The effect of using multichannel twisted tape and nanofluid on the absorber tube's heat transfer and the efficiency of a linear parabolic solar collector

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ABSTRACT

One of the most important tools for using solar energy is parabolic solar collectors (SCs). To improve the performance of these collectors, creating rotation in the fluid flow by placing twisted tape or helical paths inside the tube is an effective passive method. In this study, the role of three- and four-channel twisted tapes in increasing the rate of heat transfer (RHT) inside the collector adsorbent tube containing water-copper oxide nanofluid and its effect on energy and exergy efficiencies has been investigated numerically. Finite volume method, SIMPLE algorithm and SST k-w turbulence model for solving the equations. The study was conducted for Re = 20000–80000. Numerical results indicated that the highest Nusselt number was related to nanofluids with a volume fraction of 4% in Reynolds number of 80,000, equal to 54.7. Furthermore, the highest coefficient of thermal performance of three-channel twisted tape occurs in Reynolds of 80,000 with a volume fraction of 4%. Moreover, the best efficiency of SCs is related to nanofluid flow with Reynolds of 80,000 and volume fraction of 4%, which is equal to 26%. Furthermore, nanofluid with a volume fraction of 4% has the highest exergy efficiency.

Introduction

Solar energy has been regarded as a significant source of clean and renewable energy for about 50 years. This energy source is completely clean with no pollution [1–4,51]. Unlike fossil or nuclear sources, the continuous use of solar energy does not lead to environmental effects [5–9,52]. One of the most important equipment for utilizing solar energy is solar collector. [10–15,53]. The parabolic type has received more attention among SCs due to its high capabilities [16,17,54,55].

Assadeg et al. [18] examined an analysis of SCs using two types of fin and PCMs. Predictions were made for dissimilar mass flow rates and solar radiations. The effects of solar radiation surfaces and mass flow rate on energy effectiveness and recovery potential were assessed. The optimal energy efficacy of the suggested collector was about 73%. The exergy efficacy was approximately 2.5–4.2% for the highest solar radiation.

Kansara et al. [19] assessed a flat plate SC's performance evaluation criteria (PEC) with internal fins and a porous medium using a computational fluid dynamics approach. Also, the possible impact of air mass's velocity and heat flux resulting from the solar simulator on the temperature augmentation and heat absorbed by the air was examined. The distribution of fluid flow was also examined in the model suggested. In addition, the possible impact of the of fins number and porous foam materials, as well as foam porosity, on the collector's performance was assessed. Finally, the observed pressure difference in the collector for each of the models was investigated to evaluate the impact of the model proposed on the considered pressure drop (ΔP). Their findings demonstrated the highest RHT of the porous medium compared to the fins and other geometries. To enhance the temperature of air, a collector with a porous medium was 17.16% better than an empty channel.

Ammar et al. [20] provided some numerical analysis of a particular SC with a row of rectangular fins. This study installed an efficient flat plate SC with three rectangular fin rows at the structure bottom, which provided 81% thermal efficiency and 0.5 W pumping power. A 3D computational fluid dynamics model of some flat plate SC was provided and then solved under steady conditions. An appropriate approach was

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recommended to evaluate and optimize the performance of the 1.28 m^2 surface collector having the forced convection flow. Finally, the selected absorber was suggested to be combined with rectangular fins in the proposed novel design.

Bhagwat et al. [21] studied a finned heat pipe's performance using a SC system under the northeastern Indian climate. This study performed an experimental examination to investigate a parabolic collector tube's performance using a heat pipe with PCMs based on paraffin wax. PCMs maximum average temperature was 63 °C and 60 °C with and without fins. The latent heat energy storage capacity was about 330 kJ. The average latent heat charging efficiency when having some fin configuration was estimated to be 44.7%, which was higher than that obtained by the model with no fin. The average discharge efficiency when having the fin was 32.7% more than that obtained with no fin. In addition, the fin's presence in the evaporator system reduced the energy of the heat storage device.

Peng et al. [22] probed the absorber tube's performance in a parabolic SC with a semi-annular metal foam and fin compound structure. The possible impact of semi-annular and fin metal foam shapes on the forced convective heat transfer when it was non-uniform heat flux conditions was analyzed from a numerical point of view. The results showed that the insertion of semi-annular and fin metal foam improves the absorber tube's thermohydraulic as well as thermodynamic performance.

Zhao et al. [23] investigated a parabolic collector's overall performance using three dissimilar absorber tubes for medium heat supplies. One smooth absorber tube and two absorber tubes with internal pin-fins were experimented. The increase in air temperature was 266 °C with an airflow rate of 93 Nm^3/hour under solar radiation, which was about 900 W/m^2. The obtained experimental data showed an increment in air temperature and PD of the inner fined tube; this was significantly greater than that of the smooth tube. According to the thermo-hydraulic analysis, the SC having tubes with internal fins performs better at low airflow velocities. However, at high velocities, the PD was even greater than the enhancement in RHT. The smooth-tube SC displayed better thermo-hydraulic efficiency. Therefore, absorber tubes with internal pin fins could be useful for designing parabolic SCs that operate at low airflow rates.

SinemIşıka and Yildiz [24] analyzed the improvement of SC tank's thermal energy storage efficiency using PCMs in a new type of finned cells. The tank's performance with PCM was compared with the insulated tank without PCM. The results showed that the modified tank's solar energy storage capacity was almost 10% higher than that of the insulated tank, which is approximately 4–5% higher than that of the tank without fins. In addition, the new design of the fins allowed the tank to be kept warm for almost 2 h longer, as compared to the standard insulated one.

Qiu et al. [25] conducted a theoretical investigation to consider the heat transfer properties of some finned tube that was employed in a collector/evaporator under solar radiation conditions. The heat transfer of the fin having no solar radiation could be under the influence of solar radiation. They demonstrated that the negative effect of solar radiation could be effectively reduced by raising the heat transfer coefficient (HTC) and the diameter of the copper tube. For larger fin heights and solar conditions, an increment of the HTC at the surface of the aluminum fin does not lead to an increase in the heat which is absorbed by the finned tube; however, further heat is released into the environment. This investigation could be employed from a theoretical point of view to design and optimize the collector/evaporator.

