THE EXERGY EFFICIENCY AND PUMPING POWER OF NANOFLUID THROUGH A HELICALLY COILED TUBE HEAT EXCHANGER UNDER TURBULENT FLOW

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ABSTRACT

This paper theoretically examines the effects of water-Al2O3 nanofluid on exergy destruction, exergy efficiency and pumping power in the helically coiled tube heat exchanger under turbulent flow and subjected constant wall condition. The effects of the nanoparticles volume concentration, nanoparticle dimensions, Reynolds number, curvature ratio and dimensionless inlet temperature considered to be the main parameters in this study. It is found that when the Reynolds number increases, dimensionless total exergy destruction decreases. It is observed that by increasing the nanoparticles volume concentration from 2% to 6%, the dimensionless thermal exergy destruction reduces by 3.64% to 20.21 % compared to pure water. Also, it is seen that when nanoparticles dimensions increases, the exergy efficiency increases and pumping power decreases. Finally, the exergy efficiency increases with increasing of curvature ratio and pumping power decreases with increasing of curvature ratio.

KEYWORDS*: Helically coiled tube, Exergy efficiency, Second law analysis, Turbulent flow, Nanofluid.*

1.0 INTRODUCTION

In industry and engineering applications, helically coiled heat exchangers are effective equipment, since it is used in industrial fields including power generation, food processing, petrochemical industry, HVAC and refrigeration. (Chingulpitak and Wongwises, 2011),(Zhao et al, 2011). Helically coiled heat exchangers increase the heat transfer surface area per unit volume and enhance the heat transfer coefficient of the flow inside the tube without turbulence or additional heat transfer surface area. The centrifugal forces in the coiled tube induce a secondary flow pattern consisting of two vortices perpendicular to the axial flow direction is set up, and heat transport will occur not

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only by diffusion in the radial direction but also by convection. The contribution of this secondary convective transport dominates the overall process and enhances the rate of heat transfer per unit length of tube compared to a straight tube of equal length (Prabhanjan et al, 2002). The common fluids such as water, ethylene glycol and oil have poor heat transfer performance in heat exchanger (Godson et.al, 2010). If metallic nanoparticles with high thermal conductivity use in typically fluids, heat transfer will increase. Enhancement of heat transfer using nanoparticles suspended in a base fluid has been studied widely in recent years (Xie et al, 2002), (Buongjorno, 2006), (Bianco et al, 2009), (Shafahi et al, 2010). Xuan and Li (2003) experimentally studied the flow and heat transfer characteristics for cu-water based nanofluids through a plain tube with a constant heat flux boundary condition. They found that the nanofluids give substantial enhancement of heat transfer rate compared to pure water.

A number of researchers have investigated the performance of heat exchangers (Mohammed et al, 2011),(Ahmed et al, 2011),(Lotfi et al, 2012),(Raja et al, 2012) using nanofluids. Naraki et al. (2013) investigated experimentally the heat transfer coefficient of CuO/water nanofluids in a car radiator under laminar flow regimes. They found that the overall heat transfer coefficient with nanofluid is more than the pure water and increases with increasing the nanoparticles volume fraction from 0 to 0.4%. Peyghambarzadeh et al. (2011) experimentally studied the heat transfer of water-Al_2O_3 and EG-Al_2O_3 nanofluid in car radiator under different flow rate (2–6 liter per minute). Their results reveal that the heat transfer increases enhancement about 40% compared to the base fluids. Mukesh Kumar et al. (2013),(2014) investigated experimentally the heat transfer and friction factor of a shell and helically coiled tube heat exchanger using water-Al_2O_3 nanofluid under laminar and turbulent flow regimes. For laminar flow regime, they found that the overall heat transfer coefficient, inner heat transfer coefficient and experimental inner Nusselt number are 24%, 25% and 28%, respectively. Their results for turbulent flow regime indicated the Nusselt number for coiled tube of 0.1%, 0.4% and 0.8% nanofluids increase 28%, 36% and 56%, respectively higher than base fluid. They found that water-Al_2O_3 nanofluid was negligible pressure drop.

