the fact that heat transfer is essential in thermal systems, the pressure drop should always be considered. For this reason, in addition to examining the pressure drop in the combined system, the thermal-hydraulic evaluation index is also examined in the following.

6.6. The Effect of Turbulator Pitch Ratio on Thermal Hydraulic Performance Coefficient of Geothermal Heat Exchanger

The changes of thermal-hydraulic performance coefficient in terms of Reynolds number in geothermal heat exchanger equipped with turbulator with different pitch ratio in (a) volume fraction of 1%, (b) volume fraction of 4% of two-phase MWCNT-Cu/water hybrid nanofluid are shown in Fig. 13. As can be seen, the thermal-hydraulic index increases with the increase in the pitch ratio of the turbulator and decrease with the increase in the Reynolds number. The rate of increase of the thermal-hydraulic index at low Reynolds numbers is much higher than at higher Reynolds numbers. This is because, in all turbulator twist ratios and volume fractions of 1 and 4% of MWCNT-Cu/water two-phase hybrid nanofluid, the values of the hydraulic performance coefficient are higher than 1. Therefore, it can be concluded that using a turbulator with a step ratio of 0.5, 1, 1.5, and 2 in a geothermal heat exchanger filled with MWCNT-Cu/water two-phase hybrid nanofluid is appropriate in terms of the thermal-hydraulic index.



(a)



(b)

Fig. 13: Changes in thermal-hydraulic performance coefficient of geothermal heat exchanger equipped with turbulator

6.7. The Effect of Simultaneous Use of Turbulator and Vortex Generator on Thermal Hydraulic Performance Coefficient of Geothermal Heat Exchanger

The changes of the thermal-hydraulic performance coefficient in terms of Reynolds number in the geothermal heat exchanger equipped with a combination of turbulator and vortex generator in different volume fractions of two-phase MWCNT-Cu/water hybrid nanofluid are shown in Fig. 14. As can be seen, the thermal-hydraulic index has increased with the increase in the volume fraction of MWCNT-Cu/water two-phase hybrid nanofluid nanoparticles and decreased with the increase of the MWCNT-Cu/water two-phase hybrid nanofluid input speed. Although with these conditions, in the Re = 8000 to 32000 and volume fraction of 1 and 4% of nanoparticles, the thermal-hydraulic index values are always greater than 1. Therefore, it can be concluded that using a heat exchanger equipped with a combination of turbulator and vortex generator is always desirable in terms of the thermal-hydraulic index.

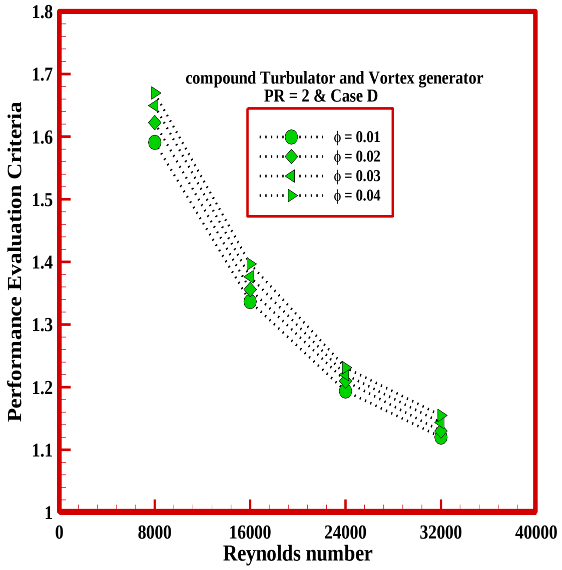
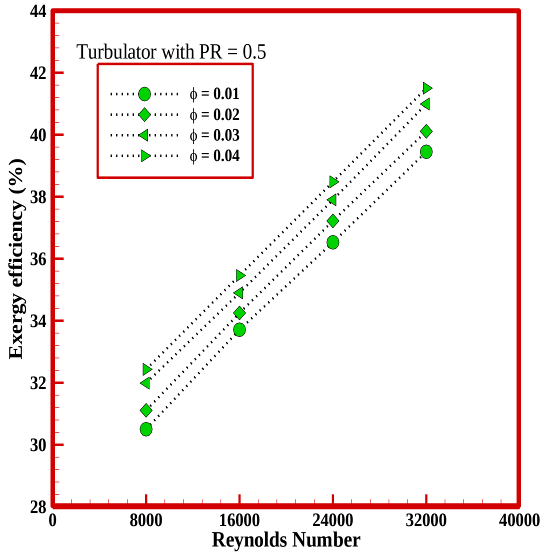


