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Heat transfer performance and exergy analyses of a corrugated plate heat exchanger using metal oxide nanofluids ☆

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ABSTRACT

Heat exchangers have been widely used for efficient heat transfer from one medium to another. Nanofluids are potential coolants, which can afford excellent thermal performance in heat exchangers. This study examined the effects of water and CuO/water nanofluids (as coolants) on heat transfer coefficient, heat transfer rate, frictional loss, pressure drop, pumping power and exergy destruction in the corrugated plate heat exchanger. The heat transfer coefficient of CuO/water nanofluids increased about 18.50 to 27.20% with the enhancement of nanoparticles volume concentration from 0.50 to 1.50% compared to water. Moreover, improvement in heat transfer rate was observed for nanofluids. On the other hand, exergy loss was reduced by 24% employing nanofluids as a heat transfer medium with comparing to conventional fluid. Besides, 34% higher exergetic heat transfer effectiveness was found for 1.5 vol.% of nanoparticles. It has a small penalty in the pumping power. Hence, the plate heat exchanger performance can be improved by adapting the working fluid with CuO/water nanofluids.

1. Introduction

During the previous five decades, quick improvements in engineering technology related to fossil and nuclear energy, electric power generation, electronic chips cooling and ink-jet printers have accelerated research in a variety of subjects associated to heat transfer. Among the themes, numerous engineering systems embrace problems related to heat transfer improvement in corrugated plate heat exchangers (PHE). Usually the plate heat exchangers are broadly used in several engineering applications for their compactness, high thermal efficiency, suitability in variable load and easiness and flexibility of sanitation. In PHEs, the number of cooling channels can be added or removed according to the heat load. Also the PHE performance during the flow degradation is one of the significant subjects that incorporated recently [1].

Heat transfer capacity is required to rise to meet the rising demand of energy density and this can be accomplished by using fluid with higher thermophysical properties. Nanometer sized solid particles suspended in the advanced heat transfer fluids are called 'nanofluids' which was invented by Choi [2]. The enhancement of heat transfer using nanofluids possibly affected by different mechanisms such as Brownian motion, sedimentation, dispersion of the suspended particles, thermophoresis, diffusiophoresis, forming a common boundary at the liquid/solid, and ballistic phonon transport. Consequently, the size of the equipment reduced, might lead to minimizing the expenses and enhancing the efficiency of the systems [3].

A number of researchers have investigated the performance of heat exchangers [4–7] using nanofluids. The performance of a plate heat exchanger using nanofluids was studied by Pantzali et al. [8]. They concluded that the volumetric flow rate of nanofluids required to lesser than that of water, which would produce minor pressure drop, resulting in less pumping power. Pantzali et al. [9] experimentally studied the efficacy of CuO/water nanofluids with 4 vol.% of nanoparticles as coolants in a commercial plate heat exchanger. They reported that the nature of coolant flow inside the heat exchanging equipment plays a significant role in the effectiveness of nanofluids. Maré et al. [10] experimentally compared the thermal performances of γAl_2O_3/water and CNTs/water nanofluids in plate heat exchangers with each other, and found a greater heat transfer coefficient for nanofluids compared to water. Zamzamian et al. [11] investigated the heat transfer performance of Al_2O_3/ethylene glycol and CuO/ethylene glycol nanofluids in a plate heat exchanger and described that, the heat transfer coefficient increased with temperature and vol.% of nanoparticles. Kwon et al. [12] analyzed the heat transfer performance and pressure drop of Al_2O_3 and ZnO nanofluids in a plate heat exchanger. Their investigation concluded that the performance of the plate heat exchanger at a given flow rate did not increase with the nanofluids. Haghshenas et al. [13] examined the plate and concentric tube heat exchangers by using ZnO/water nanofluids as the hot stream at a constant mass flow rate, and concluded that the heat transfer coefficients of nanofluids were much higher than those of the distilled water. Pandey and Nema [14] experimentally examined Al_2O_3/water nanofluids as coolants in a corrugated plate heat exchanger. Their outcomes were a bit contradictory with the consequences of the investigation performed earlier. They stated that the heat transfer performance of heat exchanger decreased with the