Exergy destruction or entropy generation minimization is a useful tool for evaluating the irreversibilities associated in process or device (Bejan et al. . Falahat and Vosough [24] computed entropy generation in a coiled tube under constant heat flux for both laminar and turbulent regimes using alumina–water nanofluids. They found that by adding 1% volume fraction of nanoparticles to the base fluid, entropy generation decreases about 3% in laminar flow. Also, they obtained an optimal Reynolds number for the turbulent flow for which the entropy generation was minimized. Ko and Ting [25] have applied this concept to find the most appropriate flow conditions of a fully developed, laminar forced convection flow through a helical coil tube for which entropy generation is minimized. Shokouhmand and Salimpour [26,27] studied deals with entropy generation analysis of fully developed laminar forced convection in a helical tube with uniform wall temperature. The second law of thermodynamic analysis of a helical coil heat exchanger using three different types of nanofluids is investigated analytically with Khairule et al. [28]. They found that, the CuO/water is best nanofluid when compared with Al_2O_3/water and ZnO/water, because the enhancement of heat transfer and entropy generation reduction in this type were obtained about 7.14% and 6.14% respectively.

To the best of authors' knowledge, the exergy analysis and pumping power of nanofluid in helically coiled tube heat exchanger under turbulent flow regime are not considered up to now. The main aims of this work are to investigate the exergy destruction or entropy generation and pumping power inside a helically coiled tube heat exchanger, subjected to constant wall temperature using nanofluid with turbulent flow regime. The effects of Reynolds number, nanoparticles volume concentration, nanoparticles dimension, coil-to-tube radius ratio and dimension inlet temperature on exergy efficiency (second law efficiency) and pumping power are investigated.

2.0 METHODOLOGY

2.1 Physical Model

A typical helically coiled tube heat exchanger has been shown in Figure 1. In this figure, d is inner diameter of the tube and D is curvature diameter of the coil, and H is the coil pitch. The curvature ratio, δ, is defined as the coil-to-tube radius ratio, d / D. The characteristics parameter and working conditions are shown in Table1. The other three important dimensionless parameters namely, Reynolds number (Re), Nusselt number (Nu) , and Dean Number (Dn) are defined as follow.

$$\mathrm{Re} = \frac{\rho U d}{\mu}, \quad Nu = \frac{h d}{k}, \quad Dn = \mathrm{Re}\left(\frac{d}{D}\right)^{0.5} \tag{1}$$

where, U and h are average velocity and convective heat transfer coefficient respectively.

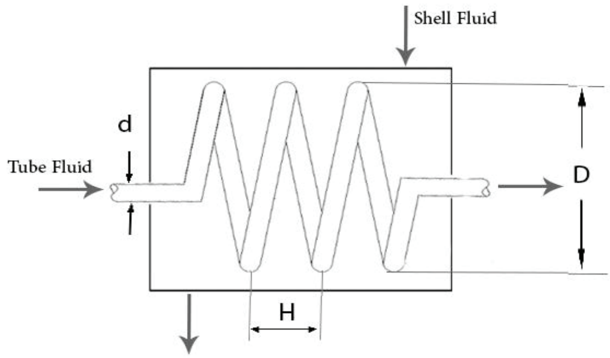


Figure 1 Geometry configuration of a helically coiled tube heat exchanger.

Table 1. Characteristic and working condition of helically coiled tube heat exchanger

Characteristic/Working conditions	Numerical values
Coil diameter, $D\,(m)$	0.12
Coil length, $l\,(m)$	0.9
Curvature ratio, δ	0.03, 0.06, 0.12
Wall temperature, $T_w\,(K)$	360
Dimensionless temperature, θ	0.05, 0.1, 0.15
Reference dead temperature, $T_o\,(K)$	298
Nanoparticle volume fraction, φ	0-6%
Nanoparticle dimensions, $d_{np}\,(nm)$	30, 50, 70
Reynolds number, Re	20000-140000

2.2 Thermo-physical properties of nanofluid

The nanofluid in the channel is Newtonian and assumed that the fluid phase and nanoparticles are in the thermal equilibrium state and they flow with the same velocity. The thermophysical properties of pure water, Al_2O_3 nanoparticles which are density, heat capacity, effective dynamic viscosity and effective thermal conductivity are given in Table 2. The density and heat capacity of the nanofluid can be defined as (Corcione,2010)

$$\rho_{nf} = (1-\varphi)\,\rho_{bf} + \varphi\,\rho_p \tag{2}$$

The effective dynamic viscosity of the nanofluid is given as (Ko and Ting(2005);

$$\frac{\mu_{eff}}{\mu_{bf}} = \frac{1}{1 - 34.8(d_{np} / d_{bf})^{-0.3} \varphi^{1.03}} \tag{3}$$