Badiei et al. [26] tried to improve the performance of solar flat plate collectors by combining them with PCMs and fines. In the present research study, a 3D model of transient computational fluid dynamics was applied to investigate some solar flat plate collectors having a PCM layer. In this study, four different PCMs with different melting temperatures were taken into account. The findings indicated that while the PCM system had a lower outlet temperature in the morning, hot water could be provided for a longer time during the evening when discharging process. Further, the efficiency of the average collector was enhanced from 33% to 46% on a summer day for a particular PCM having a minimum melting point. Further, the combination of fins intensifies the storage capacity, particularly for the PCM with higher melting temperatures. Despite this, the heat loss in the environment during the charging process in the afternoon is greater for the finned system and can reduce productivity to some extent.

Schreiber and Schaeffer [27] produced absorber fines for SCs using incremental sheets. This research presented a new production process for creating absorber fins for SCs. In this study, the process feasibility with more efficient parameters for the production of absorber fins was made possible by using a pitch of 2 mm and an angular velocity of 50 rpm.

Murugan et al. [28] proposed some centrally finned twist inserted SCs by applying corrugated booster reflectors. The results showed that the effective reflectance surface of corrugated booster reflectors was 1.6% higher than that of flat booster reflectors. In addition, centrifugal twisted corrugated booster reflectors with twisted ratio 3 offer have higher thermal efficiencies than simple-tube corrugated booster reflectors. This study also showed an experimental correlation between the Nusselt number and the friction factor (f).

Daliran and Ajabshirchi [29] conducted theoretical as well as experimental research on fins attachment by focusing on the solar air collectors' operating parameters and thermal efficiency. In this study, a fan with 0.033 kg/s as the constant mass flow rate was used to produce airflow. The findings revealed that the use of fins in the air duct reduced the Nusselt number from 19.67 to 16.23; also, it enhanced the HTC from the collector plate to the airflow due to the reduction of the hydraulic diameter and turbulent flow. The outlet air temperature reported was higher than the average difference found in outlet air temperature between the experimental and theoretical findings in the case of both collectors without and with fins and was 7.6 and 9.4%, respectively. Thermal efficiencies of 30% and 51% were calculated experimentally with and without fins. Theoretically, these values were 33% and 55%, which generally seems reasonable.

Singh [30] examined the thermo-hydraulic of a double pass solar heat collectors' performance with inline, staggered and hybrid fin settings. It was shown that the best thermo-hydraulic performance corresponded to the hybrid fin model and was about 3.5 and 3.8%, respectively, compared to the staggered and inline models. In addition, computational fluid dynamics showed interesting results for the staggered model, which created a wavy motion inside the heater and significantly enhanced heat transfer. Meanwhile, the experimental thermal efficiency of 79% was obtained for the double pass solar heater design; this was almost 13% more than that of the similar single-pass design.

Karimi et al. [31] studied some parabolic solar dish collectors coupled with finned-tube heat exchangers to produce experimentally and theoretically hot air. The model results were compared with the experimental ones, indicating the reliability of the proposed model. The effect of a number of effective parameters on the system's performance was probed. The results showed that the oil mass flow rate, air mass flow rate, and the diameter of the receiver diaphragm had a remarkable impact on the system's performance, while the initial oil mass in the storage tank had a slight effect. The system's thermal performance was examined on different days, and in the mentioned parameters desired values, the system's average daily thermal efficiency could be achieved up to 60%.

Zhu et al. [32] designed some free-piston Stirling generator which was integrated with some parabolic trough collector for solar energy thermal-to-electric conversion. The maximum efficiency of 15% was achieved for the free-piston Stirling generator. Also, at temperatures above 300 °C, overall efficiency of 3% was obtained. Significant optical loss and heat loss were obtained for further optimization.