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Nomenclature

A	Area (m^2)
c_p	Specific heat capacity (J/kg K)
C	Heat capacity rate (kW/K)
D_h	Hydraulic diameter (m)
E	Exergy loss (J)
Ex	Exergy (J)
f	Friction factor
G	Flow rate (kg/N s)
g_c	Gravitational conversion factor (kg m/Ns^2)
H	Depth of corrugation (m)
h	Heat transfer coefficient (W/m^2 K)
k	Thermal conductivity (W/m K)
L	Length of the channel (m)
m	Mass flow rate (kg/s)
Nu	Nusselt number
NTU	Number of heat transfer unit
P	Wetted perimeter (m)
Pe	Peclet number
p	Pressure (Pa)
P_c	Pumping power (W)
$\dot{Q}$	Heat transfer rate (W)
Re	Reynolds number
S	Specific entropy (kJ/kg k)
T	Temperature (K)
t	Thickness of plate (m)
U	Overall heat transfer coefficient (W/m^2 K)
u	Velocity (m/s)
V	Volume flow rate (m^3/s)
W	Channel width (m)

Greek symbols

φ	Particles volume fraction (%)
ρ	Density (kg/m$^{3)}$
μ	Dynamic viscosity (N s/m^2)
α	Thermal diffusivity (m^2/s)
ε_{ex}	Exergetic heat transfer effectiveness

Subscripts

avg	Average
bf	Base fluid
c	Cold fluid
crit	Critical
e	Environment
eff	Effective
h	Hot fluid
i	Inlet
m	Mean value
max	Maximum
min	Minimum
nf	Nanofluids
np	Nanoparticles
o	Outlet

Prefix

Δ	Elemental

enhancement of nanoparticles in base fluid. Besides this, they also showed that the exergy loss increased with increasing the volume concentration.

On the basis of the comprehensive literature review, it is revealed that the effect of using CuO/water nanofluids on the heat transfer performance, the pumping power and the exergy loss in a corrugated plate heat exchanger had rarely been reported and not so clear. Thus the authors are motivated to work on CuO/water nanofluids with different vol.% of nanoparticles and try to come out with some significant findings. In this study, the main reason for choosing CuO/water as the nanofluids is its excellent thermophysical properties at an affordable cost [15–17]. Moreover, the majority of the researches were carried out by using conventional fluids rather than nanofluids in the heat exchanger. The scope of the present study is to investigate the heat transfer coefficient, the heat transfer rate, the friction factor, pressure drop, the pumping power and the exergy loss characteristics of CuO/water nanofluids in a corrugated plate heat exchanger. It is remarkable to refer that, since the system indicates a better performance, it is applicable for different sectors and industries with a most effective way.

2. Analytical approach

The heat transfer analysis has been done by using CuO/water nanofluids with 0.5% to 1.5% particle volume concentration and compared with water. Effects of volume flow rate, temperature and volume concentration of nanofluids on the performance of the plate heat exchanger have been studied as well. The nanofluid thermophysical properties, such as density [18], viscosity [19], thermal conductivity [20] and specific heat [21], have also been calculated by applying Eqs. (1) to (4).

Density of nanofluids

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np} \tag{1}$$

Viscosity of nanofluids

$$\mu_{nf} = (1+2.5\phi)\times\mu_{bf} \tag{2}$$

Thermal conductivity of nanofluids

$$\frac{k_{eff}-k_{bf}}{k_{bf}} = 3.761088\phi + 0.017924(T-273.15)-0.30734 \tag{3}$$

Nanofluids' specific heat

$$c_{p,nf} = \frac{(1-\phi)\left(\rho c_p\right)_{bf} + \phi\left(\rho c_p\right)_{np}}{\rho_{nf}} \tag{4}$$