where d_{np} is the nanoparticle diameter, d_{bf} is the diameter of molecule of a base fluid, and it is defined as:

$$d_{bf} = \left[\frac{6M}{N \pi \rho_{bf}} \right] \tag{4}$$

N is the Avogadro number 6.022x10^{23} mol^{-1}.
The thermal conductivity of the nanofluid due to the Brownian motion is given as [30]

$$k_{eff} = k_{bf} \left[\frac{(k_p + 2k_{bf}) - 2\varphi(k_{bf-k_p})}{(k_p + 2k_{bf}) + \varphi(k_{bf} - k_p)} \right] + 5 \times 10^4 \beta \varphi \rho_{bf} C_{p_{bf}} \sqrt{\frac{\kappa T}{\rho_p d_p}} f(T, \varphi) \tag{5}$$

where

$$\beta = 8.4407(100\varphi)^{-1.07304} \tag{6}$$

$$f(T,\varphi) = (2.8217 \times 10^{-2} \varphi + 3.917 \times 10^{-3})(\frac{T}{T_{ref}}) + (-3.0669 \times 10^{-2} \varphi - 3.91123 \times 10^{-3}) \tag{7}$$

where T is the fluid temperature, T_{ref} is the reference temperature and equals 293°K and K is the Boltzman constant.

Table 2. Physical properties of water and Al_2O_3 nanoparticle.

Property	**Water**	**$A1_2O_3$**
C_p *(J / kg K)*	4179	765
ρ (kg / m3)	997.1	3600
μ (kg / m.s)	0.001	_ _ _
k (W / mK)	0.613	36

2.3 Exergy analysis

Exergy is defined as the maximum amount of work that can be obtained by a system or a flow in which complete equilibrium with a reference environment is attained. The general exergy balance in steady state flow can be written as follows [31]:

$$\sum Ex_{in} - \sum Ex_{out} = \sum Ex_{des} \tag{9}$$

or

$$Ex_{heat} - Ex_{work} + Ex_{mass,in} - Ex_{mass,out} = Ex_{des} \tag{10}$$

The rate form of general exergy balance can be expressed by Equation 11:

$$\left(1 - \frac{T_0}{T}\right) Q_W - W + m_{in}\psi_{in} - m_{out}\psi_{out} = Ex_{des} \tag{11}$$

where T is the average temperature of the fluid inside the coiled tube, estimated as [32]

$$T = \frac{T_{out} - T_{in}}{\ln\left(\frac{T_{out}}{T_{in}}\right)} \tag{12}$$

T_{out} computed from energy balance for a control volume:

$$T_{out} = T_W - (T_W - T_{in})\exp\left((-h_{nf}\,\pi\, d\, l)/m C_{P,nf}\right) \tag{13}$$

The flow exergy is computed as:

$$\psi = (h - h_0) - T_0(s - s_0) \tag{14}$$

where *h, s* and subscript zero are respectively enthalpy, entropy and properties at the restricted dead state (T_0 and P_0. The entropy and enthalpy deviations and heat transfer rate of nanofluid in the helically coiled heat exchanger can be obtained as:

$$\Delta s = s_{out} - s_{in} = C_{P,nf}\ln\left(\frac{T_{out}}{T_{in}}\right) - R\ln\left(\frac{P_{out}}{P_{in}}\right) \tag{15}$$

$$\Delta h = h_{out} - h_{in} = C_{P,nf}\left(T_{out} - T_{in}\right) \tag{16}$$

$$Q_W = m\,C_{P.nf}\left(T_{out} - T_{in}\right) \tag{17}$$

If Equations (12) to (17) is replaced in Equation (11), it may be rewritten as:

$$Ex_{des} = m\,C_{P,nf}\,T_0\left[\frac{T_{out} - T_{in}}{T_0} - \ln\left(\frac{T_{out}}{T_{in}}\right) + \frac{\Delta P}{\rho_{nf}\,C_{P,nf}\,T_0}\right] \tag{18}$$

where

$$\Delta P = \frac{\rho_{nf}\,f\,l\,U^2}{2\,d} \tag{19}$$

Dimensionless form of Equation 18 can be expressed by Equation 20:

$$e_{des} = \left[\frac{T_{out} - T_{in}}{T_0} - \ln\left(\frac{T_{out}}{T_{in}}\right)\right] + \left[\frac{\Delta P}{\rho_{nf}\,C_{P,nf}\,T_0}\right] = e_{des,\Delta T} + e_{des,\Delta P} \tag{20}$$

