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Numerical Investigation of Nanofluid Al_2O_3/Water in Elliptical Tube Equipped with Twisted Tape

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ABSTRACT

This research was undertaken to investigate the thermal effect of Al_2O_3- water nanofluid flow with twisted tapes in elliptical tubes through the use of a numerical method. Simulation was done for three-dimensional and incompressible flow with constant properties in the Reynolds range. The numerical results demonstrated that adding Al_2O_3 nanoparticles to water as a baseflow caused an increase in the heat transfer enhancement of the nanofluid compared to that of the base fluid. The obtained results show that simultaneous use of twisted tape with nanofluid had a better influence on heat transfer enhancement and thermal efficiency compared to the single usage of nanofluid or twisted tape, separately. Specifically, results showed that increasing the concentration of nanofluid and decreasing the twisted tape ratio caused increases in Nusselt number, thermal efficiency, and pressure.

1. INTRODUCTION

Frequent fluids which are used for heat transfer enhancement (HTE) have a low thermal conductivity coefficient. HTE is classified into three main techniques, namely, active, passive, and compound. The active techniques require an external force such as electric field, acoustic, or surface vibration. The early studies measured suspensions of millimeter or micrometer size particles which show some enhancements, but it has problem of poor suspension stability, clogging in systems using mini and or microchannels.

An important and useful way of passively incrementing the amount of heat transfer in tubes is the use of a nanofluid instead of base fluid [1].

Nanoparticles increase the conductivity coefficients of these fluids due to their high conductivity and improve the amount of heat transfer in the fluid, so the use of them become very commonplace in recent years.

Another technique for passively enhancing the heat transfer in tubes is using the swirl flow devices such as Twisted Tapes (TTs) which produce secondary computation on the axial flow goes to an increase of tangential and radial turbulent vibration. [2-6]. Lee et al. [7] have detected the 5 % increment of Al_2O_3 and CuO nanofluid thermal conductivity and assess by using transient hot wire method. Choi et al achieved 160 % enhancement in thermal conductivity of 1.0 % volume concentration of CNTs in engine oil [8].

Nanofluid TiO_2/Water which was heated in a circular horizontal tube was used to measure the heat transfer and pressure drop of turbulent flow. The results of this study showed that the heat transfer coefficient increases with increases in the volume fraction of nanoparticles and does not change with variations in Reynolds number [9]. Heyhat et al. observed the nanofluid heat transfer coefficient increased with increases in the Reynolds number and particle concentration [10]. Numerical analysis was carried out by Azwadi et al. to improve heat transfer in a flat tube using ethylene glycol and aluminum oxide as nanoparticles under turbulent flow conditions [11]. Bhuiya MMK et al. have found that the Nusselt number, efficiency, and friction coefficient for a twisted tape through the pipe are higher than those for a plain tube [12]. Simultaneous use of nanofluid and twisted tape increased heat transfer compared to single usage of nanofluid or twisted tape separately [13]. The heat transfer was improved of a double pipe heat exchanger using aluminum/Water nanofluid and baffled twisted tape and it was observed that the rectangular baffled twisted tape performance evaluation was better than the other twisted tapes [14].

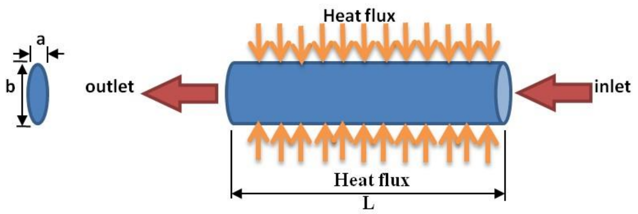
Another study using Fe_3O_4/Water nanofluid with varying cut-radius twisted tape inserts was performed in a hairpin heat exchanger. The results of this research revealed an improvement in the heat exchanger performance parameter, such as heat transfer coefficient friction factor, by increasing the volume concentration of the nanofluid [15].

