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Numerical investigation of turbulent CuO-water nanofluid inside heat exchanger enhanced with Double V-cut Twisted Tapes

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Abstract

This numerical investigation aims to study the turbulent characteristics and thermal enhancement parameter of CuO-water nanofluids through heat exchangers enhanced with double V-cut twisted tapes. The twist ratio of the twisted tapes is 5.25, and the cut ratio (b/c) is varied from 0 (conventional twisted tape) to 1.8. The Reynolds number is in the range of 5,000 to 15,000 and nanoparticles volume fraction is in the range of $0 < \phi < 1.5\%$. The flow is fully turbulent and (RNG) $k - \epsilon$ turbulent model is used for the numerical analysis. The results reveal that strong turbulent kinetic energy and additional vortex flow through the cuts of the modified twisted tapes is the main reason for better fluid mixing and heat transfer enhancement. The heat transfer enhances about 14.5% for the case of $\phi = 1.5\%$. Furthermore, using double V-cut twisted tapes improves the Nusselt number of the nanofluid flow inside heat exchangers about 138% compared to conventional twisted tape without cuts. The maximum value of the thermal performance $(\eta = 1.99)$ is achieved by using nanofluid with $\phi = 1.5\%$ and b/c=1.8 at Re=5000.

Keywords: CuO-water Nanofluid; Double V- cut twisted tape; CFD; Heat transfer; Turbulent flow

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1. Introduction

Heat transfer augmentation is essential in the design of heat exchangers and other thermal systems. There are various techniques for enhancing the heat transfer rate and thermal efficiency of these thermal systems, which also decrease the size of the heat exchangers. The following methods are popular in recent years because of simple installation and low costs: (i) using nanofluids as the working fluid [1, 2], (ii) using twisted tapes (TTs) [3-6], (iii) conical rings [7, 8], grooved surfaces [9], hollow cylinders [10], and (iv) combined use of vortex generators and nanofluids [11-13].

Using nanofluids for heat transfer improvement inside heat exchangers is a popular method that improves the thermal performance factor due to the improved fluid properties compared to pure water [14]. The recent review articles of Mahian et al. [15, 16] regarding the main achievements in the field of nanofluids indicated that various numerical simulations have been performed in the past two decades on convective heat transfer enhancement inside different thermal systems. It was concluded that Brownian motions and thermo-phoretic forces of nanoparticles play a vital role to balance the drag force and heat transfer augmentation. Selimefendigil and Oztop [17] examined the heat transfer enhancement of nanofluids between coaxial cylinders by rotating the inner cylinder. Their numerical results revealed that heat transfer could be enhanced by up to 25.3% by using nanofluids with $\phi = 4\%$. Yahiaoui et al. [18] examined the Nusselt number augmentation in a cavity with wavy walls by using nanofluid. Their numerical simulation revealed that heat transfer significantly improved by using nanofluids instead of pure water. Nakhchi and Esfahani [19] investigated the influence of cross-cut twisted tapes on turbulent flow inside heat exchangers. Their findings stated that the amount of Nusselt rises up to 23%, by raising the volume concentration of Cu nanoparticles up to 1.5%. Besides, the thermal performance factor increases up to 46% by using Cu-water nanofluid instead of the pure water. Hatami [20] employed TiO_2 and Al_2O_3-water nanofluids for heat transfer enhancement in rectangular cavities equipped with two hot fins. The numerical simulations indicated that the average Nusselt number for the TiO_2 nanoparticles is superior to Al_2O_3 nanoparticles in the range of $0.03 < \phi < 0.06$. Shi et al. [21] numerically analyzed the nanofluids flow characteristics inside a quarter cylinder channel by considering the shapes of the nanoparticles. They used the KKL model for estimating the dynamic viscosity of the nanofluid. Their analysis indicated that platelet nanoparticles cause the best Nusselt number enhancement. Besides, adding CuO nanoparticles to water has significant influence on the heat transfer increment.

Using twisted tapes (TTs) is a popular method for heat transfer augmentation inside heat exchanger tubes and other thermal systems [22-24]. Several kinds of TTs are employed for heat transfer enhancement in recent years. Eiamsa-Ard et al. [25] examined the Nusselt number and thermal performance inside a heat exchanger tube enhanced with short length TTs. Their experimental analysis indicated that Nusselt number and friction loss decreases up to 14% and 9.5%, respectively by using short-length TTs instead of conventional ones. He et al. [26] employed cross hollow TT inside heat exchangers to investigate thermal performance of the system. The results indicated that heat transfer can be enhanced up to 5.7% in comparison with plain tubes. Piriyarungrod et al. [27] studied the effects of multiple TTs on thermal performance augmentation of heat exchangers. The results showed that using six small twisted tapes around a big twisted tape at the center of the tube perform better than the others due to the better fluid mixing and recirculation flow. Using twisted tapes with cuts is a novel technique for heat transfer augmentation inside heat exchanger tubes because of stronger fluid mixing among the tube center and the pipe walls in the presence of cut edges [28]. Murugesan et al. [29] investigated the

Nu number and friction loss inside heat exchangers equipped with square-cut twisted tapes. They concluded that the square-cut TTs with y/w=2.0 performed best among the tested geometries and the maximum value of η was 1.25 in their analysis. Salam et al. [30] observed that by employing twisted tapes with rectangular cuts, the average Nusselt number enhances up to 290% compared to a tube without inserts. Murugesan et al. [31] performed an experimental investigation on the thermal performance and friction loss in a pipe enhanced with trapezoidal -cut twisted tapes. Their analysis suggested that the rate of heat transfer and friction loss enhanced with replacing conventional twisted tapes with improved ones. Other investigations on V-cut TT [32], U-cut TT and wing-cut TT [33] demonstrated enhanced heat transfer compared to twisted tapes without cuts. Nakhchi and Esfahani [19] numerically examined the thermal performance inside tubes enhanced with TTs with cross-cuts. The effects of the cut ratio on the thermal performance parameter were examined. Their simulations indicated that the cross-cut twisted tapes with the cut ratio of 0.9 and the width ratio of 2.5 performed best between test cases. In another numerical study, Nakhchi and Esfahani [34] analyzed the heat transfer inside tubes fitted with rectangular-cut TTs with a single cut and double cuts on the edges. The findings showed that the Nu number for the turbulent flow around the double cut TTs was higher than single cut TT. The effects of double V-cut TT (DVCTT) on the thermal enhancement parameter of the heat exchangers were numerically investigated by Nakhchi and Esfahani [35]. The simulations showed that the thermal performance could be increased up to 1.83 by employing DVCTT with cut ratio of b/c = 1.8 and twist ratio of 5.25 at Re=5000. This indicates that the thermal enhancement parameter of DVCTTs is much better than the other modified twisted tapes inside heat exchanger tubes under turbulent fluid flow conditions.

The combined use of the twisted tapes and nanofluids is a novel method to augment the thermal performance factor of the laminar and turbulent flows inside heat exchangers [36]. Sundar and Sharma [37] experimentally investigated the combined effects of nanofluid and twisted tapes inside heat exchanger tubes. The Reynolds number was in the range of 1000-22000 in their study. They concluded that the Nu number of the nanofluids flow with volume concentration of 0.5% and twist ratio of 5 is 33.51% higher compared with the turbulent water flow in a plain tube. Wongcharee and Eiamsa-Ard [38] employed TTs with alternate axis and CuO-water nanofluid in a heat exchanger tube under laminar flow conditions (900<Re<1990). Their experimental results revealed that combined use of nanofluid flows and modified TTs augments the heat transfer about 13.8 times of pure water flow inside a plain tube.