Obaid et al. [33] investigated the thermal and economic

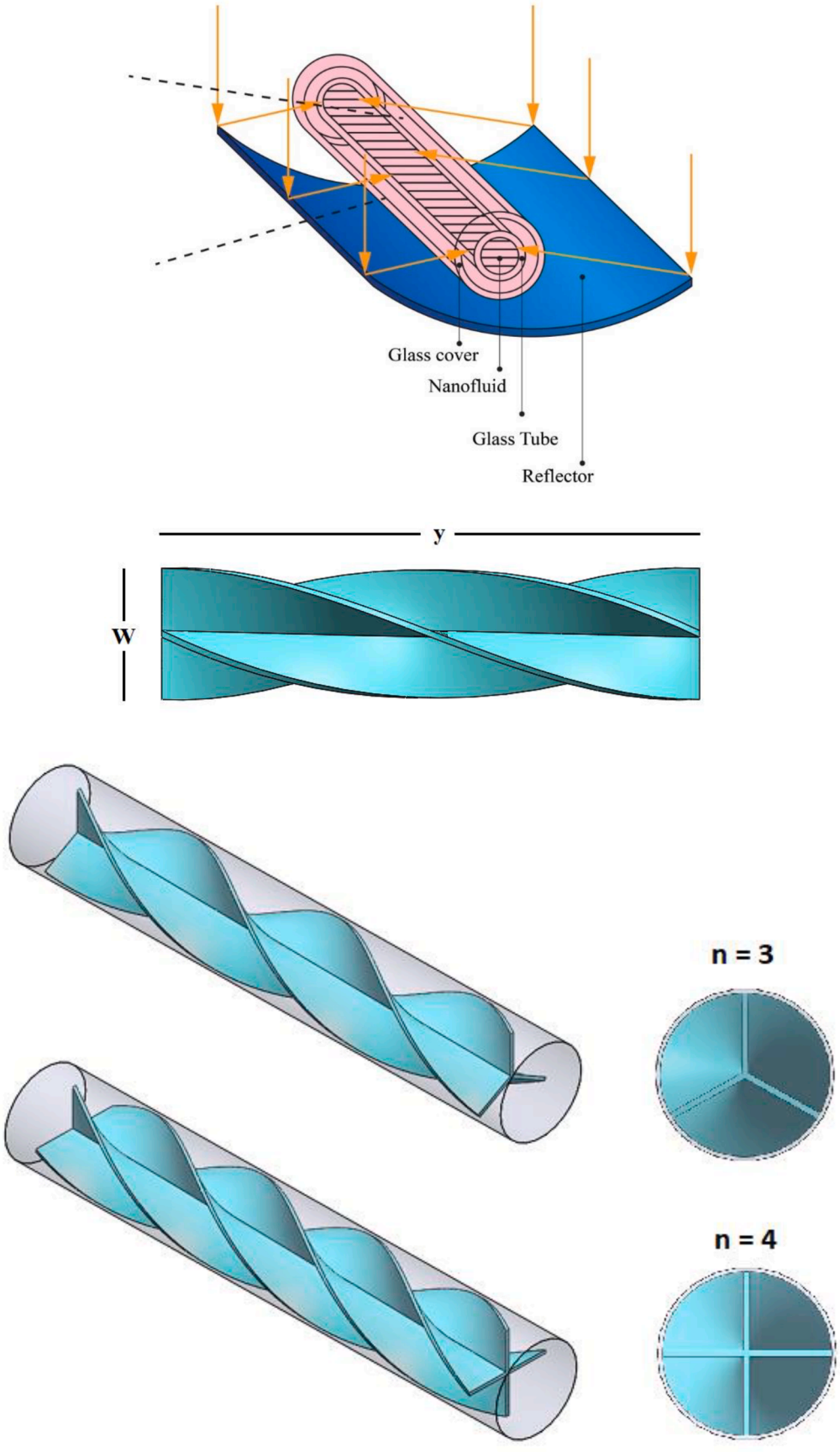


Fig. 1. Linear parabolic SC, absorber tube equipped with three- and four-channel twisted tape.

Table 1
The size of the parameters used in the present study.

Parameter	Reynolds number (Re)	Twisted ratio	Inner tube diameter (D)	Twisted tape width (W)	Twisted length (y)	Twisted tape length (L)	Twisted tape thickness (t)
Value	20,000 50,000 80,000	4	22(mm)	20(mm)	80(mm)	480(mm)	1(mm)

Table 2
Thermophysical properties of the nanofluid.

Nanofluid	$\rho(kg/m^3)$	$\mu(kg/m.s)$	$k(W/m.K)$	$C_p(J/Kg.K)$
water	998.20	0.001003	0.613	4179
water + 1%CuO	1050.33	0.001080	0.631	3959.7
water + 2%CuO	1103.56	0.001198	0.650	3761.7
water + 3%CuO	1156.80	0.001330	0.666	3417.8
water + 4%CuO	1210.02	0.001493	0.680	3581.8

characteristics of solar air collectors having diverse delta turbulators arrangements. The advantages of applying some solar air collector having varied turbulator absorber plates were evaluated from an experimental point of view to evaluate such a collector in the Iraq climate. The results showed that delta turbulators could promote the economic properties and collectors' overall thermal performance due to the production of vortices and the weakening of the thermal boundary layer developed in the airflow direction. Significant progress has been made to reduce life cycle costs and enhance energy savings using delta turbulators. The study also provided a new direction in the climatic conditions related to western and central parts of Iraq on the winter days.

Khargotra et al. [34] examined diverse turbulator forms performance in solar water heating collector systems. The effects of inserting a spring coil windshield on RHT, mass flow rate, etc. were assessed by creating the disturbance in the flow in absorber tubes of some flat plate SC. The RHT in the collector was enhanced by 18 to 70%. Solar water heaters worked better in finned tubes than conventional tubes. Heat losses were observed due to reducing the thermal performance by 70% compared to simple water heaters under similar operating conditions. The used coil spring serving as the windshield was placed in the lifting tube, whereas the twisted tape was put in the wire coil to create a continuous rotational flow along the tube wall. The comparison of heat transfer results with the available ones was then made.

Bellos et al. [35] probed how the parabolic collector's performance was improved by applying nanofluids and turbulators. The analysis was performed with a valid computational fluid dynamics model using SolidWorks software for different fluid temperatures. Based on the findings, applying nanofluids, internal fins, and their combination intensified the thermal efficiency by 0.76%, 1.10%, and 1.54%, respectively.

Vasyl et al. [36] examined the thermal processes physical modeling in a solar air collector with a flow turbulator. The results showed that there is a heat transfer motion in the air duct of the SC as well as the maximum convection HTC between the flow and air turbulator was observed at an inclined angle of 45°. Furthermore, the simulations demonstrated that the power of the proposed solar air collector is enhanced by 23%, when compared to the SC having a flat heat absorbing plate.

Babaei Mahani et al. [37] analyzed the hybrid nano-additives thermal–hydraulic performance when they contained multi-walled carbon nanotube-Al_2O_3 in some parabolic by using SC having turbulators. This was intended to get the maximum PEC. Water-based multi-walled carbon nanotubes and aluminum oxide (80:20) Newtonian composite nanofluid and K-ω SSD turbulence model were used. For the theta of 180°, the maximum average Nusselt was obtained for all Reynolds numbers, which was compared with the theta of 90° and theta of 0°.

According to previous studies, the impact of applying multichannel twisted tapes and nanofluid on the absorber tube's RHT and the linear parabolic SC efficiency has not been the focus of much research. On the other hand, with the increasing speed of computers and the development of software companies, researchers began to use simulation software to solve complex problems [38–43]. Their results show well that numerical and mathematical works can be trusted [44–49]. Therefore, the present study evaluates the effect of multichannel twisted tapes in the absorber tube and their effect on the efficiency at different Reynolds numbers and volume fractions numerically. The most important innovation of this study is the use of a new type of three- and four-channel twisted tapes in a linear parabolic collector with nanofluid.

Mathematical modeling

Linear parabolic collectors include parabolic reflective surfaces mounted on a supporting structure. The energy receivers are cylindrical absorber tubes with a selective coating that are covered by glass and placed along the parabolic reflector focal line. The nanofluid passes through the absorber tubes as a heat transfer fluid (Fig. 1).