The purpose of this research was to study the heat transfer, pressure drop, and heat efficiency in a tube with an ellipsoidal cross section under constant heat flux of 740 watts by increasing the volume fraction of Al_2O_3 nanoparticles and inserting twisted tapes with different twist ratios by using fluent software. It was found thermal efficiency was increased by reducing the twisted tape ratio and increasing the concentration of nanofluid.

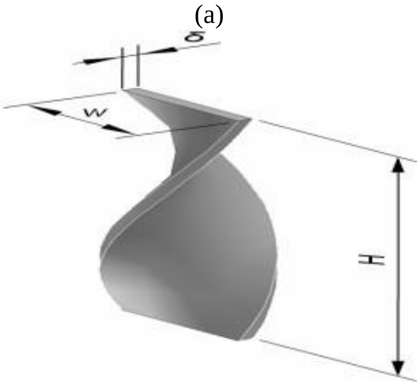
2. MATERIALS AND METHODS

2.1 Physical model

In this study, a copper tube with an elliptic cross-section was selected with a large diameter (b), a small diameter (a), and a length (L) of 27, 9, and 1000 mm, respectively. The hydraulic diameter of this pipe was D_h=24 mm and this tube was heated with constant heat flux q=740 w. Aluminum twisted tapes with twist ratios 3.125 < H/W < 18.75 were considered inside the tube. The nanofluid particles applied in this study were aluminum oxide (Al_2O_3, particle size changes from 1 nm to 100 nm). The physical design of the tube and the twisted tape are shown in Figures 1 (a) and 1 (b). Furthermore, the physical properties of the twist tapes are shown in Table 1.



(a)



(b)

Figure 1. (a) Physical image of the problem, (b) Physical view of the twisted tape inside the tube

Table 1. The physical properties of the twist tapes

Twisted tape number	W (mm)	δ (mm)	H (mm)	Twist ratio (H/W)
1	8	1	150	18.750
2	8	1	75	9.375
3	8	1	25	3.125

W: Width, δ: Height, H: Pitch

2.2 Governing equations

The related equations of flow including mass, momentum, and energy conservation were as follows:

The mass, momentum and energy conservation equations were shown 1 to 3.

- Mass

$$div(p\vec{V}) = 0 \quad (1)$$

- Momentum

$$div(p\vec{V}\vec{V}) = -gradp + \nabla.(\mu\nabla\vec{V}) \quad (2)$$

- Energy

$$div(p\vec{V}C_pT) = div(KgradT) \quad (3)$$

where *T*, *P*, and $\vec{V}$ were temperature, pressure, and vector of speed, respectively.

In the single-phase method for nanofluid flow, equivalent thermophysical properties for nanofluids have been introduced into the equations. The following relationships have been used in order to calculate the density, viscosity, thermal capacity, and thermal conductivity coefficient of the nanofluid.

$$\rho_{nf} = \varphi.\rho_s + (1-\varphi).\rho_w \quad (4)$$

where, ρ_{nf}, ρ_s, and ρ_w are the nanofluid, nanoparticles, and water densities, respectively, and φ is the volume fraction of the nanofluid, Eq. 4.

$$\mu_{nf} = \mu_w.(1+2.5\varphi) \quad (5)$$

where, μ_{nf} and μ_w are the nanofluid and water viscosities, respectively, Eq. 5.

$$Cp_{nf} = \frac{\varphi.(\rho_s.Cp_s)+(1-\varphi).(\rho_w.Cp_w)}{\rho_{nf}} \quad (6)$$

where, Cp_{nf}, Cp_s, and Cp_w are the specific heat capacity of nanofluids, nanoparticles, and water, respectively, Eq. 6.

$$K_{nf} = \left[\frac{K_s+2K_w+2(K_s-K_w)(1+\beta)^3.\varphi}{K_s+2K_w-(K_s-K_w)(1+\beta)^3.\varphi}\right].K_w \quad (7)$$

where, K_{nf}, K_s, and K_w are the thermal conductivity of nanofluids, nanoparticles, and water, and β is the ratio of the nanolayer thickness to the average particle radius, which is considered to be 0.1, Eq. 7.