The above literature review indicates that using DVCTTs can considerably augment the heat transfer rate in heat exchangers. However, the effects of nanoparticles on turbulent heat transfer inside heat exchangers fitted with these types of modified vortex generators are not investigated. In the present study, turbulent flow characteristics and thermal performance enhancement of CuO-water nanofluid flows inside pipes equipped with double V-cut twisted tapes with different cut ratios are investigated by using the CFD method. The Re number $\left(\mathrm{Re}=\rho u D / \mu\right)$ is within the range of $5,000<\mathrm{Re}<15,000$, and the CuO nanoparticles volume concentration is in the range of 0-1.5%. The effects of nanoparticles on flow streamlines, turbulent kinetic energy, velocity and temperature contours are also discussed by using numerical simulations.

2. Physical description

The geometry of the heat exchanger tube equipped with DVCTT is presented in Fig. 1. It includes a circular pipe with diameter $\left(D\right)$ of 25mm and length $\left(L\right)$ of 840mm. The heat exchanger tube is enhanced with modified twisted tapes. The design parameters of the DVCTT are tape thickness $(\delta = 2mm)$, twist pitch $(w = 20mm)$ and twist width $(y = 105mm)$. CuO–water nanofluid is chosen as the effective fluid. The nanofluid flow is fully developed, incompressible and steady. The inlet temperature of the nanofluid (T_{in}) is uniform at 300*K*, while the wall temperature (T_w) is kept uniform at 350*K* and no-slip boundary condition is implemented on the twisted tapes and the pipe surface. The velocity of the nanofluid at the tube inlet in uniform and the Reynolds number (Re) differs from 5,000 to 15,000 in the present study. Water and CuO nanoparticles are considered to be in thermal equilibrium. The thermophysical properties of CuO nanoparticles are: $C_p = 540 J/kg.K$, $\rho_p = 6500 kg/m^3$ and $k_p = 18\ W/m.K$. Table 1 shows the geometric parameters and schematic view of the DVCTTs used in this study. The cut ratio (b/c) is varied from 0 (conventional TT) to 1.8.

3. Mathematical Formulations

The governing of the steady-state turbulent fluid flow for the current study can be expressed as [39]:

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

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

$$\frac{\partial}{\partial x_j}(\rho u_i T) = \frac{\partial}{\partial x_i}\left\{\frac{\partial T}{\partial x_i}\left[\frac{\mu_t}{\Pr_t} + \frac{\mu}{\Pr} + \right]\right\} \tag{3}$$

The turbulent viscosity (μ_t) and Reynolds stresses $\left(\rho \overline{u_i' u_j'}\right)$ terms can be defined as [34]:

$$-\rho\overline{u_i{}'u_j{}'} = -\frac{2}{3}\rho k\,\delta_{ij} + \mu_t\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] - \frac{2}{3}\mu_t\frac{\partial u_k}{\partial x_k}\delta_{ij} \tag{4}$$

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \tag{5}$$

k and ϵ equations based on the RANS model are defined as [40]:

$$\frac{\partial}{\partial x_i}(\rho u_i k) = \frac{\partial}{\partial x_j}\left\{\left[\frac{\mu_t}{\sigma_k} + \mu\right]\frac{\partial k}{\partial x_j}\right\} + G_k - \rho\epsilon \tag{6}$$

$$\frac{\partial}{\partial x_i}(\rho u_i \epsilon) = \frac{\partial}{\partial x_j}\left\{\left[\frac{\mu_t}{\sigma_\epsilon} + \mu\right]\frac{\partial \epsilon}{\partial x_j}\right\} + \frac{\epsilon}{k}\left[C_{1\epsilon}G_k - \rho C_{2\epsilon}\epsilon\right] \tag{7}$$

where $G_k = -\rho\overline{u_i{}'u_j{}'}\frac{\partial u_j}{\partial x_i}$. The constants of the turbulence model are assumed to be [41]:

$$C_{1\epsilon} = 1.42,\ C_{2\epsilon} = 1.68,\ C_\mu = 0.084,\ \Pr_t = 0.85,\ \sigma_k = 1,\ \sigma_\epsilon = 1.3 \tag{8}$$

The effective density, specific heat and viscosity of CuO-water nanofluids for different nanoparticle volume fractions $(0 < \phi < 1.5\%)$ can be obtained by using the following equations [42, 7]:

$$\rho_{eff} = (1-\phi)\rho_f + \phi\rho_p \tag{9}$$

$$C_{eff} = \frac{(1-\phi)\rho_f C_f + \phi\rho_p C_p}{\rho_{eff}} \tag{10}$$

$$\mu_{eff} = \frac{\mu_f}{(1-\phi)^{2.5}} \tag{11}$$

where ϕ, f and p are volume concentration of nanoparticles, water and CuO nanoparticles, respectively. The Thermal conductivity of nanofluid can be calculated as [43]:

$$\frac{k_{eff}}{k_f} = \frac{k_p + 2k_f + 2\phi\left(k_p - k_f\right)}{k_p + 2k_f - \phi\left(k_p - k_f\right)} \tag{12}$$

To analyze the heat transfer, pressure loss and the thermal efficiency of the turbulent flows through heat exchangers equipped with DVCTTs, the following equations are employed in the present study [8]:

$$\mathrm{Re} = \frac{\rho u D}{\mu} \tag{13}$$

$$Nu = \frac{hD}{k} \tag{14}$$

$$f = \frac{2D}{L}\frac{\Delta p}{\rho u^2} \tag{15}$$

$$\eta = \frac{\left(Nu / Nu_s\right)}{\left(f / f_s\right)^{1/3}} \tag{16}$$

3.1. Computational method

The computational domain used in the numerical simulation is shown in Fig. 2. As can be seen, an inflated mesh is employed near the walls to capture the laminar viscous sub-layer effects of the turbulent fluid flow. y^+ values remain in the range of 1-3 in the whole domain. The finer mesh is used near the cuts to capture the turbulent kinetic energy and vortex flow in this area.

The numerical simulations for the heat exchanger tube enhanced with DVCTTs are performed by Ansys Fluent 19.1 software by employing the finite volume technique. The momentum and the energy equations are discretized by using the second-order upwind scheme and the SIMPLE algorithm is used for the CFD simulations. Fig. 3 displays a comparison of numerical analysis of four various turbulence models compared with the experimental correlations [44]. As expected, the RNG k-ε turbulence model performs better than the other RANS models and it is selected for further simulations. The convergence criteria for the governing equations (except energy) are less than 10^{-6}, while, for the energy equation is less than 10^{-8}.

3.2. Grid independence study

To guarantee that the numerical findings are independent of the mesh size, a grid independence test is employed. Table 2 shows the Nusselt numbers and friction loss results for various grid numbers. It can be observed that the variations in Nu and f between element number of 1,298,705 and 1,884,396 are 0.2% and 0.7%, respectively. Thus, the grid number of 1,298,705 elements is selected for further simulations of the turbulent flow inside the tubes enhanced by DVCTTs with b/c=1.8 at Re=15000 (extreme condition).

4. Results and discussion

The 3-D flow streamlines of turbulent flow in pipes with and without DVCTTs are depicted in Fig. 4. It is clearly seen that the tube without insert only generates an axial flow. The twisted tape generates swirl flow, which improves the recirculating flows between the walls and the center of the heat exchanger tube. It also should be pointed out that the turbulent flow in the radial direction increases the fluid flow path in the pipe which augments the heat transfer rate.

The effects of TTs on the axial velocity contours of nanofluid flows through heat exchangers tubes are shown in Fig. 5. It should be pointed out that the axial velocity contours are plotted in the fully developed region. The strong axial velocity of the fluid flow near the TTs disrupts the thermal boundary layer and improves the heat transfer between the central region and pipe walls. The results show that recirculation flow near the cut edges can intensify the heat transfer rate because of stronger fluids mixing between the TTs and tube walls.