Every channel has an equivalent flow area and a wetted perimeter is derived from

$$A_o = HW \tag{5}$$

$$P = 2(W+H) \tag{6}$$

The hydraulic diameter of the channel is calculated using the following formula,

$$D_h = \frac{4A_o}{P} \tag{7}$$

Thermal diffusivity

$$\alpha = \frac{k}{\rho c_p} \tag{8}$$

Specific flow rates for the fluids

$$G = \frac{m}{A_o} \tag{9}$$

The dimensionless Reynolds number and Peclet number can be estimated using Eqs. (10) and (11).

$$Re = \frac{GD_h}{\mu} \tag{10}$$

$$Pe = \frac{uD_h}{\alpha} \tag{11}$$

Nusselt number can be calculated using Eq. (12) [14].

$$Nu_m = \left(0.26 + 0.02\phi - 0.0051\phi^2\right)Pe^{0.27} \tag{12}$$

General formula to evaluate the convective heat transfer coefficient is

$$h = \frac{Nu\,k}{D_h} \tag{13}$$

Heat transfer rate was calculated from Eq. (14).

$$\dot{Q} = m c_p \Delta T \tag{14}$$

The friction factor of a corrugated plate heat exchanger is found from Eq. (15) [14].

$$f = \left(2.9 + 5.6\phi + 0.12\phi^2\right)Pe^{-0.13} \tag{15}$$

Pressure drop is calculated from Eq. (16) [14].

$$\Delta p = f\left[\frac{LG^2}{2D_h\rho g_c}\right] \tag{16}$$

Pumping power is estimated from Eq. (17),

$$P_c = \frac{m\Delta p}{\rho} \tag{17}$$

Exergy losses of the two different types of working fluids are derived below.

Heat lost to the environment = heat given by water (hot fluid) − heat absorbed by nanofluids (cold fluid)

$$= m_h c_{p,h}\left(T_{h,i} - T_{h,o}\right) - m_c c_{p,c}\left(T_{c,o} - T_{c,i}\right)$$

In this analysis, the heat exchanger was assumed to be adiabatic. Hence, heat loss to the environment considered negligible.

The exergy loss of a steady state open system can be calculated as follows [22].

$$E = E_h + E_c \tag{18}$$

The exergy changes for the two fluids are obtained as given below. For hot fluid (i.e. water) and cold fluid (i.e. nanofluids),

$$E_h = T_e\left[m_h\left(S_{h,o} - S_{h,i}\right)\right] \text{ or, } E_h = T_e\left[C_h \ln\left(\frac{T_{h,o}}{T_{h,i}}\right)\right] \tag{19}$$

$$E_c = T_e\left[m_c\left(S_{c,o} - S_{c,i}\right)\right] \text{ or, } E_c = T_e\left[C_h \ln\left(\frac{T_{c,o}}{T_{c,i}}\right)\right] \tag{20}$$

Replacing exergy changes in Eq. (18) by Eqs. (19) and (20), and the exergy loss is expressed as follows,

$$E = T_e\left[C_h \ln\frac{T_{h,o}}{T_{h,i}} + C_c \ln\frac{T_{c,o}}{T_{c,i}}\right] \tag{21}$$

Exergetic heat transfer effectiveness is calculated by Eq. (22),

$$\varepsilon_{ex} = \frac{\dot{Q}\left(1 - \frac{T_o}{T_a}\right)}{\dot{Q}_{max}\left(1 - \frac{T_o}{T_a}\right)_{max}} \tag{22}$$

where T_a is thermodynamic average temperature that is obtained from the correlation by Bejan et al. [23].

If $C_h > C_c$ then	If $C_h < C_c$ then
$C_h = \left(mc_p\right)_h = C_{max}$	$C_h = \left(mc_p\right)_h = C_{min}$
$C_c = \left(mc_p\right)_c = C_{min}$	$C_c = \left(mc_p\right)_c = C_{max}$

Fig. 1 shows the thermal exergy profiles in a counter flow plate heat exchanger. The present study has some consideration to simplify the analysis. In this analysis, it is assumed that the nanofluids flow through the plate heat exchanger are fully developed both thermally and hydrodynamically, and also assumed that the nanofluids flow through the plates are incompressible and turbulent flow regime. The thermophysical properties of nanofluids are considered at 300 K constant temperatures. The design specifications and geometrical dimensions of the corrugate plate heat exchanger are obtained from the literature [14]. Fig. 2 shows a schematic diagram of the heat exchanger considered in the analyses. During the analysis, the volume flow rate of hot fluid is considered at 2 L/min. Table 1 shows the properties of nanoparticle and base fluid.