The thermophysical properties of the base fluid and the nanoparticle are in accordance with Table 2 [16].

Table 2. Thermophysical properties of base fluid and nanoparticle

Substance	ρ (kg/m3)	Cp (J/kg.k)	K (W/m.k)	μ (kg/m.s)
Water(w)	998.2	4182	0.6	0.001003
Al_2O_3(s)	3700	880	46	-

According to Table 2 and equations (4) to (7), the thermophysical properties equivalent for the nanofluid are shown in Table 3:

Table 3. Thermophysical properties for Al_2O_3/Water

Nano fluid	φ (%)	ρ (kg/m3)	Cp (J/kg.k)	K (W/m.k)	μ (kg/m.s)
Al_2O_3 /Water	0.2	1003.604	4156.95	0.61770	0.00100800
Al_2O_3 /Water	0.5	1011.709	4120.92	0.62400	0.00101550
Al_2O_3 /Water	1	1025.218	4062.15	0.63600	0.00102800
Al_2O_3 /Water	2	1052.236	3949.13	0.66128	0.00105315

For the flowing nanofluid inside the pipe, the Reynolds number (Eq. 8), friction coefficient (Eq. 9), heat transfer coefficient (Eq.10), pressure drop (Eq. 11), and efficiency (Eq. 12) were calculated as follows [16-17]:

$$Re_{nf} = \frac{\rho_{nf}.D_h\bar{U}}{\mu_{nf}} \tag{8}$$

where D_h is the hydraulic diameter of the pipe.

$$f = \frac{64}{Re} \tag{9}$$

$$\overline{h_{nf}} = \frac{q}{A.(T_w - T_b)_M} \tag{10}$$

where, T_w and T_b are the wall temperature and the volume temperature of the nanofluid, respectively.

$$\Delta P = \frac{fl\rho V^2}{2D} \tag{11}$$

where, f, L, and V are the friction factor, pipe length, and average velocity inside the tube, respectively.

$$\eta = [\frac{Nu_e / Nu_p}{(f_e / f_p)^{0.333}}] \tag{12}$$

where Nu_e, f_e, Nu_p, and f_p are the Nusselt number and the friction coefficient, respectively, with and without the twisted tape, respectively.

2.3 Numerical solution method

The flow was considered as three-dimensional, steady, incompressible, and laminar inside the elliptical tube under constant heat flux. Continuity, momentum, and energy equations were solved after the discretization by controlling the volume and with the help of fluent software version 6.3.26 [18].

2.4 Production of the grid and boundary conditions

Three-dimensional grid production was done through Gambit 2.2.30 software [19]. For a pipe with a twisted tape, a three dimensional and irregular tetrahedral mesh was used. The geometry and network of the twisted tape are as indicated in Figure 2. By considering fully-developed flow of the nanofluid, velocity inlet is applied at the input; at the output, pressure outlet and a no-slip boundary condition is applied at the solid wall (which was under constant heat flux 740 W/m^2).