Fig. 6 shows the effects of cut ratio (b/c) on the turbulent kinetic energy streamlines of the turbulent flows in the circular pipe equipped by conventional and double V-cut TTs in the fully developed region (z=0.64-0.84m). The results show that the turbulence kinetic energy at the cut edges is higher compared to the other areas. This can be a result of additional flow disturbance near the cuts. The results show that the turbulent kinetic energy for b/c=1.8 is higher than conventional TT. The results indicate that stronger recirculation flow is the main physical reason for stronger kinetic energy near the cut edges. Stronger TKE disrupts the thermal BL and intensifies the heat transfer rate due to recirculation flow between the walls and the tube center.

Fig. 7 depicts the turbulent dissipation rate (TDR) contours for the nanofluids flows through a circular pipe and the pipes equipped with conventional and V-cut TTs. The maximum of TDR is mainly near the walls of the twisted tape. The turbulent dissipation rate near the cut edges of the DVCTT is stronger than in other cases. This is because the additional recirculation flows through the cuts of the modified TTs.

Fig. 8 displays the temperature contour of CuO-water nanofluid flows in circular tubes and the tubes enhanced with DVCTTs with different cut ratios. The results show that the nanofluid temperature enhances by using double V-cut TTs with bigger cuts. The additional swirl flow generated near the cuts considerably improves fluid mixing, while the fluid flow inside the plain tube is only in the axial direction. Double V-cut TTs enhance fluid mixing between the tube center and the walls. This indicates that fluid mixing augments by using double V-cut TTs which enhance the turbulence intensity of the flow inside tubes equipped with modified TTs. It should be noted that the recirculating flow and fluid perturbation disrupts the thermal boundary layer and increases the nanofluid temperature in the axial direction. It also should be pointed out the temperature of the nanofluid flow inside a circular tube is considerably lower compared to the tubes fitted with double V-cut TTs.

Fig. 9 shows that the temperature contours of the turbulent flow inside the tubes enhanced with DVCTTs for $\phi = 0 - 1.5\%$ at Re=5000. The results show that the gradient of the temperature near the wall enhances with increasing the volume concentration of the nanoparticles. Temperature gradient enhancement is mainly because of the higher thermal conductivity of nanofluid in comparison with water. The temperature of the turbulent nanofluid flow increases in the axial direction. It can be observed that temperature enhancement for the case of $\phi = 1.5\%$ is the highest among test cases. Decreasing the heat capacity of the Cu-water nanofluid increases the thermal diffusivity of the working fluid $\left(\alpha = k / \rho C_p\right)$ and therefore the heat moves rapidly through the heat exchanger tube due to the fact that the material conducts heat rapidly relative to the volumetrical heat capacity.

The effects of DVCTT on the Nu number of turbulent nanofluid flows with $\phi = 1\%$ inside the heat exchangers are presented in Fig. 10. As anticipated, the Nu number augments with increasing the Re number because of higher turbulent intensity close to the tube walls. The findings indicate that the heat transfer rate for the case of b/c=1.8 is the highest among different cases. The real reason for heat transfer augmentation is stronger swirl flow near the cut edges. It can be deduced that higher fluids attachment between the pipe surface and the center of the tube is another main physical cause for heat transfer augmentation in the existence of DVCTTs. The results show that there is an enhancement of 115.1% in the average Nu number for *b/c*=1.8. The Nusselt number shows maximum enhancement of 73.7, 93.2%, 118.6%, and 138.1% compared to conventional TT for *b/c*=0.6, 1, 1.4 and 1.8, respectively.

The effects of CuO nanoparticles volume concentration on average Nusselt number of the turbulent nanofluids inside tubes equipped with double V-cut TT with b/c=1.8 are presented in Fig. 11. The results indicate that Nusselt number augments up to 14.5% for $\phi = 1.5\%$ compared to pure water. Physically speaking, adding nanoparticles to water modifies the thermophysical properties of that significantly intensify the heat transfer rate inside heat exchangers tubes. The other physical reason for heat transfer augmentation is Brownian motions of the nanoparticles.

Fig. 12 depicts the influence of cut ratio (b/c) on the friction factor of the CuO-water nanofluid flow with $\phi = 1\%$. It can be observed that the f value of nanofluids flow for the case of $b/c = 1.8$ is the highest among different DVCTTs. The main reason for friction loss increment for DVCTTs with larger cuts is stronger recirculation flow near the cut edges which enhances the friction loss inside the heat exchanges. The friction factor shows maximum enhancement of 59.7%, 68.6%, 77.6% and 101.5% in comparison with the conventional TT (b/c=0) for b/c= 0.6, 1, 1.4 and 1.8, respectively.

Fig. 13 shows the influence of CuO nanoparticles volume concentration (ϕ) on friction loss of nanofluids inside the tubes enhanced by DVCTTs. As expected, the friction factor augments by raising the nanoparticles volume concentration from 0 to 1.5%. The main reason for friction loss increment is enhanced effective viscosity of the nanofluid compared to pure water. The results show that at $\phi = 0.5\%$ the friction factor enhances about 1.04-times compared to pure water $(\phi = 0)$ at Re=15000. The increase in the friction factor for $\phi = 1$ percent and 1.5 percent is 1.08 and 1.12 times, respectively, in comparison $\phi = 0\%$ with for b / c=1.8

Fig. 14a depicts the influences of Re number on the thermal enhancement factor of the turbulent nanofluid flow with ϕ=1%, inside heat exchanger tubes enhanced with DVCTTs with different cut ratios. The results show that the thermal enhancement factor decreases considerably with raising the Re number from 5,000 to 15,000. The thermal enhancement factor of the heat exchanger for *b/c*=1.8 is about 81.6% higher than typical twisted tapes (*b/c*=0) when Re increased from 5,000 to 15000. Fig. 14b displays the effects of (ϕ) on the thermal performance factor. It can be deduced that η enhances about 8.5% by enhancing ϕ from 0% to 1.5 %. The maximum thermal enhancement factor of 1.99 could be reached by employing DVCTTs with ϕ =1.5% and $b/c=1.8$ at the Re=5000.

5. Conclusions

This study deals with the numerical investigation of turbulent nanofluid flow heat transfer inside heat exchangers fitted with DVCTTs with various cut ratios. The working fluid is CuO-water with nanoparticles volume concentration of $(0<\phi<1.5\%)$ and 5,000<Re<15,000. The main conclusions of this study are:

1. The additional recirculation flow near the cut edges of DVCTTs significantly improves the heat transfer rate of the nanofluid flow. This is due to thermal boundary layer disruption and stronger swirl flow inside the heat exchangers in the presence of DVCTTs. Modified TTs with deeper cuts (b/c=1.8) improve the fluid mixing and thermal performance much better than the other cases.
2. The Nusselt number and friction factor enhance with increasing ϕ from 0 to 1.5%. The heat transfer increases up to 14.5% for the case of $\phi=1.5\%$ compared to pure water. The friction loss for nanoparticles volume concentration of 1.5% is 1.08-times and 1.12-times, respectively, in comparison with $\phi=0$. Decreasing the heat capacity of the nanofluid

increases the thermal diffusivity and therefore the heat moves rapidly through the heat exchanger tube.

3. The Nusselt number augments 73.7, 93.2%, 118.6%, and 138.1% as compared to the conventional TTs for *b/c*=0.6, 1, 1.4 and 1.8, respectively.
4. The maximum thermal enhancement parameter (η) of 1.99 could be reached by using DVCTTs with ϕ=1.5% and $b/c=1.8$ at the Re=5,000.

Acknowledgment

This research is financially supported by the Ferdowsi University of Mashhad under contract No. 48676.