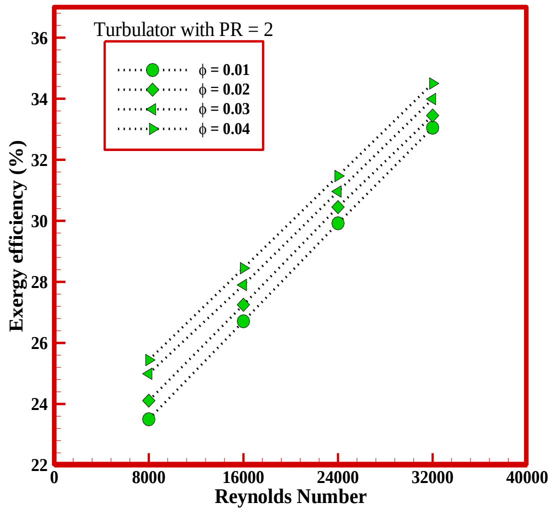
Fig. 14: Changes in the thermal-hydraulic performance coefficient of the geothermal heat exchanger equipped with a combination of turbulator and vortex generator

6.8. Effect of Turbulator Pitch Ratio on Exergy Efficiency of Geothermal Heat Exchanger

Fig. 15. shows the changes in exergy efficiency in terms of Reynolds number in a geothermal heat exchanger equipped with a turbulator with different volume fractions of MWCNT-Cu/water two-phase hybrid nanofluid in (a) PR = 0.5 and (b) PR = 2. As it can be seen, in a fixed pitch ratio of the turbulator, an increase in the volume fraction of MWCNT-Cu/water two-phased hybrid nanofluid nanoparticles has increased the exergy efficiency. Also, the exergy efficiency has increased by an increase in the speed of the two-phased MWCNT-Cu/water hybrid nanofluid at the inlet of the geothermal heat exchanger. However, as it can be seen, an increase in the pitch ratio of the turbulator has a negative role in the exergy efficiency and has reduced it. Exergy analysis, by stemming from the second law of thermodynamics, is useful in identifying the causes, locations, and magnitudes of process inefficiencies. The exergy associated with an energy quantity is a quantitative assessment of its usefulness or quality. In a geothermal heat exchanger with a turbulator with a pitch ratio of 0.5 (PR = 0.5) and a volume fraction of 4% MWCNT-Cu/water two-phased hybrid nanofluid, the exergy efficiency increases by 27.97% with an increase in the Re = 8000 to 32000. Also, in the geothermal heat exchanger with turbulator with a pitch ratio (PR = 2) and volume fraction of 4% of MWCNT-Cu/water two-phased hybrid nanofluid, with increasing Re = 8000 to 32000, exergy efficiency increases by 32.53%.



(a)



(b)

Fig. 15: Exergy efficiency changes in the geothermal heat exchanger with turbulator

6.9. The Effect of Simultaneous Use of Turbulator and Vortex Generator on Exergy Efficiency of the Geothermal Heat Exchanger

Exergy efficiency (also known as second-law efficiency or rational efficiency) measures how effective a system is compared to its performance under reversible conditions. An idealized or reversible version of the system heat is defined as the ratio of the actual thermal efficiency to the idealized or reversible version of the system heat. The changes in exergy efficiency in terms of Reynolds number in the geothermal heat exchanger equipped with the combination of turbulator and vortex generator with the shape in different volume fractions of two-phased MWCNT-Cu/water hybrid nanofluid are shown in Fig. 16. As it can be seen, the exergy efficiency has increased with the volume fraction of MWCNT-Cu/water two-phased hybrid nanofluid nanoparticles. Also, by increasing the Reynolds number, or in other words, by increasing the speed of MWCNT-Cu/water two-phased hybrid nanofluid at the inlet of the geothermal heat exchanger, the exergy efficiency increases.