Geometrical model

The geometrical model used in this study includes the absorber tube of a linear parabolic SC which is equipped with three-channel (n = 3) and four-channel (n = 4) twisted tape. In this model, the twisted ratio (y/W) is 4 and the twisted tape thickness is 1 mm (Fig. 1). The geometrical specifications of the model can be seen in Table 1.

In the current research, copper oxide (CuO) nanoparticles with different volume percentages (from one to four percent) are added to water to enhance RHT. The features of the nanofluids used can be seen in Table 2.

Governing equations

In this research study, three-dimensional steady incompressible flow is simulated. The governing equations include the mass conservation equation (continuity), the momentum equation, the energy equation, and the turbulent flow equations. These equations are:

Continuity equation.

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation.

$$\frac{\partial}{\partial x_j}(\rho u_i u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\overline{u_i' u_j'}\right] \tag{2}$$

Energy equation.

$$\frac{\partial}{\partial xj}(\rho u_i T) = \frac{\partial}{\partial xj}\left((\Gamma + \Gamma_t)\frac{\partial T}{\partial x_j}\right) \tag{3}$$

Here, u is velocity, ρ is the density, and μ is the dynamic viscosity.

The equations of the k-ωSST model are:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \tag{4}$$

Table 3
Boundary conditions.

Location	Boundary conditions
Inlet	Uniform velocity and temperature $u = u^{\circ}$ and $T = T^{\circ} = 300\,K$
Wall	Uniform heat flux 2000 $\frac{W}{m^2}$
Outlet	Zero pressure gradient

Table 4
Grid independence results for the Nusselt number.

Number of elements	Nusselt number	Error percentage
755,000	78.42	–
1,231,000	67.53	14%
1,785,000	59.12	12%
2,216,000	54.31	8%
2,695,000	53.20	2%

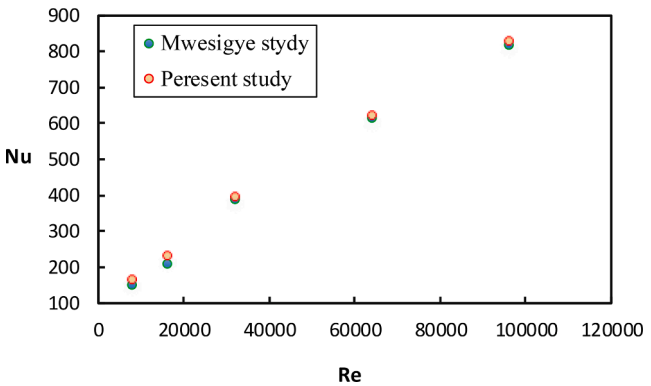


Fig. 2. Nusselt number according to the Reynolds number for absorber tube with conventional twisted tape in the present study and the study of Mwesigye et al. [50].

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x_j}(\rho\omega u_j) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \tag{5}$$

Simulations performed for RHT evaluation include Re, Nu, f, PEC, and the exergy and energy efficiencies of collector.

$$Re = \frac{\rho u D}{\mu} \tag{6}$$

$$Nu = \frac{hD}{k} \tag{7}$$

where μ is the dynamic viscosity and k is the thermal conductivity of the fluid.

The friction factor in turbulent flow through the tube can be estimated by applying the equation represented below:

$$f = \frac{\Delta P D}{2\rho L u^2} \tag{8}$$

PEC, which is used to evaluate the fluid flow's thermal behavior in a heat exchanger or SC, can be regarded as the convection heat transfer rate (Nu/Nu_p) to the rate of friction factor (f/f_p) ratio under the same conditions [37].

$$PEC = (Nu/Nu_p)/(f/f_p)^{1/3} \tag{9}$$

where Nu_p and Nu are Nusselt numbers for pipe without and with twisted tape, respectively. Moreover, f_p and f are respectively friction factors for pipe without and with twisted tape is analyzed using thermal efficiency. Thermal efficiency, as a criterion for analyzing the thermal performance of SCs, may be obtained as the energy absorbed by the fluid flowing into the absorber tube divided by the direct irradiative energy striking the surface of the reflector plate.

$$\eta_c = \frac{Q_{in}\rho_{in}c_{Pin}(T_{out} - T_{in})}{6 \times 10^4 IA} \tag{10}$$

Exergy efficiency or the second-law efficiency for parabolic collectors is expressed as net useful exergy divided by the exergy of direct sunlight entering the collector and is calculated as follows:

$$\eta_{ex} = \frac{\dot{Q}_{HTF} - \dot{m}_{HTF}C_{P,HTF}\ln\left(\frac{T_\infty}{T_{i,HTF}}\right)}{\dot{Q}_{HTF} - \dot{m}_{BF}C_{P,BF}\ln\left(\frac{T_{o,BF}}{T_{i,BF}}\right) + VI\eta_P} \tag{11}$$

where η_P is the efficiency of pump Vand is assumed about 85%.

Numerical method

The simulations are performed using the ANSYS FLUENT 2020 software. The k-ω SST model is used to model the turbulent flow. Most two-equation turbulence models predict higher values of turbulence stresses in wake areas compared to the real physics and therefore do not work well in predicting the boundary layer under reverse pressure gradients. As a result, this model is a desirable option if the boundary layer is important in the simulations. One of the challenges of using the k-ω SST turbulence model at high Reynolds numbers is its relatively difficult convergence. For numerical solution convergence, the governing equations of a mesh with an optimum number of nodes are first solved by the first-order forward discretization method. After that, the second-order forward discretization method is used. The convergence criterion of this model for all variables is 10^{-6}.