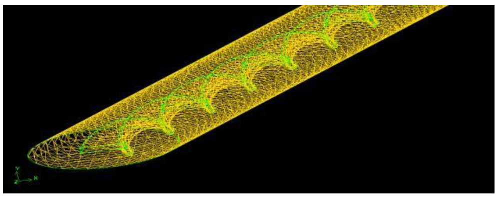


Figure 2. Elliptical pipe networking with twisted tape

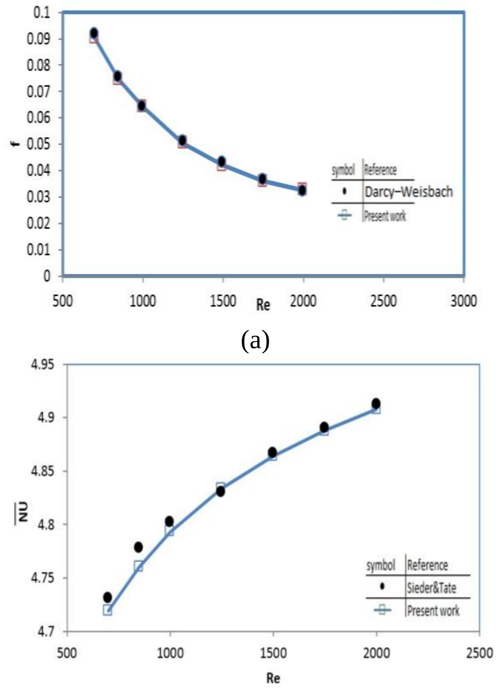
2.5 Mesh independency

In order to verify the independence of the number of nodes, four different types of meshes with the corresponding number of nodes (185321, 458451, 912383, and 139741) were investigated using Gambit software. For each mesh, the friction factor and Nusselt number were calculated. According to the obtained results, the number of nodes equal to 912383 was used to increase the accuracy of the calculation.

3. RESULTS AND DISCUSSION

3.1 The validation of numerical results with experimental data

In Figure 3 (a), the effect of increasing the Reynolds number on the friction factor (in the Reynolds range 700<Re<2000) in the elliptical tube is compared with the experimental work of the Darcy–Weisbach equation. As can be seen, the results of the present study revealed an error of 0.15 to 1.8 %. Furthermore, in Figure 3 (b), the variation of the Nusselt number in terms of the Reynolds number for the elliptic tube in the Reynolds range 700<Re<2000 is compared with the experimental results of Sieder & Tate [20]. The following comparison also showed a good agreement between the numerical and experimental results.

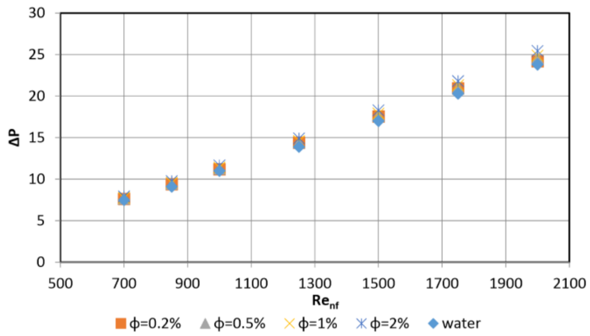


(b)

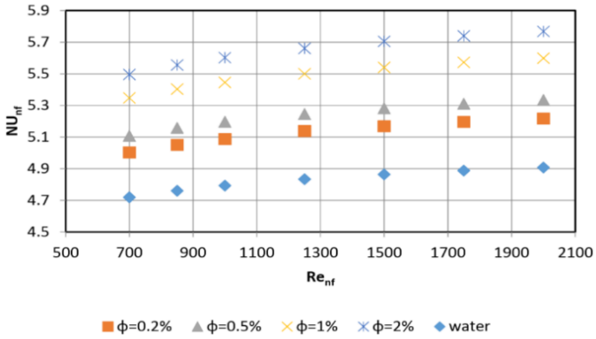
Figure 3. (a) The effect of Reynolds number as the friction factor (a) and the Nusselt number (b)

3.2 Effect of nanofluid on pressure drop and Nusselt number

Figure 4 (a) illustrates the effect of increasing the nanofluid (Al_2O_3/Water) concentration on pressure drop. According to Figure 6, it can be concluded that increasing the volume fraction of nanofluid from 0.2 to 2 % causes an increase in the pressure drop from 2.1 to 5.5 %. Moreover, the effect of increasing the nanofluid (Al_2O_3/Water) concentration on the Nusselt number is shown in Figure 4 (b). It can be seen from this figure that by increasing the volume fraction of nanofluid from 0.2 to 2 %, the Nusselt number is increase by about 16.5 % on average.