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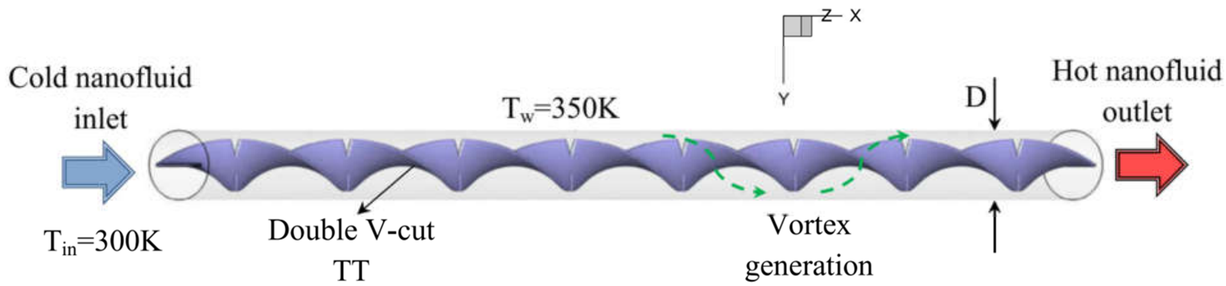
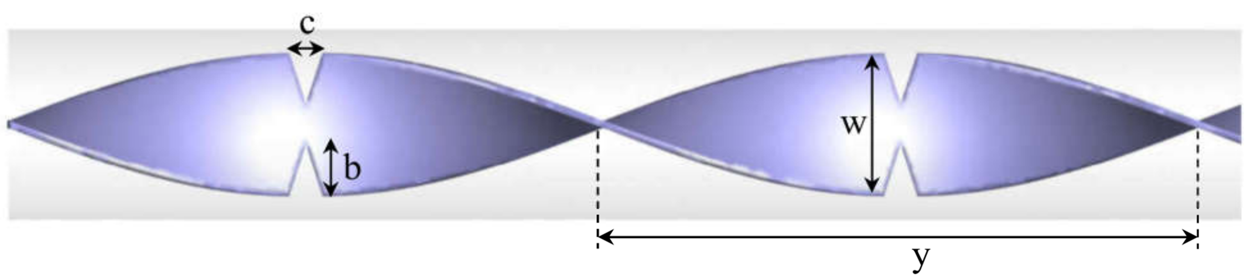


a) Full scale



b) Detailed view of double V-cut TT

Figure 1 Schematic view of the heat exchanger tube fitted with double V-cut TT

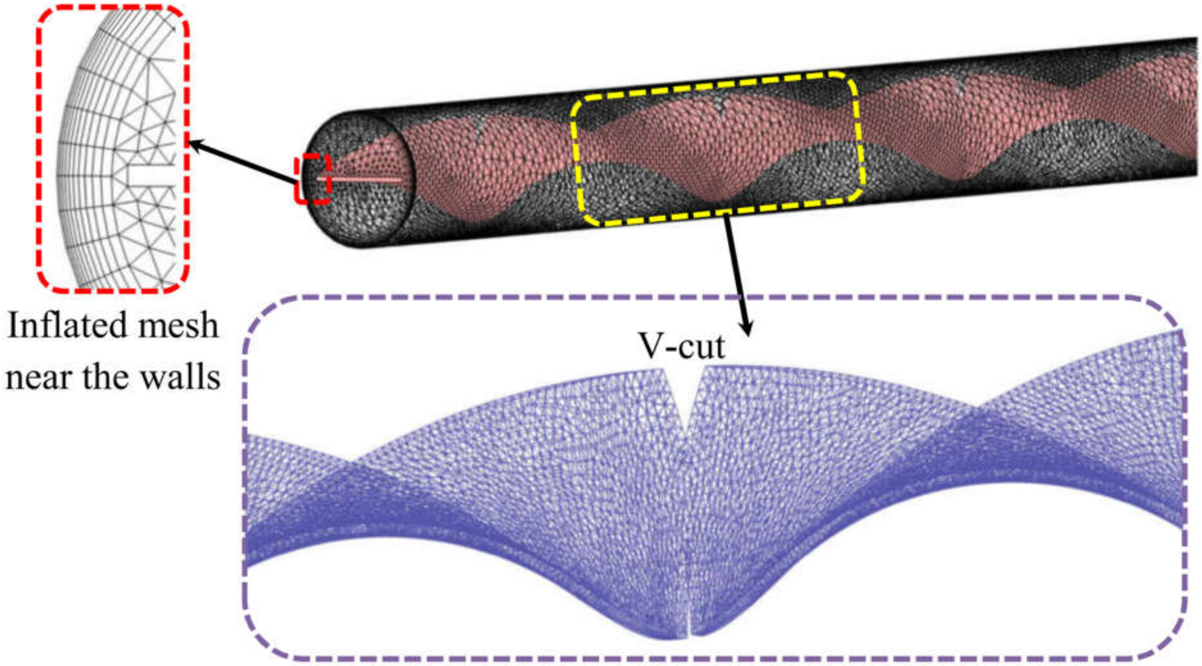


Figure 2 Computational domain mesh of the heat exchanger tube fitted with double V-cut TT (b/c=1/4)