Boundary conditions

Simulations are performed at Reynolds numbers of 20,000, 50,000,

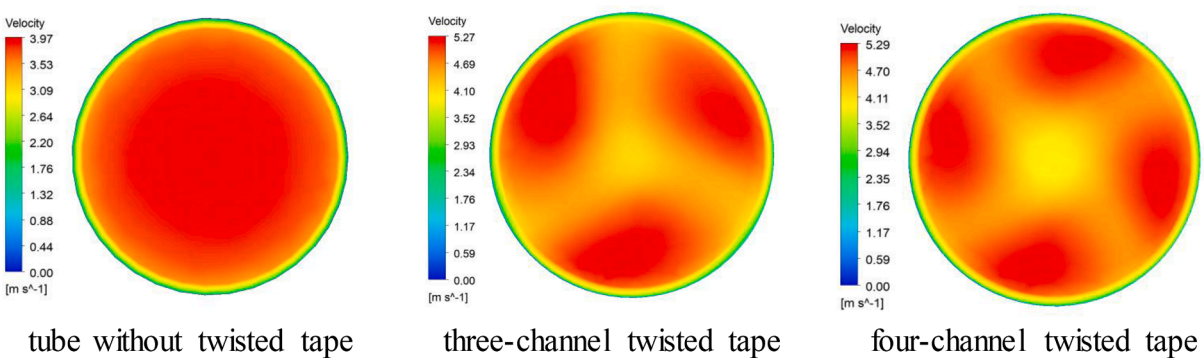


Fig. 3. Impact of multichannel twisted tape on flow velocity.

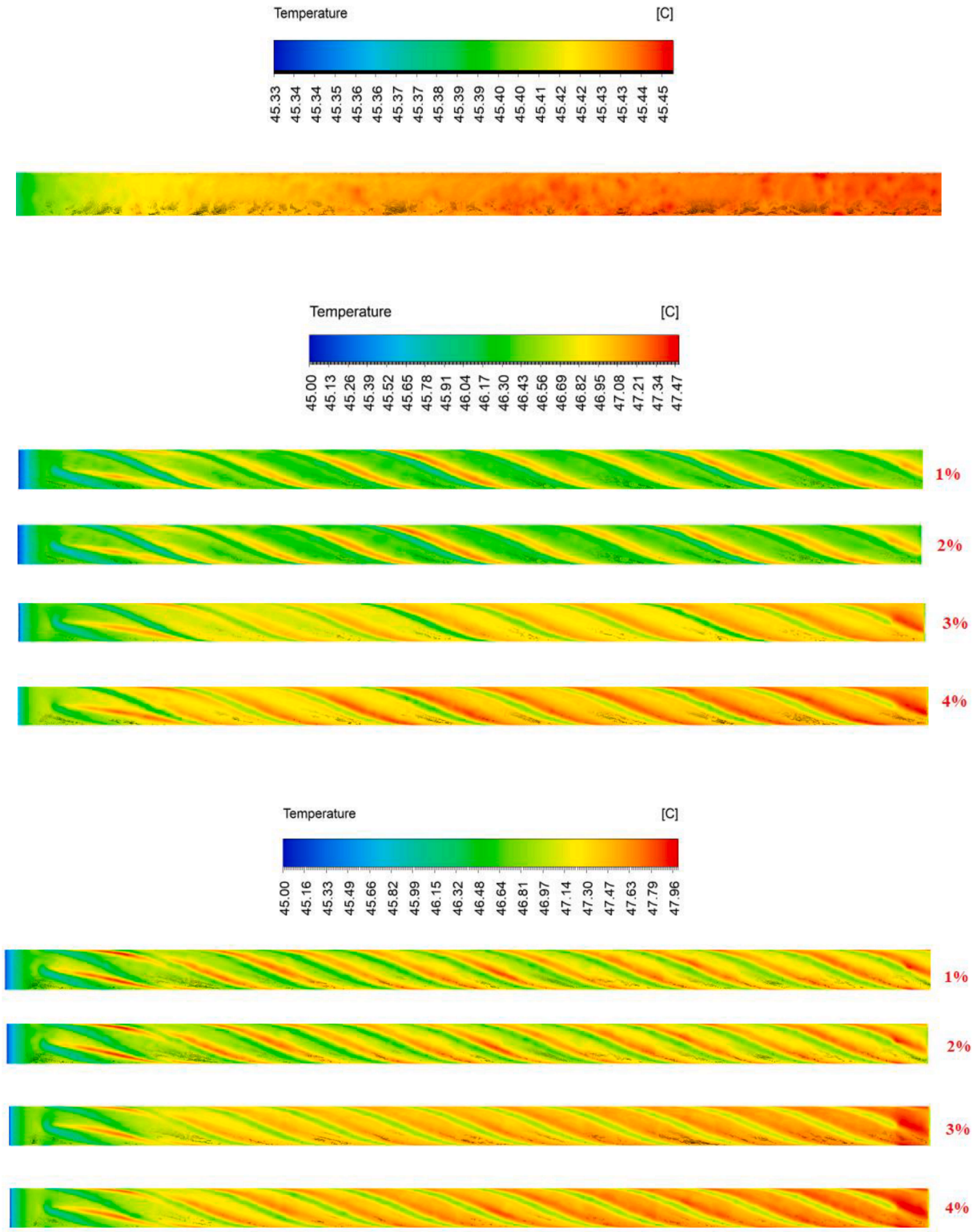


Fig. 4. Temperature distribution on the horizontal plane passing through the center of the pipe without twisted tape, with three-channel twisted tape, and four-channel twisted tape for different volume percentages and Re = 80000.

and 80,000. The boundary conditions represented in Table 3 are employed for the absorber tube with three- and four-channel twisted tape.

Grid-independence test

The present study meshes the computational domain by quadrilateral cells using ANSYS Meshing 2020 software. Since the velocity gradient of the fluid is large near the walls, the fluid flow near the walls must be simulated with high accuracy to achieve the correct results in the modeling. To determine the independence of the solution to the grid, examining the independence of the results from the generated grid is essential. For this purpose, the simulations are implemented using five meshes with the number of elements of 755000, 1231000, 1785000,

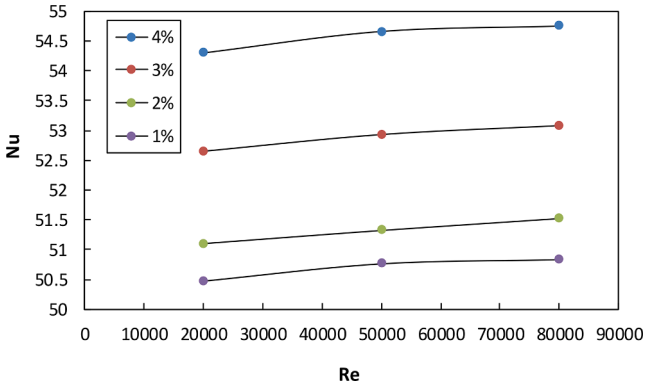


Fig. 5. The Nusselt number in nanofluid with diverse volume percentages at various Reynolds numbers.