3. Results and discussion

3.1. Heat transfer coefficient and heat transfer rate

Fig. 3 shows the variation of the coolant mass flow rate with the variation of volume flow rate. Higher mass flow rate is pointed out for a higher volume fraction of nanofluids. Maximum 8.27% increased mass flow rate is found for 1.5 vol.% of nanoparticles compared to water. The mass flow rate was calculated from the following relation,

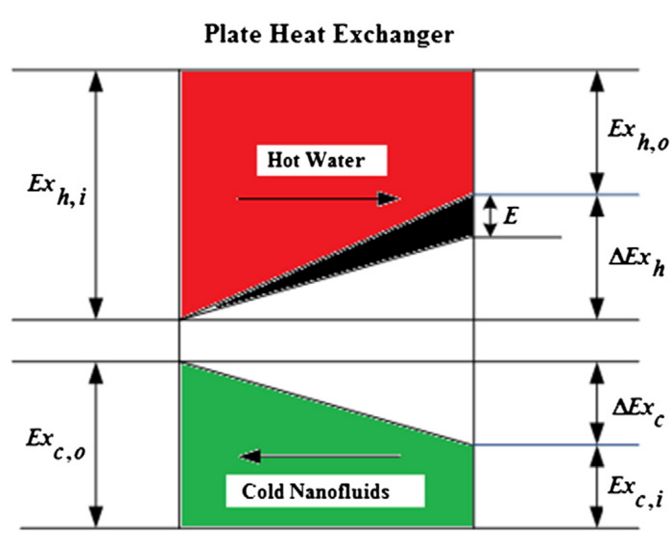

Fig. 1. Simplified diagram of the thermal exergy profiles in a counter flow plate heat exchanger.