The exergy efficiency or second law efficiency is computed as Dipippo(2004);

$$\varepsilon = 1 - \frac{Ex_{des}}{Ex_{in}} = 1 - \frac{C_{P,nf}(T_{out} - T_{in}) - T_0\,C_{P,nf}\,\ln\left(\frac{T_{out}}{T_{in}}\right) + \frac{\Delta P}{\rho_{nf}}}{C_{P,nf}(T_{in} - T_0) - T_0\,C_{P,nf}\,\ln\left(\frac{T_{in}}{T_0}\right) + \frac{\Delta P}{\rho_{nf}} + C_{P,nf}(T_{out} - T_{in})(1 - \frac{T_0}{T})} \tag{21}$$

The Nusselt number and friction in coiled tube heat exchanger are calculated using the same correlations as described below (Kakac and Liu);

$$Nu = \left(1 - 3.6(1-\delta)\,\delta^{0.8}\right)\left(0.024\,(\mathrm{Re}^{0.8})\,\mathrm{Pr}^{0.4}\right) \tag{22}$$

$$f\,\delta^{0.5} = 0.0084\,\left(\mathrm{Re}\,\delta^{-2}\right)^{-0.2} \quad for \quad \mathrm{Re}\,\delta^{-2} < 700 \quad and \quad 7 < \delta < 104 \tag{23}$$

Another important parameter for performance of heat exchanger is pumping power (PP), which can be expressed by Equation 24:

$$PP = (\frac{m}{\rho_{nf}})\Delta P \tag{24}$$

The pressure drop can be expressed by Equation 19 and the mass flow rate can be expressed by Equation 25:

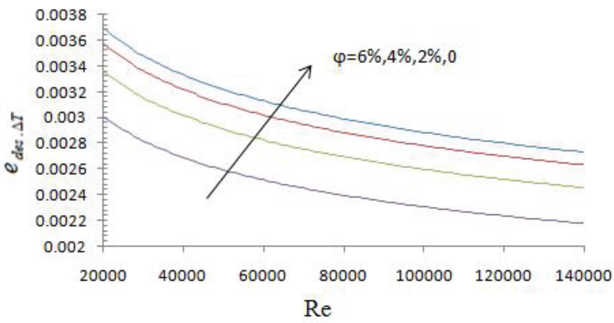
$$m = \frac{\pi}{4}\mathrm{Re}\, d\mu_{nf} \tag{25}$$

3.0 RESULTS AND DISCUSSION

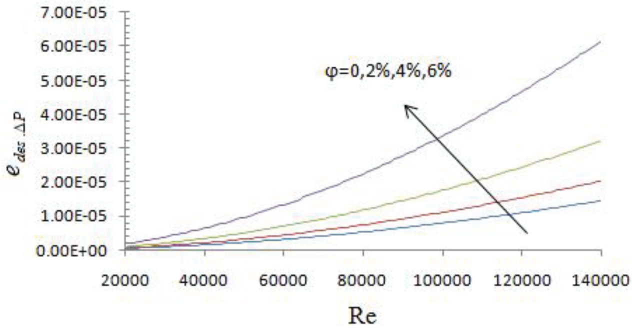
The results of this work are presented in two sections. In the first section, the exergy analysis of nanofluid and in the second section, the pumping power are discussed.