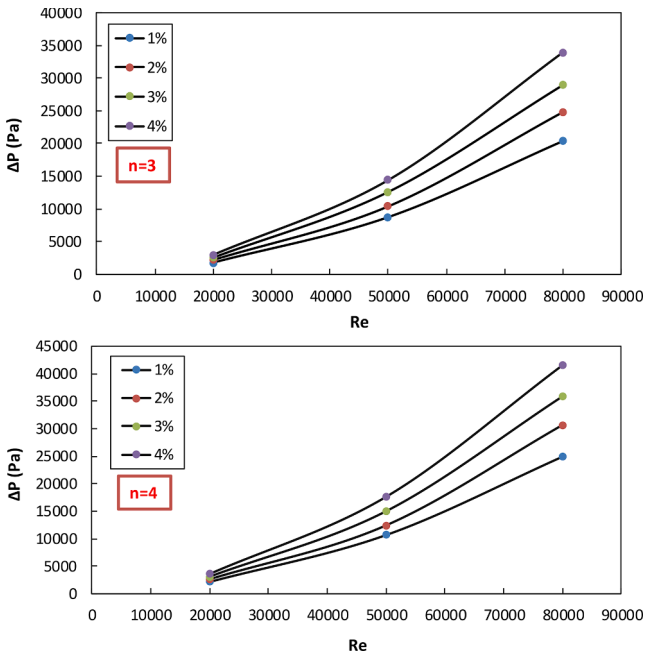


Fig. 6. ΔP inside the tube with three- and four-channel twisted tape containing nanofluid with different volume percentages at various Reynolds numbers.

2216000, and 2695000. Since no noteworthy changes could be seen in the findings, the mesh with 2,216,000 elements is designated as the main mesh to diminish the computational volume (Table 4).

Verification

To ensure the accuracy of numerical results, they must be verified with valid experimental or numerical data. The simulated model proposed by Mwesigye et al. [50] is first examined to validate the present numerical work. They evaluated the RHT in a parabolic collector's absorber tube with a conventional twisted tape. First, the absorber tube having some typical twisted tape with dimensional characteristics and boundary conditions is simulated and analyzed according to Mwesigye et al. [50]. The Nusselt number at different Reynolds numbers is displayed in Fig. 2, indicating a good agreement between the obtained results. Thus, the accuracy of the present results is ensured.

Results and discussion

In this part of the paper, the numerical results of the present

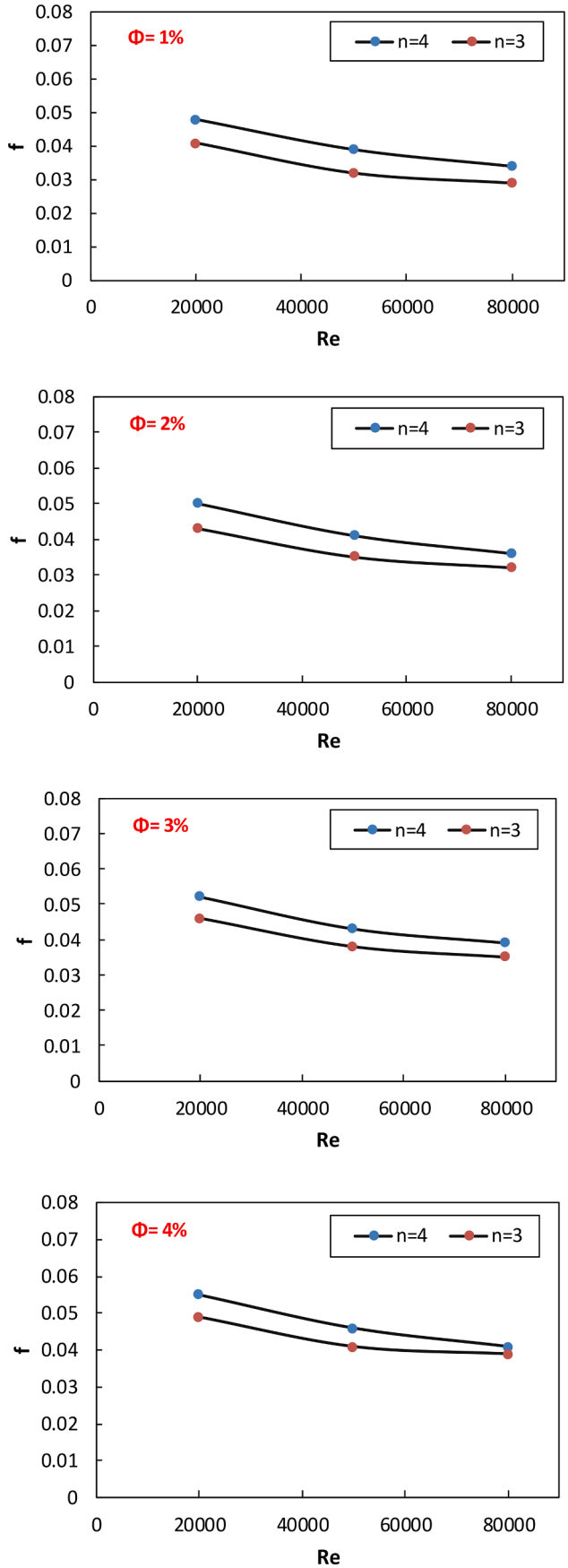


Fig. 7. Friction factor in three- and four-channel twisted tape for dissimilar volume percentages at various Reynolds numbers.