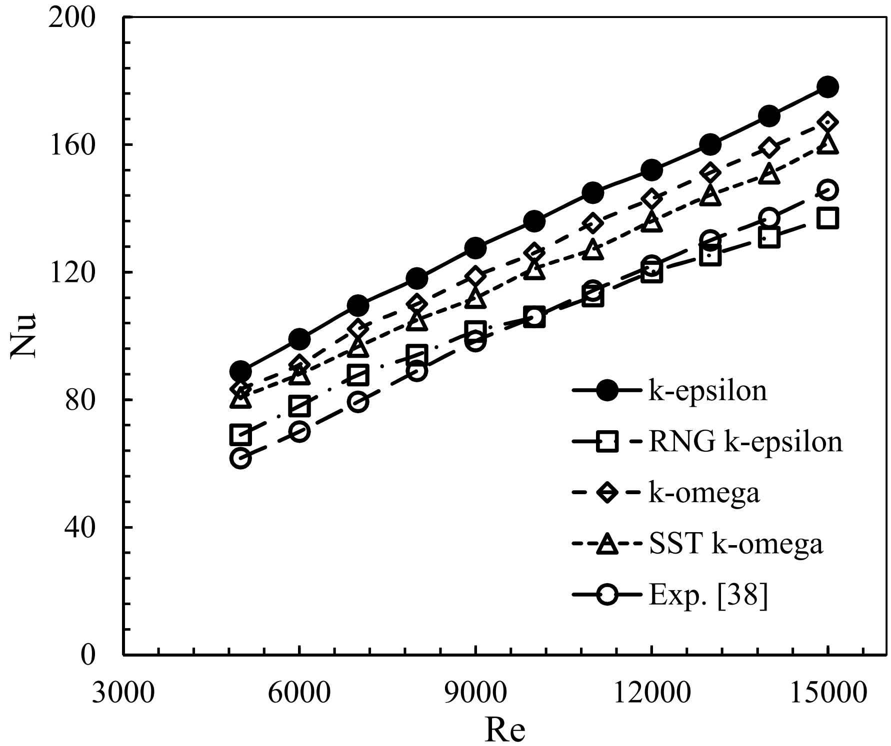
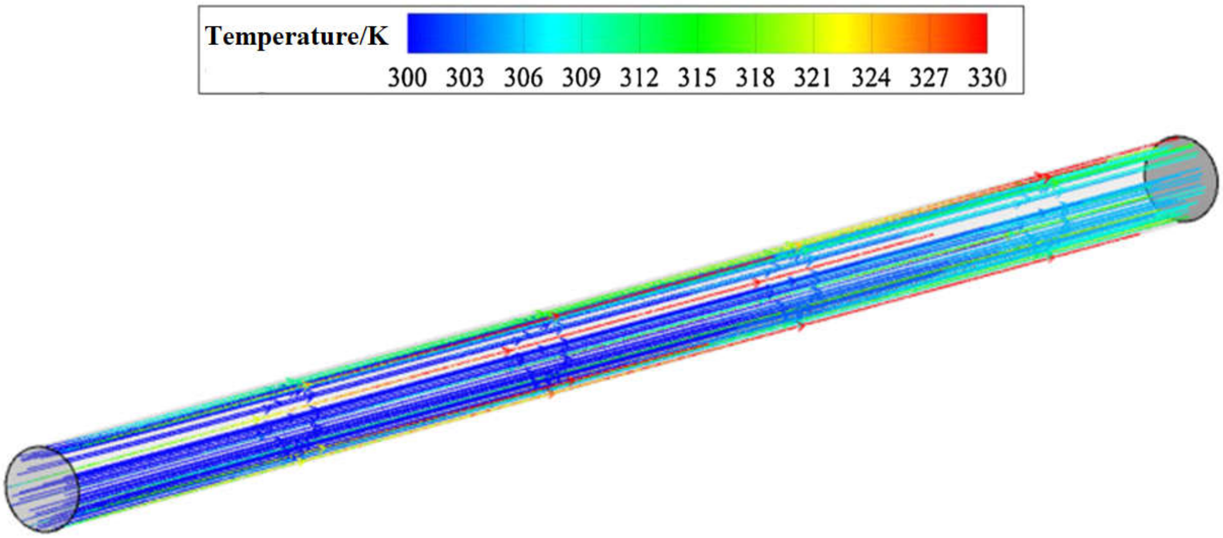
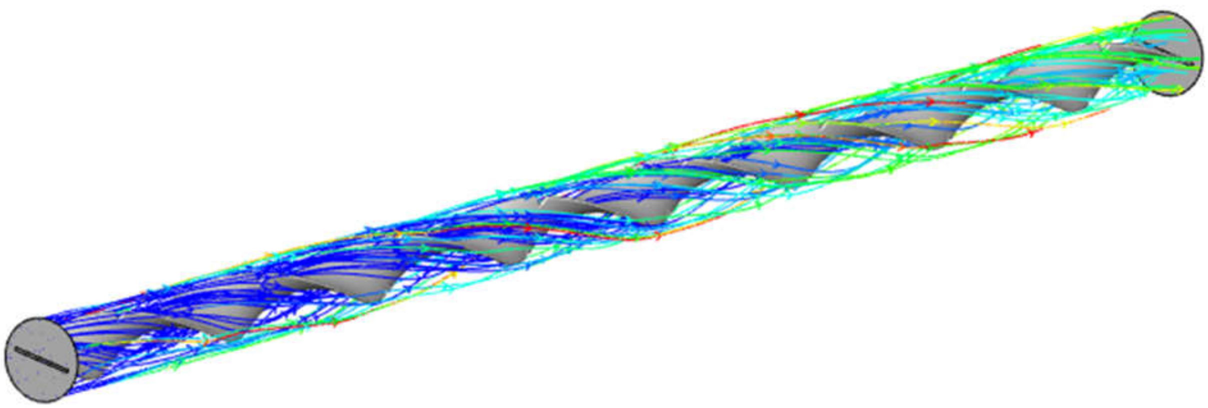


Figure 3 Validation of 4 different turbulent models with experimental results [44] for conventional TT (y/w=2)

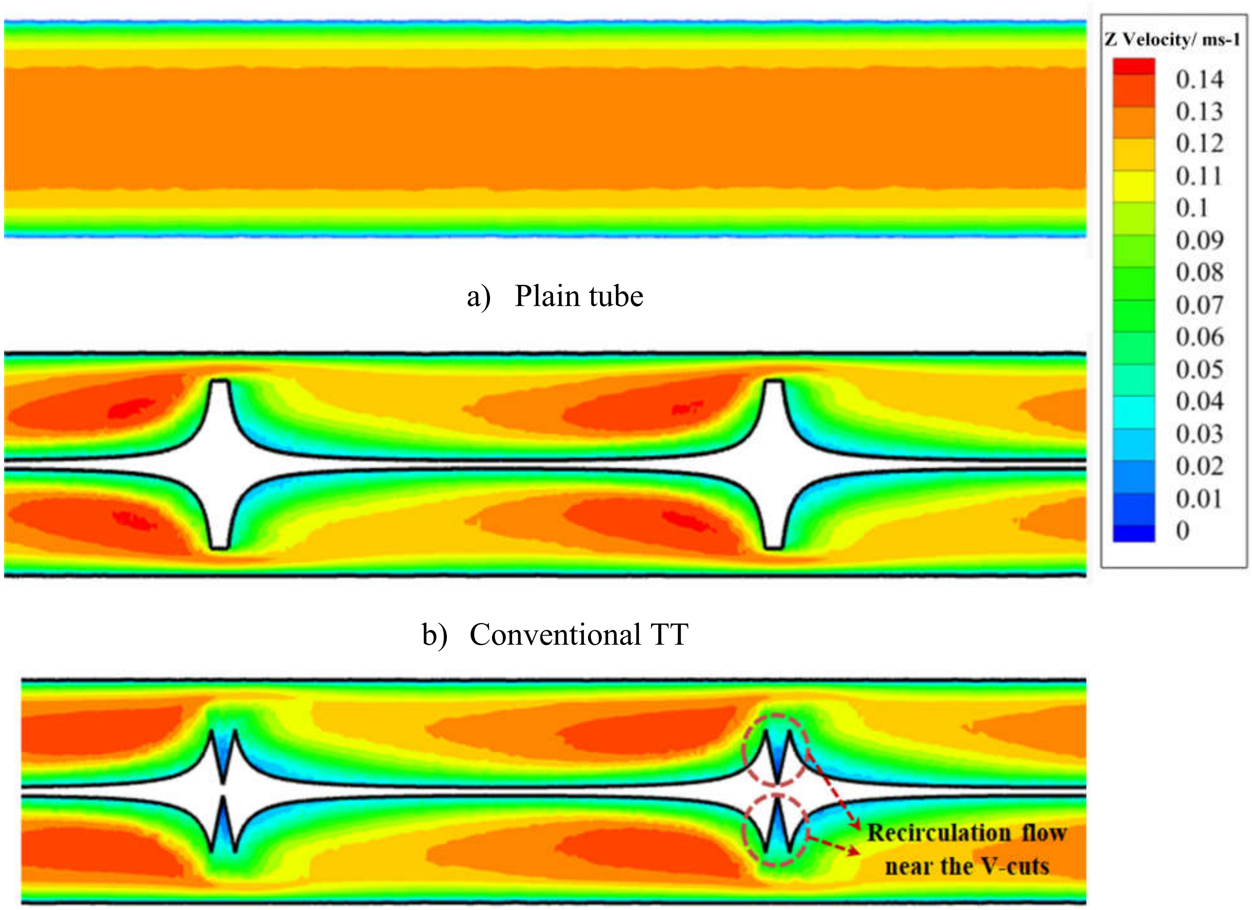


a) Plain tube



b) DVCTT (b/c=1)

Figure 4 Flow streamlines of the turbulent nanofluid flow inside circular tube and the tube fitted with DVCTT at $\mathrm{Re} = 5000$