3.1 Exergy analysis results

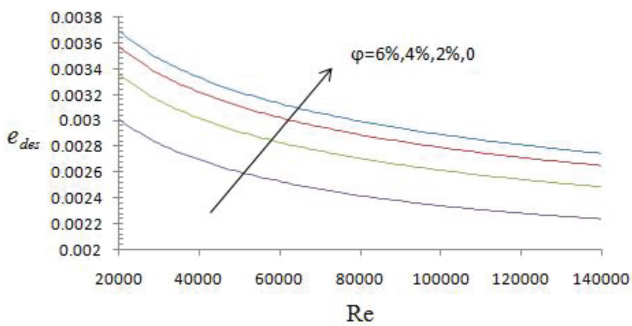
Figure 2(a), (b) and (c) illustrates the dimensionless total, thermal and frictional exergy destruction rate as a function of Reynolds number for different nanoparticles volume concentration. Parameters that are fixed constant in this results include d_{np}=*30nm*, δ = 0.06 and θ = 0.05. The dimensionless thermal exergy destruction decreases with increasing Reynolds number and nanoparticles volume concentration. This is because a higher nanoparticles volume concentration enhances Nusselt number and increasing thermal conductivity of nanofluid. By increasing the nanoparticles volume concentration from 2% to 6%, the dimensionless thermal exergy destruction reduces by 3.45% to 19.29% for low Reynolds number (Re=40000) and 3.64% to 20.21 % for high Reynolds number (Re=120000) compared to pure water. It is seen from Figure 2(b), the dimensionless frictional exergy destruction increased with increasing Reynolds number and nanoparticles volume concentration. When nanoparticles volume concentration increases, the viscosity increased and causing a increasing in frictional losses. This, consequently, results in increasing the dimensionless frictional exergy destruction. Figure 2(c) shows that the dimensionless frictional exergy destruction has a minor effect on dimensionless total exergy destruction because the value of frictional exergy destruction is too small for all nanoparticles volume concentration. Also this figure indicates that the behavior of dimensionless total exergy destruction is similar to dimensionless thermal exergy destruction.



(a)



(b)



(c)

Figure 2. Variation of dimensionless exergy destruction with Reynolds number for several nanoparticles volume concentration (a) thermal,(b) frictional and (c) total

Figure 3 shows the exergy efficiency as a function of Reynolds number for different nanoparticles volume concentration. Parameters that are fixed constant in this results similar Figure 2. It can be seen that the exergy efficiency increases with increasing Reynolds number and nanoparticles volume concentration. This enhancement is because of the fact that, by increasing nanoparticles volume concentration, heat transfer increases. Also, the curvature effect lead to forms the secondary flow in helically coiled tube [35] and this phenomena enhances heat transfer an increases exergy efficiency. For water-Al_2O_3 nanofluid and nanoparticles volume concentration 2%, 4% and 6%, the enhancement of exergy efficiency is about 1.2%, 3.23% and 6.7% respectively when compared with pure water. For every nanoparticles volume concentration, when Reynolds number increase from 20000 to 140000, the exergy efficiency increases about 10% and no exist optimal Reynolds number for minimizing the exergy efficiency.

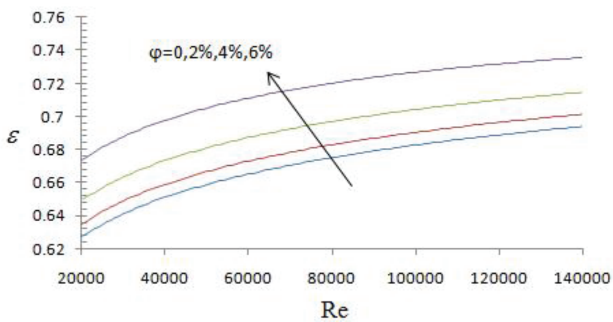


Figure 3. Variation of exergy efficiency with Reynolds number for several nanoparticles volume concentration

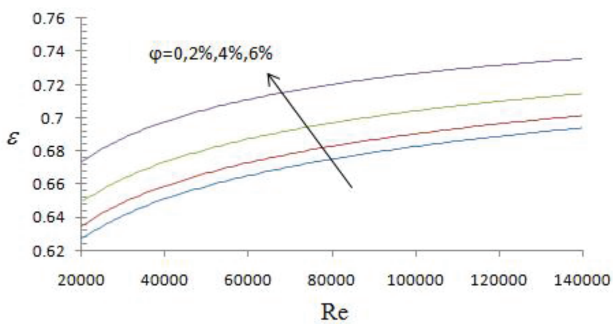


Figure 4. Variation of exergy efficiency with nanoparticles volume concentration for several nanoparticles dimension

The influence of nanoparticles dimension on exergy efficiency is shown in Figure 4. Parameters that are fixed constant in this results include Re = 100000, δ = 0.06 and θ = 0.05. It can be seen that the exergy efficiency increases with increasing nanoparticles volume concentration and decrease with increasing nanoparticles dimension. This is because of the fact that smaller nanoparticles dimensions has a higher surface of interaction with the base fluid and increases heat transfer as well as the increase thermal conductivity and decreasing the dimensionless thermal exergy destruction, also smaller nanoparticles dimensions increases viscosity of nanofluid strongly and increasing the dimensionless frictional exergy destruction, but the dimensionless frictional exergy destruction has a minor effect. Therefore exergy efficiency increases. One of important parameter in helically coiled tube heat exchanger is a Curvature ratio. Figure 5 illustrates the effect of δ on exergy efficiency for several nanoparticles volume concentration. Parameters that are fixed constant in this results include Re = 100000, $d_{np} = 30nm$ and θ = 0.05. It can be seen that exergy efficiency increases with the increase of δ for pure water and increases by increasing the nanoparticles volume concentration. For all nanoparticles volume concentration, when δ increases from 0.03 to 0.12, the exergy efficiency increases approximately 33%.