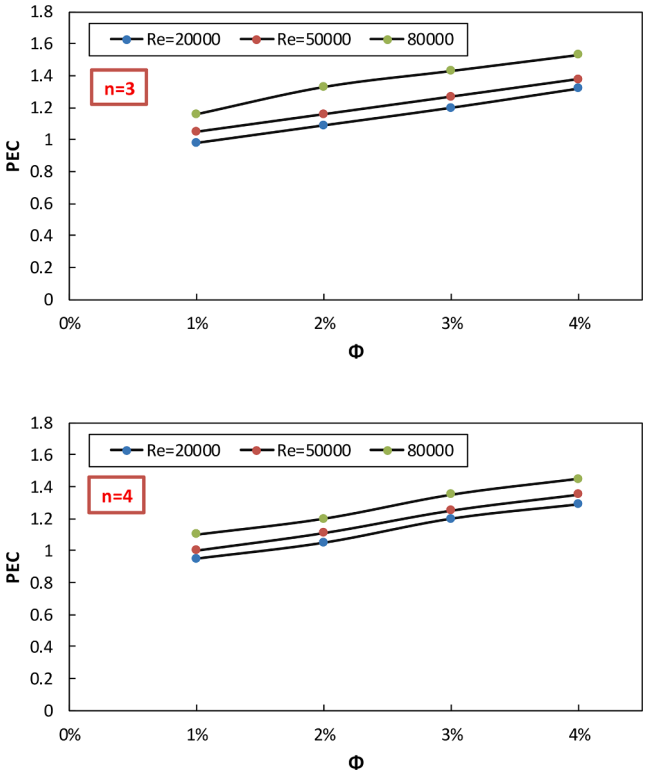


Fig. 8. PEC for three- and four-channel twisted tape for dissimilar volume percentages at various Reynolds numbers.

simulations are analyzed. The parameters studied in this research study included Nusselt number (Nu), pressure drop (ΔP), friction factor (f), PEC, and exergy and energy efficiencies of a linear parabolic collector with absorber tube which was equipped with twisted tape when water-CuO nanofluid with different volume percentages (∅ = 1%, 2%, 3%, 4%) were presented. The results are assessed at three Reynolds numbers of 20,000, 50,000, and 80,000 to obtain the model with the best performance.

Fig. 3 represents the outlet velocity contours in the absorber tube with no twisted tape using water as working fluid and the absorber tube with multichannel twisted tape when copper oxide nanoparticles were present. As shown, in the three-channel twisted tape (n = 3) the flow is divided into three, and in the four-channel twisted tape (n = 4) the flow is divided into four separate parts. A swirling flow is observed in each part, and the velocity around the twisted tape is lower for the two models.

Fig. 4 represents the fluid temperature distribution in an absorber tube without a twisted tape for water and an absorber tube with a multichannel twisted tape for copper oxide nanoparticles with different volume percentages at Reynolds number of 80000. Based on the boundary conditions, the outlet fluid temperature is enhanced due to the uniform heat flux applied to the absorber tube. As shown, the presence of twisted tape intensifies the heat transfer surface, leading to an increment in the fluid outlet temperature compared to the pipe without twisted tape. In addition, the four-channel twisted tape increases the outlet temperature due to its higher contact surface with the fluid. Also, in both models, the temperature of the outlet fluid increases by enhancing the volume percentage of nanoparticles in water. For example, in a tube with a four-channel twisted tape with a 4% volume fraction of nanoparticles, the outlet temperature reaches 48 °C.

The values of Nusselt number for absorber tube with multichannel twisted tape in the presence of nanofluid with different volume percentages are shown in Fig. 5. As shown, the Nusselt number is enhanced with the Reynolds number. Increasing the volume fraction of nanoparticles leads to an increase in thermal conductivity, which increases the RHT and, as a result, increases the average Nusselt number. Also, an increment in the volume percentage of nanoparticles improves the conductive heat transfer, thus intensifying the Nusselt number. The maximum Nusselt number is related to the volume fraction of 4% at Reynolds number of 80,000, equal to 54.7.

The ΔP change in three- and four-channel twisted tape in the presence of nanofluid with diverse volume fractions is shown in Fig. 6. Nanoparticles dispersion in the base fluid can enhance fluid viscosity, increasing nanofluid ΔP. Hence, nanofluid has the highest ΔP when ∅ = 4% for both models of twisted tape. Also, the higher the Reynolds number, the higher the nanofluid velocity, which intensifies the ΔP. On the other hand, due to the geometry of twisted tapes and the fluid facing more obstacles to pass through the pipe, the ΔP of the four-channel twisted tape is about 20% higher than the three-channel one.

The velocity and the friction factor are contrariwise related. Consequently, the friction factor decreases with the Reynolds number. Furthermore, the friction factor is increased by increasing the volume percentage of particles in the base fluid due to the increase in density and viscosity. In both twisted tape models, the volume fraction of 4% and Reynolds number of 80,000 lead to the maximum ΔP.

Fig. 7 compares the friction factor in three- and four-channel twisted tape for different volume percentages. As expected, for all cases, the friction factor of the four-channel twisted tape is more when compared to that obtained for the three-channel twisted tape.

Higher PEC means better thermo-hydraulic performance. The absorber tube with three-channel twisted tape has a higher thermal performance than the absorber tube with four-channel twisted tape. By enhancing the nanoparticles volume percentage in the base fluid, PEC is enhanced. Also, as the Reynolds number is intensified, the PEC is increased. According to Fig. 8, the maximal amount of PEC occurs at the Reynolds number of 80,000 for three-channel twisted tape when ∅ = 4%, which is equal to 1.5. This value indicates a 60% increase compared to the performance of the absorber tube with the same working fluid and without twisted tape. As ∅ increases, the amount of PEC enhances due to the increase in RHT.

As mentioned, the maximum PEC occurs for the three-channel twisted tape at Reynolds number of 80,000 and ∅ = 4%. Fig. 9 shows the streamlines and pressure distribution for some tubes having a three-channel twisted tape in nanofluid with ∅ = 4%.