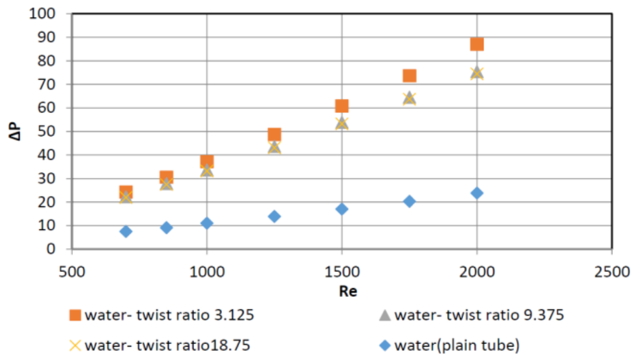
(a)



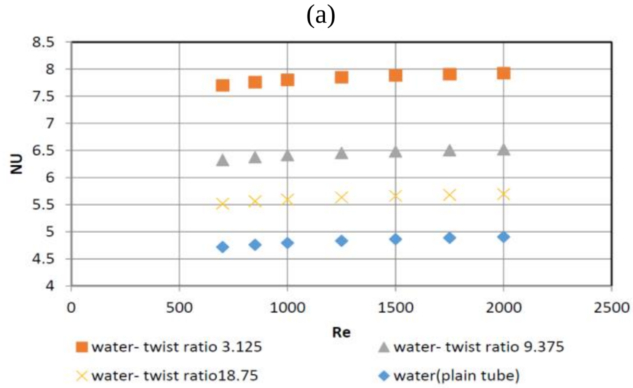
(b)

Figure 4. Reynolds number - pressure drop (a), Reynolds number - Nusselt number (b) for different volume concentrations of nanofluid Water/Al_2O_3

3.3 Effect of twisted tape on pressure drop and Nusselt number



(a)



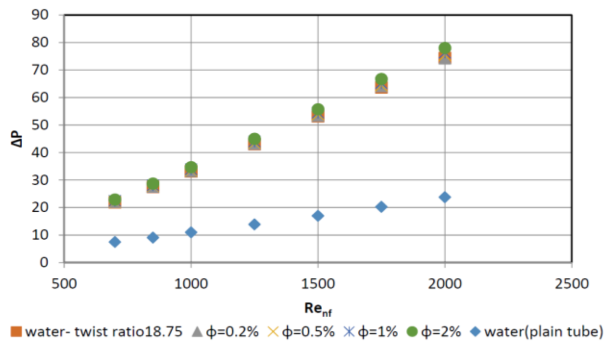
(b)

Figure 5. Reynolds number - pressure drop (a), Reynolds number - Nusselt number (b) for different twisted tape ratios

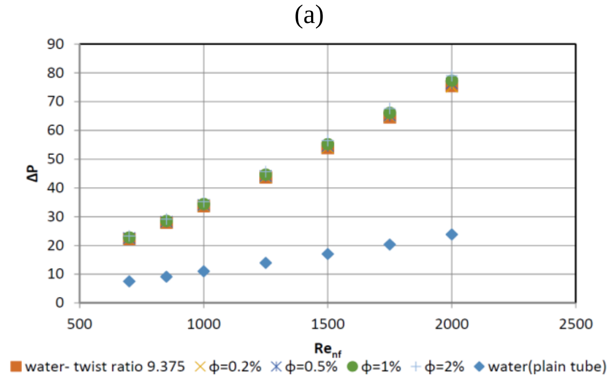
Figures 5 (a) and 5 (b) illustrates the variations in pressure drop and Nusselt number with Reynolds number with different twisted tape ratios (18.75, 9.375 and 3.125). According to the numerical results, the pressure drop was increased from 192 to 223 % by reducing the twisted tape ratio from18.75 to 3.125. Furthermore, the Nusselt number was increased from 17 to 63 % by reducing the twisted ratio from 18.75 to 3.125. The effect of inserting the twisted tape in the flow path generated higher heat transfer rates than the same flow in a plain tube, resulting in a thinner thermal boundary layer along the tube wall and thus higher convective heat transfer.