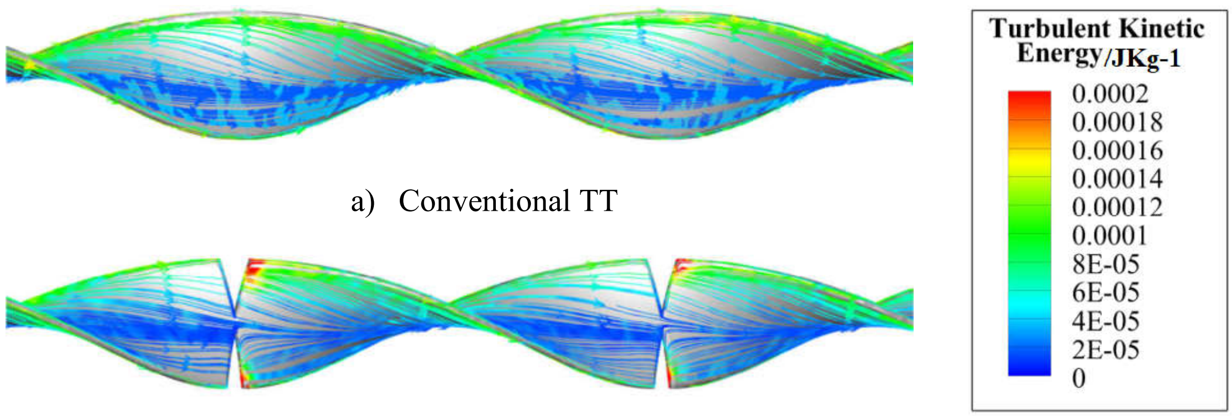


a) Plain tube

b) Conventional TT

c) DVCTT (b/c=1.8)

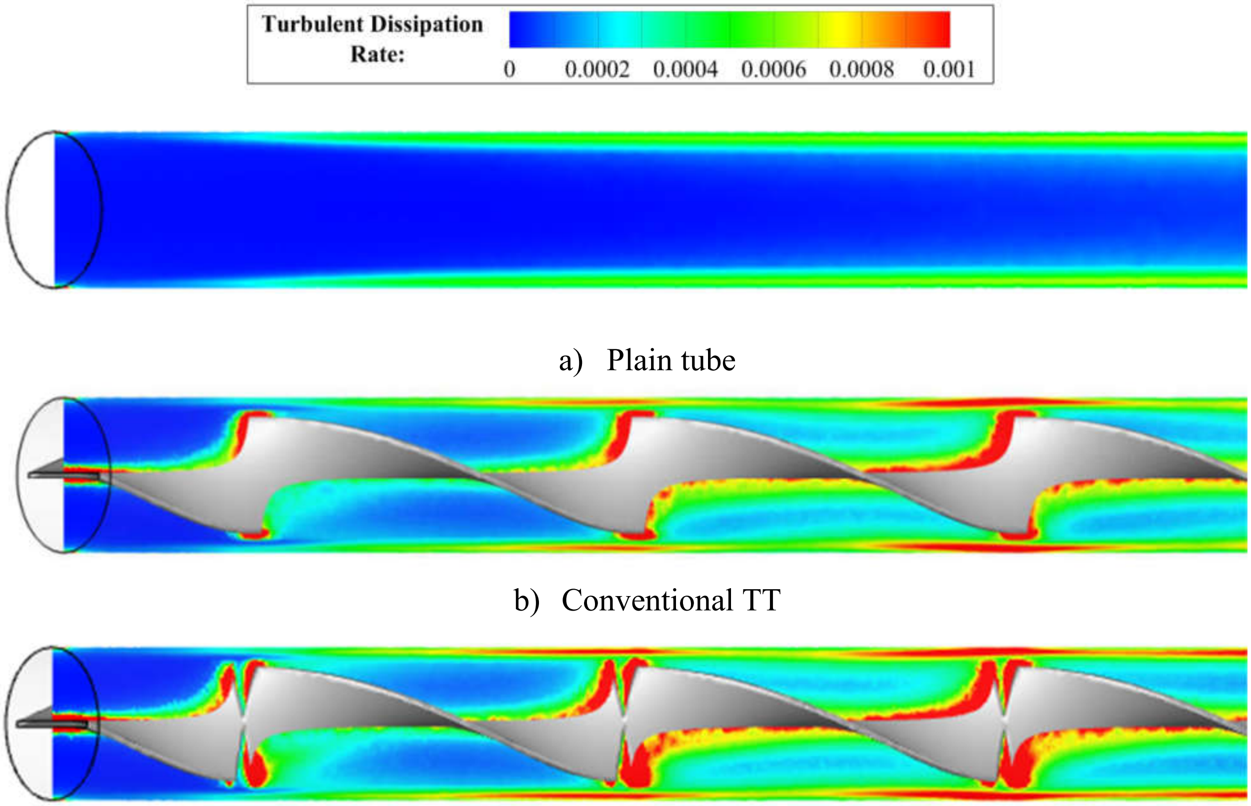
Figure 5 Axial velocity contours of nanofluid flow inside heat exchanger tube at Re=5000 and $\phi = 1\%$.



a) Conventional TT

b) Double V-cut TT (b/c=1.8)

Figure 6 Surface streamlines of turbulent kinetic energy on the twisted tape surface at $Re = 5000$.



a) Plain tube

b) Conventional TT

c) b/c=1.8

Figure 7 turbulent dissipation rate contours at $\mathrm{Re} = 5000$.

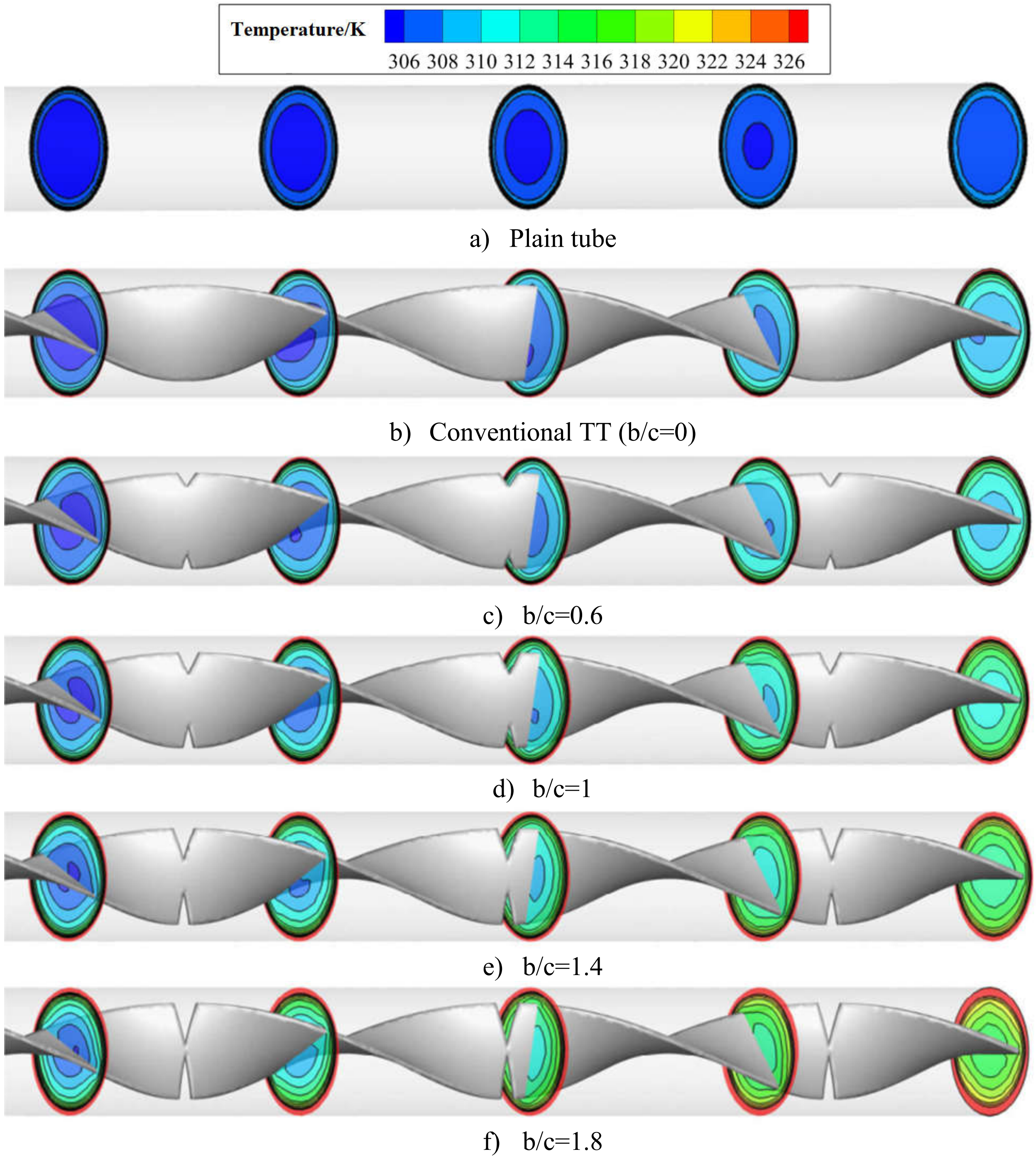
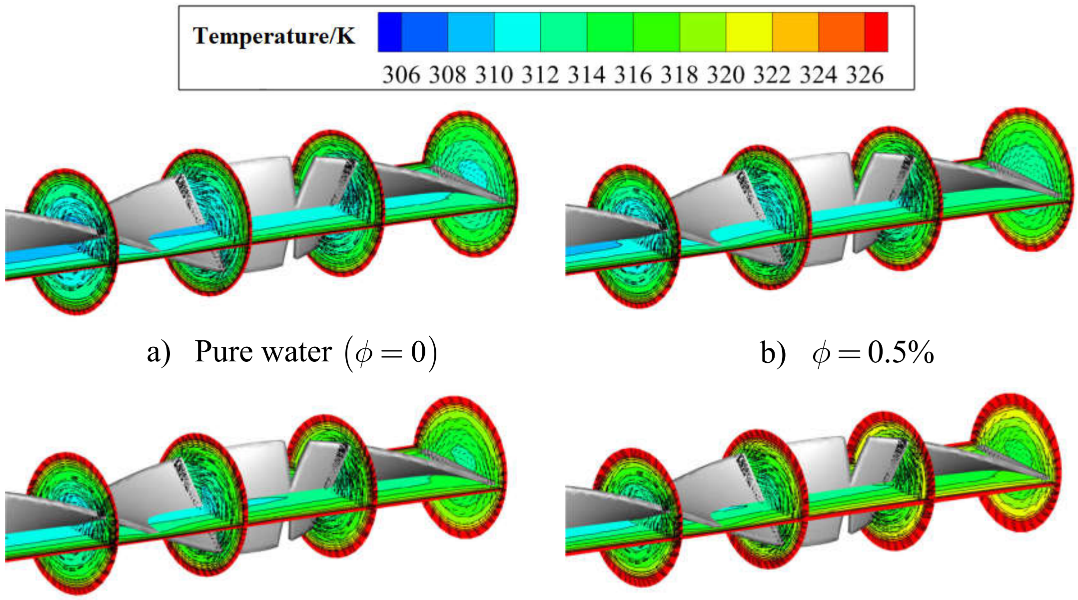