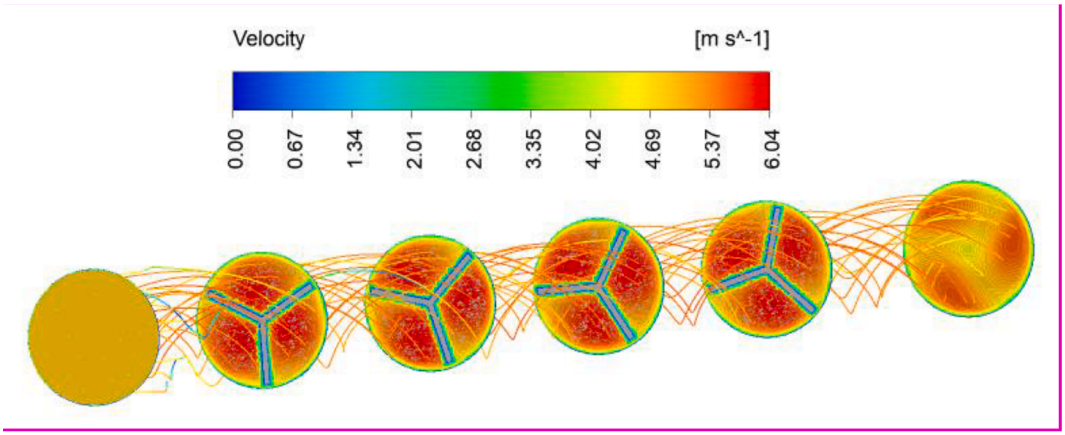
A SC's thermal efficiency can be defined by Eq. (10) is the most important parameter for assessing a SC. Fig. 10 represents the changes in thermal efficiency according to Reynolds number for some SCs with a tube including a three-channel twisted tape in nanofluid with dissimilar volume fractions. As observed, the nanofluid thermal conductivity is improved with the volume percentage, leading to more solar radiation absorption through the nanofluid. Hence, more thermal energy is generated. Meanwhile, at Reynolds number of 80,000, the nanofluid with ∅ = 4% and thermal efficiency of 26% has the best performance. This is because the mass flow rate increases with the enhancement of nanoparticles volume percentage, and the velocity is decreased.

Based on Eq. (11), an increment in the concentration of working fluid can improve the collector's energy efficiency so that the nanofluid with ∅ = 4% has the maximum exergy efficiency. Furthermore, due to the higher HRT in the Reynolds number of 80,000, heat efficiency also increases.

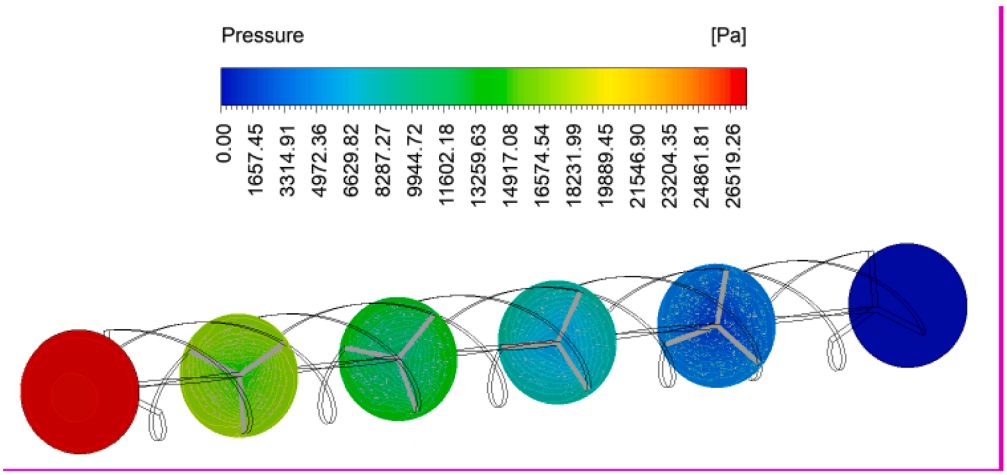
Conclusions

The present study analyzed the absorber tube of some parabolic SC which was equipped with three- and four-channel twisted tape and water-copper oxide (CuO) nanofluid.

- The use of nanofluid enhanced the HRT and ΔP in the tube, so with the rise of the nanofluid concentration, the Nusselt number and ΔP



(a)



(b)

Fig. 9. Streamlines (a), and pressure distribution (b) in a pipe with a three-channel twisted tape for a volume percentage of 4% and Re = 80000.

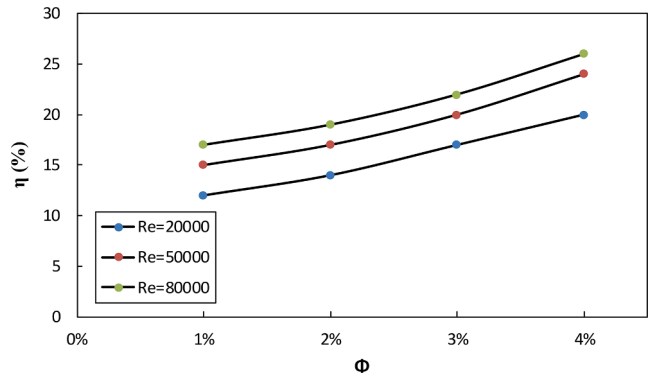


Fig. 10. SC efficiency according to Reynolds number in the presence of nanofluid with different volume percentages.

were increased. Also, the value of the Nusselt number was enhanced with the Reynolds number for all cases.

- The use of multichannel twisted tape intensified the HRT (Nusselt number) in comparison of the tube without twisted tape.
- The four-channel twisted tape caused more ΔP in the flow than the three-channel twisted tape.
- The lower friction factor in the three-channel twisted tape made the PEC of this turbulator higher than the four-channel twisted tape.
- The maximal value of PEC of three-channel twisted tape occurred at Reynolds number of 80,000 and ∅ = 4%.
- The obtained results revealed that the SC's efficiency could be promoted by applying nanoparticles suspended in the base fluid.
- The best performance was obtained for the nanofluid with ∅ = 4%. In addition, the use of nanofluid intensified the exergy efficiency of the collector.

CRediT authorship contribution statement

Jawed Mustafa: Supervision, Writing – original draft. **Saeed Alqaed:** Validation, Writing – original draft. **Mohsen Sharifpur:** Conceptualization, Writing – review & editing. **Shahid Husain:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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