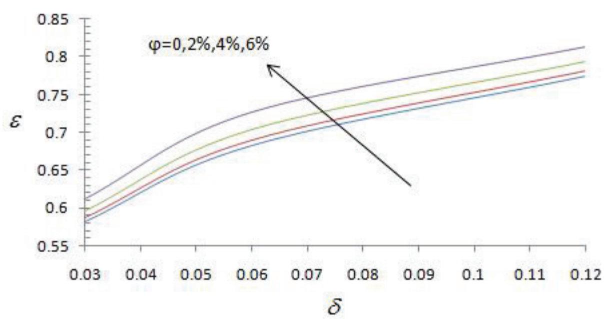


Figure 5. Variation of exergy efficiency with δ for several nanoparticles volume concentration

Figure 6 shows the exergy efficiency as a function of dimensionless temperature for different nanoparticles volume concentration. It can be seen that exergy efficiency decreases with increasing θ, because when dimensionless temperature increases, the temperature difference between the wall of tube and the average nanofluid temperature decreases and heat transfer reduces.

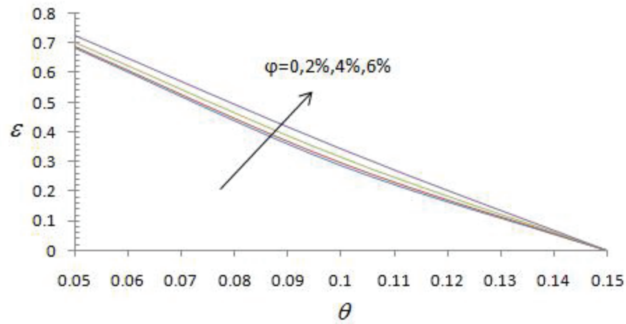


Figure 6. Variation of exergy efficiency with θ for several nanoparticles volume concentration

3.2 Pumping power results

Figure 7 illustrates the effect of nanoparticles volume concentration on the pumping power. It can be seen that, when Reynolds number increases, the pumping power increases, because for fluid flowing at higher Reynolds number, more pumping power is required but for flows with a very small Reynolds number, pumping power trends to zero. Pumping power increases with increasing nanoparticles volume concentration for fixed Reynolds number because by adding nanoparticles to increase in fluid friction and pressure drop. This results are matched with Falahat and Vosough (2012) and Kabeel et al. (2013).

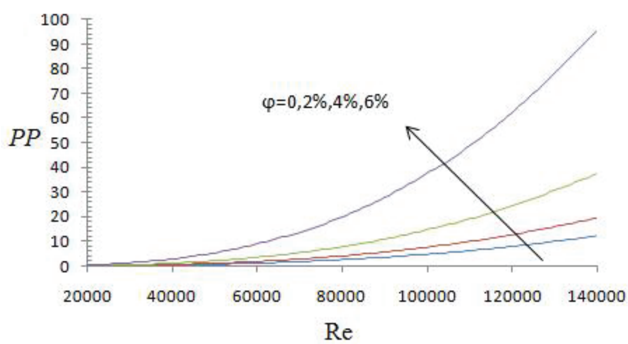


Figure 7. Variation of pumping power with Reynolds number for several nanoparticles volume concentration

Figs. 8 shows the results of pumping power at various nanoparticles volume concentration and nanoparticles dimension. It is observed from the figure that the pumping power increases with increasing nanoparticles volume concentration and decreases with increasing nanoparticles dimension. According to this figure, when nanoparticles dimension increases from 30 to 70 nm, the maximum pumping power decreasing is about 47% at 6% nanoparticles volume concentration.