3.4 Simultaneous effect of twisted tape and nanofluid on pressure drop and Nusselt number

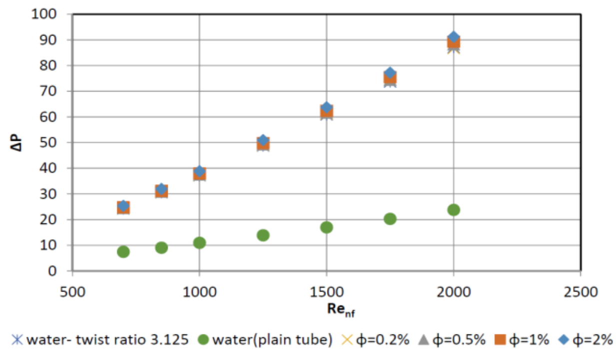
The effects of increasing the volume concentration of nanofluid Al_2O_3/Water with different twisted tape ratios on pressure drop are shown in Figures 6 (a), 6 (b), and 6 (c). The results showed that reducing the twisted tape ratio from 18.75 to 3.125 and increasing the concentration of nanofluid from 0.2 to 2 % caused an increase in pressure drop from 193.8 to 238 % (compared to that of the plain tube).



(a)



(b)



(c)

Figure 6. Reynolds number - pressure drop in different twisted ratio 18.75(a), 9.375 (b) and 3.125(c) with various volume concentrations of Nanofluid Water/Al_2O_3

The effects of increasing the volume concentration of nanofluid Al_2O_3/Water with different twisted tape ratios on the Nusselt number are shown in Figures 7(a), 7(b), and 7(c). The results showed that the Nusselt number was increased from 24 to 91 % by reducing the twisted tape ratio from 18.75 to 3.125 and increasing the nanofluid concentration from 0.2 to 2 %.

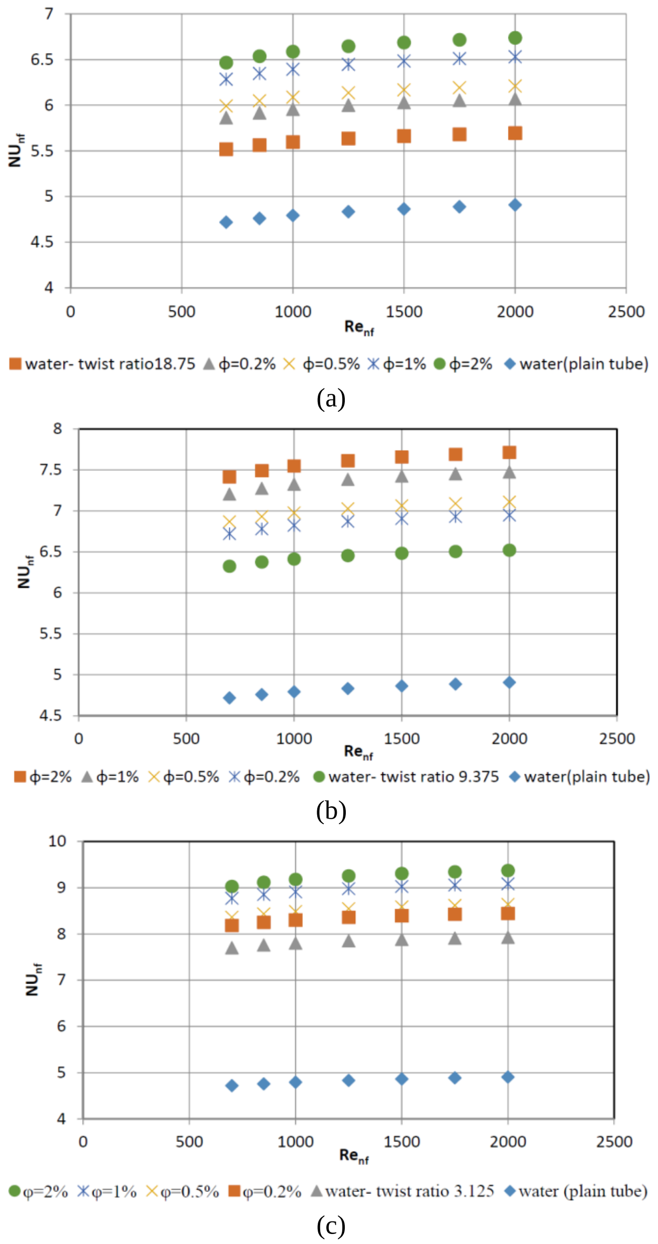


Figure 7. Reynolds number - Nusselt number in different twisted ratio 18.75(a), 9.375 (b) and 3.125(c) with various volume concentrations of Nanofluid Water/Al_2O_3