Figure 8 The effect of cut ratio (b/c) on temperature contours of nanofluid flow inside heat exchanger tubes at Re=5000



a) Pure water $(\phi = 0)$ b) $\phi = 0.5\%$

c) $\phi = 1\%$ d) $\phi = 1.5\%$

Figure 9 Effect of nanoparticle volume fraction on temperature contours for $\mathrm{Re} = 6000$ and $b/c = 1.8$.

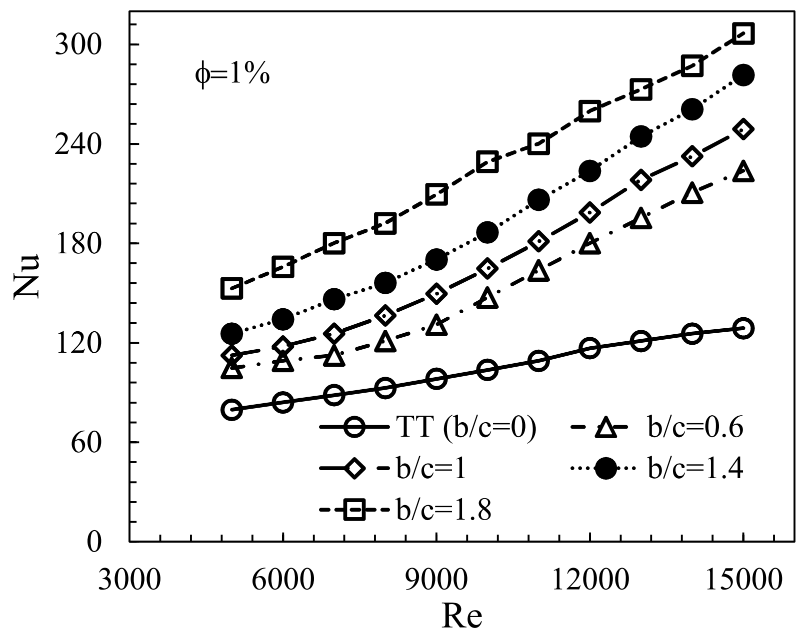


Figure 10 The effects of cut ratio on the average Nusselt number of nanofluid flow with $\phi = 1\%$

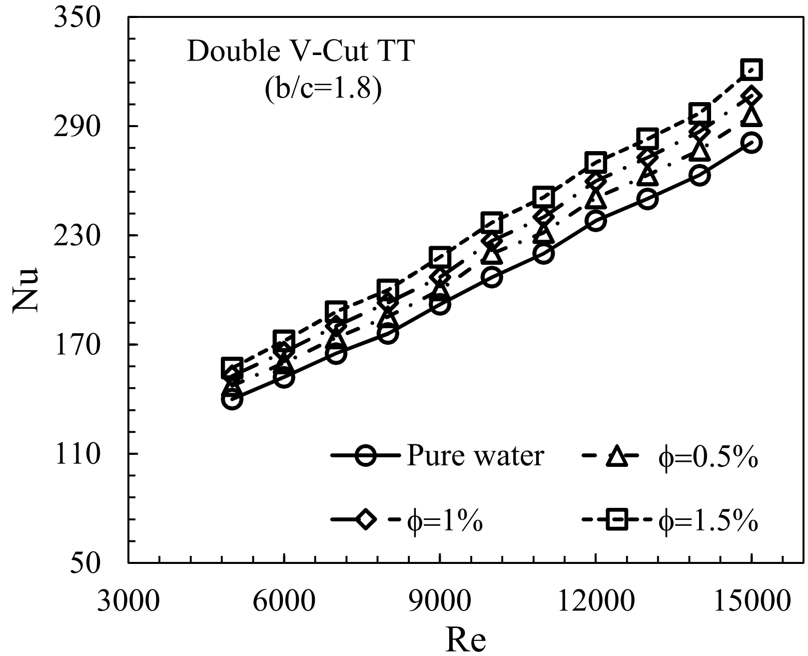


Figure 11 The effects of CuO nanoparticle volume concentration (ϕ) on the heat transfer rate of nanofluid flow inside heat exchanger tubes equipped with double V-cut TT b/c=1.8.