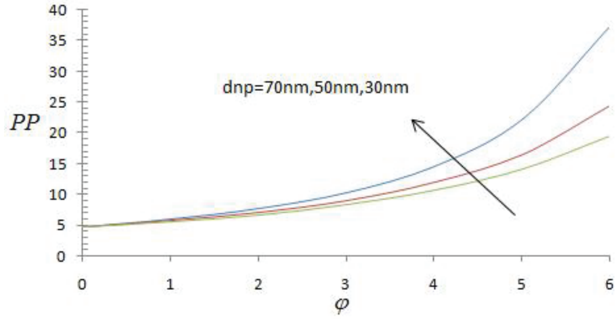


Figure 8. Variation of pumping power with nanoparticles volume concentration for several nanoparticles dimension

Figure 9 shows the pumping power as a function of curvature ratio for different nanoparticles volume concentration. The figure shows that the pumping power decreases with increasing curvature ratio and increases when nanoparticles volume concentration increases and. This is because of the fact that, When coiled diameter is constant, by increasing curvature ratio, diameter of tube increases and pressure drop is reduced. Also, we can be seen that, in larger curvature ratio, increasing of nanoparticles volume concentration has a minor effect on pumping power and this effect is significant on smaller curvature ratio.

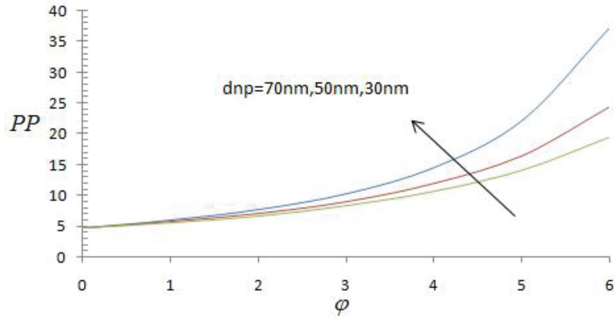


Figure 9. Variation of pumping power with δ for several nanoparticles volume concentration

4.0 CONCLUSIONS

In the present paper, an analytical analysis was carried out to study the effects of nanoparticles volume concentration, nanoparticles dimension, Reynolds number, curvature ratio and dimensionless inlet temperature of water-Al_2O_3 nanofluid on the dimensionless exergy destruction and exergy efficiency and pumping power in a helically coiled tube heat exchanger under turbulent flow regime. The results of this study show that:

- With increasing the Reynolds number, the dimensionless thermal exergy destruction decreases and the dimensionless frictional exergy destruction increases but the dimensionless frictional exergy destruction has a negligible effect on dimensionless total exergy destruction. Therefore trends of dimensionless total exergy destruction is similar to dimensionless thermal exergy destruction.
- It is observed that with increasing nanoparticles volume concentration led to decreasing on dimensionless thermal exergy destruction. For example, by adding 6% nanoparticles volume concentration, dimensionless thermal exergy destruction decreases about 20% compared to pure water.
- The exergy efficiency increases with increasing Reynolds number and nanoparticles volume concentration.
- When nanoparticles dimensions increases, the exergy efficiency increases and pumping power decreases. This is because of the fact that smaller nanoparticles dimensions increases heat transfer as well as the increase thermal conductivity and decreasing the dimensionless thermal exergy destruction, increases viscosity of nanofluid that led to increasing pumping power.
- The exergy efficiency increases with increasing of curvature ratio and pumping power decreases with increasing of curvature ratio. For example, when δ increases from 0.03 to 0.12, the exergy efficiency increases approximately 33%.
- The exergy efficiency decreases with increasing dimensionless inlet temperature.

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NOMENCLATURE

C_P	specific heat, $kJ/kg\,K$
D	Coil diameter, m
d	Tube diameter, m
Dn	Dean number
d_{np}	Particle size, nm
Ex	Exergy rate, W
f	friction factor
h	heat transfer coefficient, $W/m^2\,K$
k	thermal conductivity of the fluid, $W/m\,K$
l	length of coiled tube, m
m	mass flow rate, kg/s
N	Avogadro number
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Q_W	Heat transfer rate, W
Re	Reynolds number
s	specific entropy, $kJ/kg\,K$
T	temperature, K

Greek symbols

μ	viscosity of the fluid, $Pa.s$
ρ	density, kg/m^3
φ	nanoparticles volume fraction
δ	Coil-to-tube ratio
ε	Exergy efficiency
θ	dimensionless temperature, $\frac{T_w - T_{in}}{T_w}$

Subscripts

bf	base fluid
in	inlet
out	outlet
nf	Nanofluid
p	particles
o	dead state
w	Wall

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