3.5 Effect of nanofluid on thermal efficiency

Figure 8 illustrates the effects of increasing the nanofluid (Al_2O_3/Water) concentration on thermal efficiency. As can be seen, increasing the volume concentration of nanofluid from 0.2 to 2 % causes an increase in thermal efficiency from 105 to 115 %.

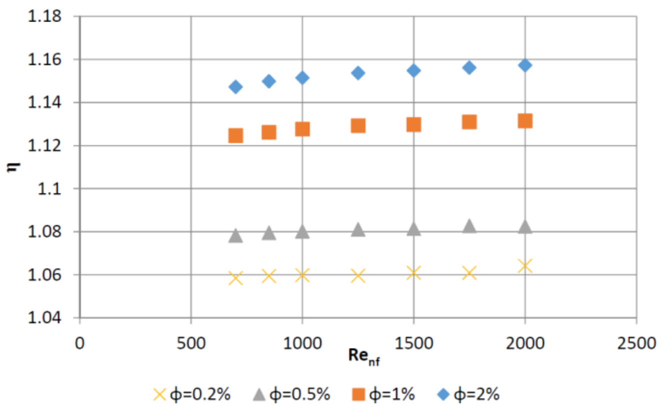


Figure 8. Relation between Reynolds number and thermal efficiency for different volume concentrations of Nanofluid Water/Al_2O_3

3.6 Effect of twisted tape on thermal efficiency

Figure 9 shows the variations of thermal efficiency with Reynolds number in different twisted tape ratios (18.75, 9.375, and 3.125).

According to the obtained numerical results, thermal efficiency was increased from 85 to 107 % by reducing the twisted tape ratio from 18.75 to 3.125.

Furthermore, increasing the Reynolds number caused a decrease in thermal efficiency due to the insertion of twisted tape along the tube, which caused an intensive pressure drop in the flow path.

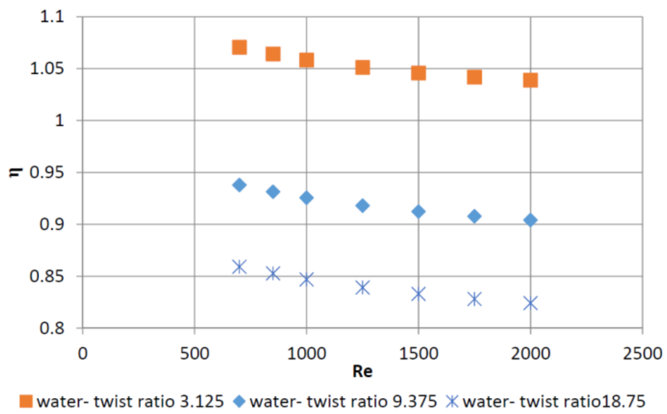
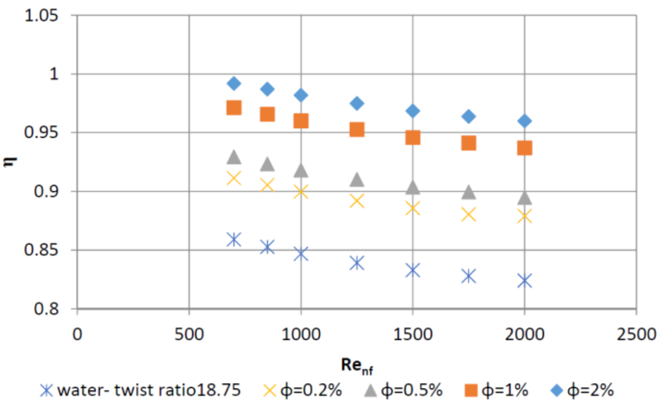