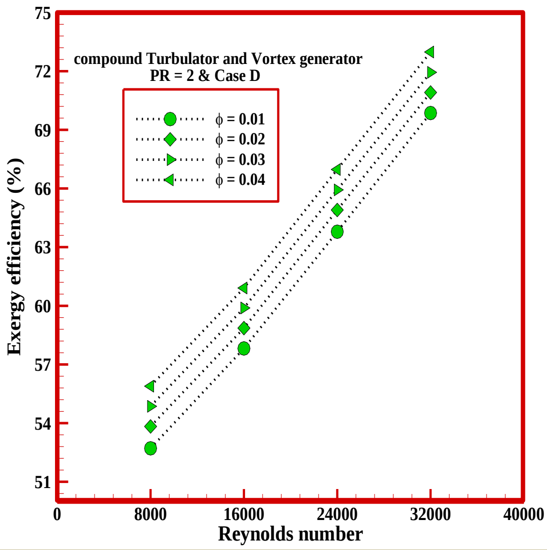


Fig. 16: Exergy efficiency changes in the geothermal heat exchanger equipped with a combination of turbulator and vortex generator

7. Conclusion

In this study, a geothermal heat exchanger equipped with a turbulator and the simultaneous combination of a turbulator and a vortex generator filled with two-phased MWCNT-Cu/water hybrid nanofluid have been numerically simulated using computational fluid dynamics. The geometry of the geothermal heat exchanger has been analyzed in 3D using Anasys Fluent version 2022 software. The study was carried out under constant, stable, and turbulent flow. K-Epsilon Realizable turbulence model was used to model viscosity. Also, considering two-phased flow, a mixed model was used for numerical simulation. In order to couple speed and pressure, a simple algorithm was used. This study was carried out assuming a warm semi-arid climate for Isfahan province at a depth of 1 m from the ground. The study carried out for Reynolds numbers 8000 to 32000, the volume fraction of 1 to 4% of copper nanoparticles and multi-walled carbon nanotubes in water base fluid, pitch ratio of 0.5, 1, 1.5 and 2 of the turbulator and the combination of turbulator and vortex generator. The results obtained from this study are:

- In the geothermal heat exchanger, the thermal performance increased significantly by increasing the inlet velocity and the volume fraction of MWCNT-Cu/water two-phased hybrid nanofluid.
- In volume fraction of 4% of MWCNT-Cu/water biphasic hybrid nanofluid and Reynolds number of 32000, the use of turbulator with pitch ratio 2 (PR = 2) in the geothermal heat exchanger caused the average Nusselt number to be 71.67% compared to the case where the Geothermal converter heat without a turbulator would increase.
- Based on the results obtained from the thermal performance, using the combination of turbulator and vortex generator simultaneously in the geothermal heat exchanger created far more heat transfer than the time when the heat exchanger was only equipped with a turbulator.
- Based on the results obtained from the pressure drop, using the combination of a turbulator and vortex generator simultaneously in the geothermal heat exchanger created far more pressure drop than the time when the heat exchanger had only been equipped with a turbulator or vortex generator.
- The results from the thermal-hydraulic index showed that the use of a turbulator, vortex generator, and the combination of turbulator and vortex generator was 1 in all higher cases. Therefore, using the cases in terms of the PEC index was desirable.
- In the geothermal heat exchanger in a fixed geometric state, the exergy efficiency increased by increasing the inlet velocity and MWCNT-Cu/water two-phased hybrid nanofluid volume fraction.

In a geothermal heat exchanger with turbulator with a pitch ratio of 2 (PR = 2) and volume fraction of 4% of MWCNT-Cu/water two-phased hybrid nanofluid, with an increasing Reynolds number from 8000 to 32000, the exergy efficiency value increased by 32.53%.

Nomenclature

A	Area (m^2)
Cu	copper
c_p	Specific heat capacity (kJ/kg. °C)
FVM	Finite volume method
f	Friction coefficient
HNF	Hybrid Nanofluid
k	Thermal conductivity (W/m.K)
MWCNT	Multi-walled carbon nanotube
NFs	Nanofluids
NPs	Nanoparticles
Nu	Nusselt number
P	Pressure (Pa)
PEC	Performance evaluation criteria
Re	Reynolds number
T	Temperature (˚C)
U	Heat transfer coefficient (W/m2·°C)
u, v, w	velocity vector
ΔP	Pressure drop (Pa)
Greek symbol	
ϕ	Volume fraction (%)
μ	Dynamic viscosity (cP)
ρ	Density (kg/m^3)
μ_t	Turbulence viscosity
τ	Shear stress (Pa)
subscripts	
out	Outlet
in	Inlet
bf	base fluid
nf	nanofluid
np	nanparticle

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