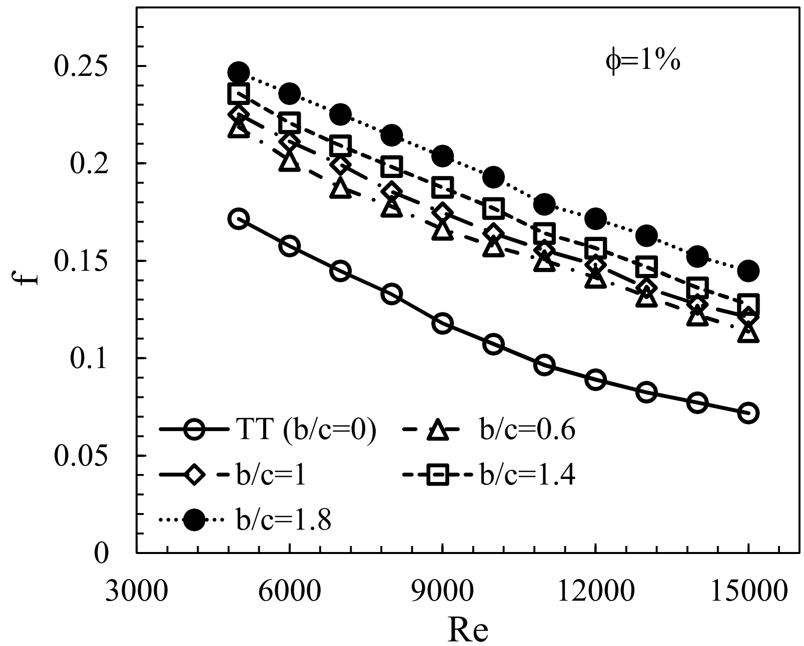


Figure 12 The effects of cut ratio on the friction factor of nanofluid flow with $\phi = 1\%$

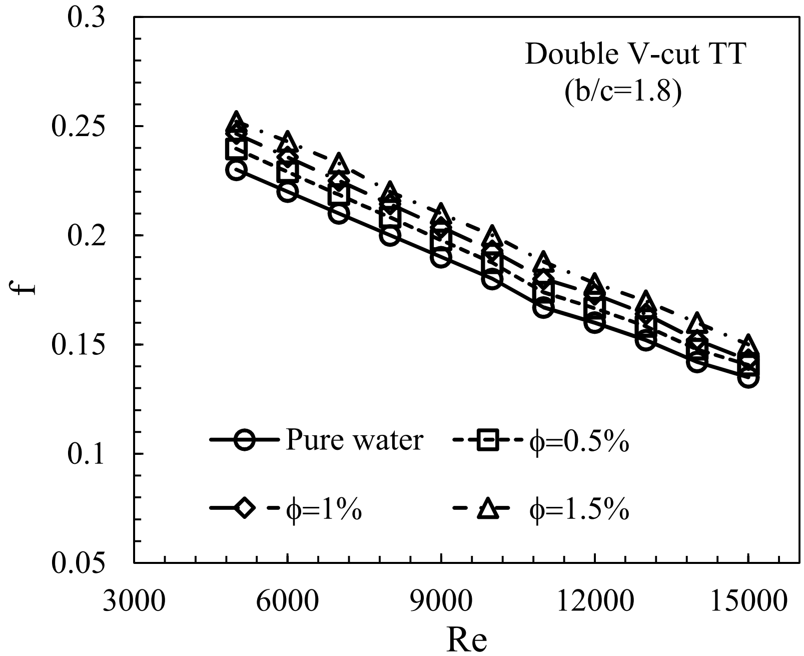
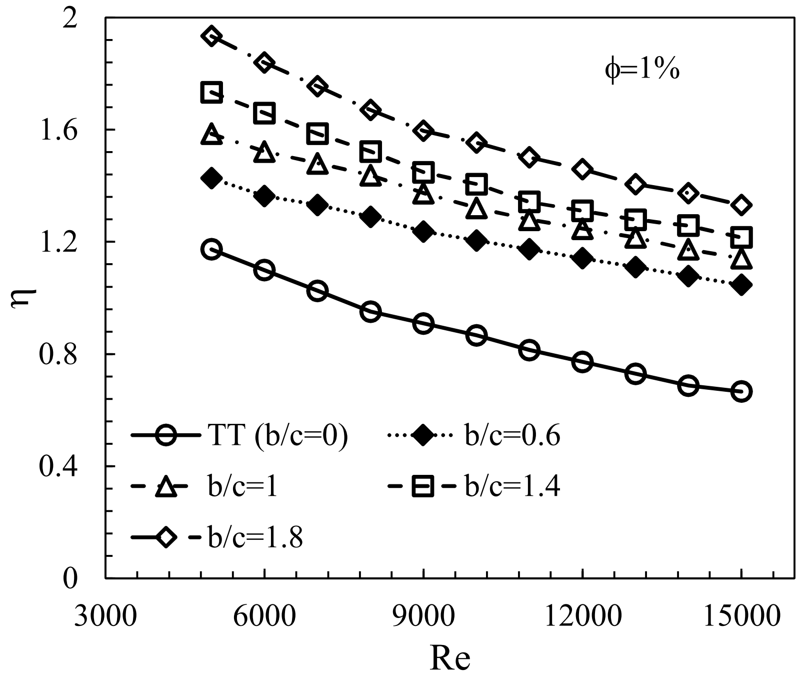
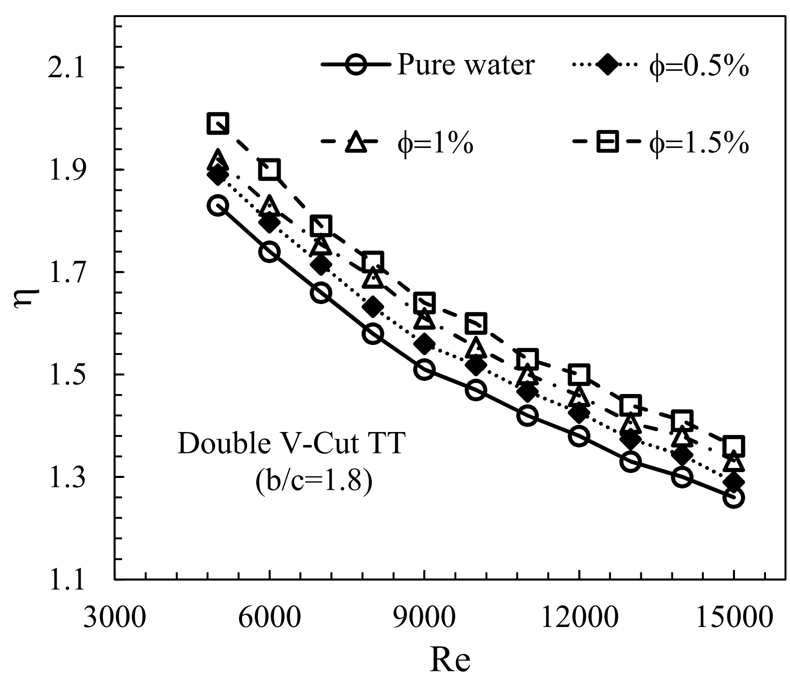


Figure 13 The effects of CuO nanoparticle volume concentration (ϕ) on the friction factor of nanofluid flow inside heat exchanger tubes equipped with double V-cut TTs with b/c=1.8.



a) Effect of cut ratio



b) Effect of nanoparticle volume fraction

Figure 14 Variation of thermal performance with Reynolds number for nanofluid flows through tubes fitted with DVCTT with different cut ratios

List of Tables

Table 1 Geometrical parameters of the double V-cut TTs

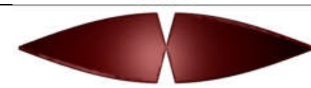
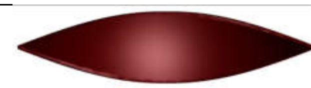
Twisted Tape	V-Cut depth (b)	V-Cut width (c)	Cut ratio (b/c)	Shape
Case 1	3 mm	5 mm	0.6	
Case 2	5 mm	5 mm	1	
Case 3	7 mm	5 mm	1.4	
Case 4	9 mm	5 mm	1.8	
Validation (Conventional TT)	-	-	0	

Table 2 Grid independence test for b/c=1.8 with $\mathrm{Re}=15000$ and $\phi=1\%$.

Number of elements	Nu	Variation (%)	f	Variation (%)
408,302	267.82	-	0.133	-
735,031	299.21	10.5	0.138	3.6
1,298,705	305.86	2.1	0.142	2.8
1,884,396	306.64	0.2	0.143	0.7