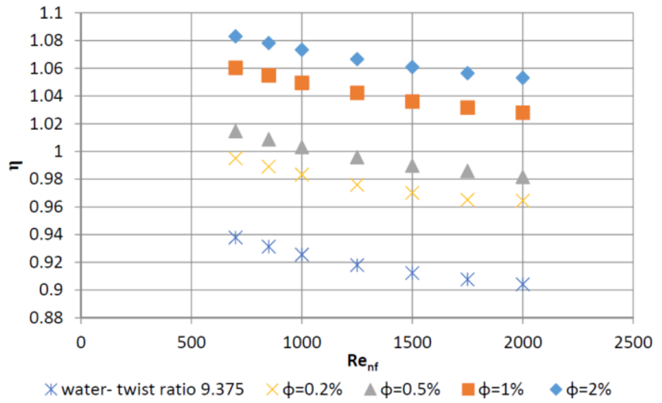
Figure 9. Variations of Reynolds number and thermal efficiency for different twisted tape ratios

3.7 Simultaneous effect of twisted tape with nanofluid on thermal efficiency

The effects of increasing the volume concentration of nanofluid Al_2O_3/Water with different twisted tape ratios on thermal efficiency are shown in Figures 10 (a), 10 (b), and 10 (c). As is clear from the figures, thermal efficiency was increased from 91 to 123.6 % by reducing the twisted tape ratio from 18.75 to 3.125 and by increasing the concentration of nanofluid from 0.2 to 2 %.



(a)



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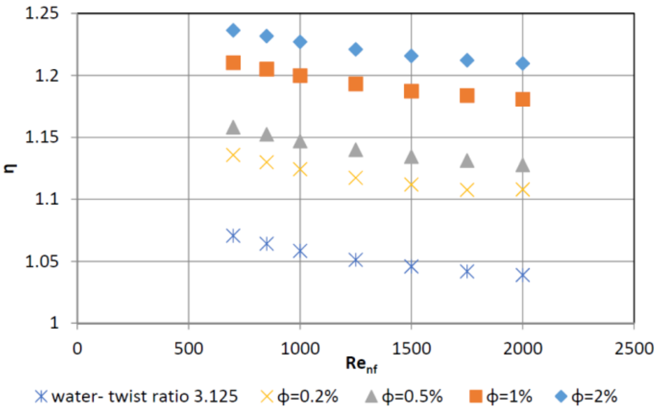

(c)

Figure 10. (a) Variation of Reynolds number with thermal efficiency in diffrent twisted ratio 18.75(a), 9.375 (b) and 3.125(c) with various volume concentrations of Nanofluid Water/Al_2O_3

4. CONCLUSIONS

In this study, heat transfer enhancement, pressure drop, and the thermal efficiency factor of Al_2O_3/Water nanofluid with different volume concentrations ($0<\varphi<2\%$) and different twisted tape ratios ($3.125<H/W<18.75$) in a laminar flow regime were numerically investigated. The highest Nusselt number was obtained in 2 % volume fraction Al_2O_3/Water nanofluid and a twisted tape with a twisted ratio of 3.125 and a Reynolds number of 2000. In addition, the maximum thermal efficiency was obtained around 2.1 with a Reynolds number of 700 and the simultaneous use of twisted tape with a twisted ratio of 3.125 by Al_2O_3/Water nanofluid in a volume fraction of 2 %. Specifically, reducing the twisted tape ratio from 18.75 to 3.125 and increasing the nanofluid concentration from 0 to 2 %, the average Nusselt number, thermal efficiency, and pressure drop were increased by around 91, 124, and 300 %, respectively. From the overall finding of this work it can be concluded that each parameter that cause enhancement in the amount of heat transfer, also increases the concentration of nanofluid make more pressure drop in tubes.

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