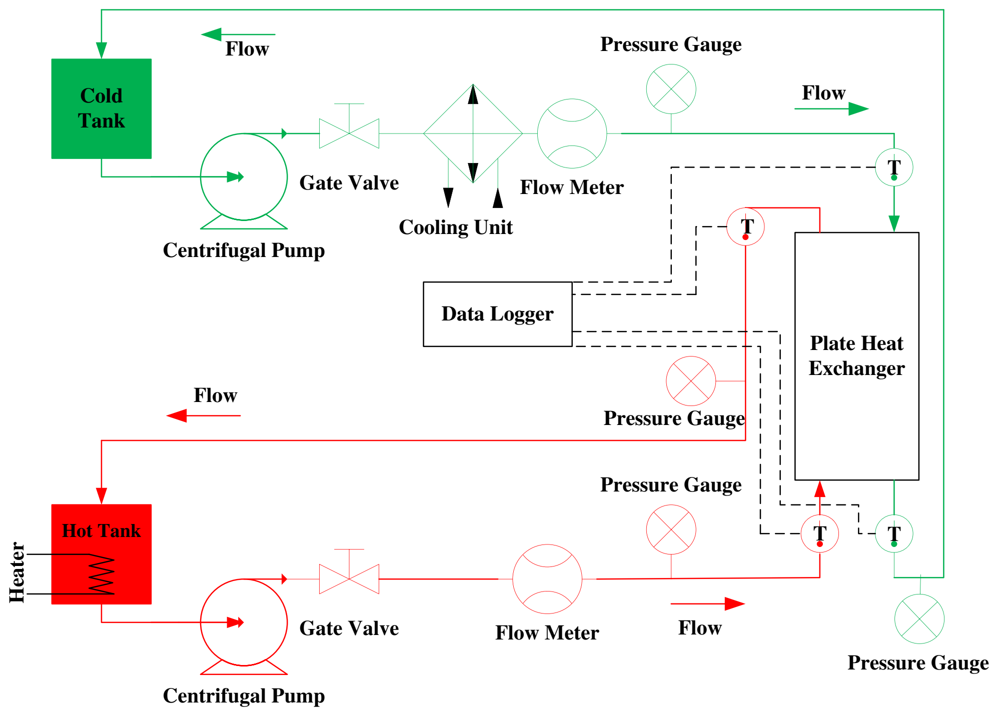

Fig. 2. Schematic diagram of a plate heat exchanger.

$m = V\rho$, whereas nanofluids density was calculated by using Eq. (1) and properties Table 1. ρ represents the density of fluid in kg/m^3. For a particular geometrical dimension, density and nanoparticle volume fraction is responsible for varying the mass flow rate as well as Reynolds number. The calculated results shows that for same volume flow rate, density and mass flow rate of CuO/water nanofluids, become higher than that of water nanofluids. Results are agreed with Sohel et al. [15].

Fig. 4 illustrates the variation of the heat transfer coefficient of water and CuO/water nanofluids with three distinct particle volume concentrations at diverse Peclet number. The Peclet number and heat transfer coefficient are calculated by using Eqs. (11) and (13). The maximum heat transfer coefficient finds 24.7% for nanofluids with compare to water at 1.5 vol.% of CuO nanoparticles. On the contrary, in case of 0.5% and 1.0% volume fraction, the heat transfer coefficient is found nearly 17.70% and 21.80% respectively higher than that of water. Usually enhanced heat transfer coefficient is observed by adding nanoparticle in base fluids. It is because of the improvement in thermal conductivity of nanofluids with relating to water (Table 2). Since, the thermal conductivity is proportional to the heat transfer coefficient. Jiang et al. [25] stated that the heat transfer coefficient of a fluid is higher when the thermal conductivity of the fluid also higher for an identical Nusselt number condition. Hence, higher convective heat transfer coefficient has observed at greater particle volume fraction. Adding nanoparticle in a base fluid might improve the heat transfer coefficient by suspending the thermal boundary layer formation. CuO/water nanofluids thermal conductivity and the effect of disturbance of the CuO nanoparticles both could rise at the higher volume fraction of nanoparticles. Therefore, the heat transfer coefficient increases with the increase of Peclet number. For a specified heat exchanger, the Peclet number is directly proportional to volume flow rate of working fluids and thermal diffusivity. Results are agreed with Kabeel et al. [26] and Hashemi and Akhavan–Behabadi [27].

Fig. 5 demonstrates the variation of the Nusselt number of the coolant with Peclet number. The Nusselt number is a dimensionless parameter that was calculated by using Eq. (12). The outcomes obviously show the increase of the Nusselt number for nanofluids with the nanoparticles volume percentage. The heat transfer coefficient (Fig. 4) and thermal conductivity are improved (Table 2) with the increase in the vol.% of CuO nanoparticles of a given Peclet number. Consequently, heat transfer coefficient and thermal conductivity of working fluids have a tendency to raise the Nusselt number. Reynolds number allows the momentum diffusion rate whereas the Peclet number concedes both momentum and thermal diffusivity rates. Thus, the Peclet number may be believed as a better platform for comparing the plate heat exchanger performance with diverse coolants [14]. The present results are similar to that observed by Ahmed et al. [28]. The analysis characterizes that the lowest Nu belonged to the water and the maximum values of Nusselt number are obtained for nanofluids. Though CuO/water nanofluids exhibited different values of Nu compared to each other, all the values are higher than the base fluid.

Table 1
Properties of nanoparticle and base fluid (water) at $T = 300$ K [24].

Thermophysical properties	Water	CuO
Density, ρ(kg/m^3)	998.2	6500
Dynamic viscosity, μ(N s/m^2)	1.00E−03	
Thermal conductivity, k(W/m · K)	0.6	20
Specific heat, c_p(J/kg · K)	4182	535.6

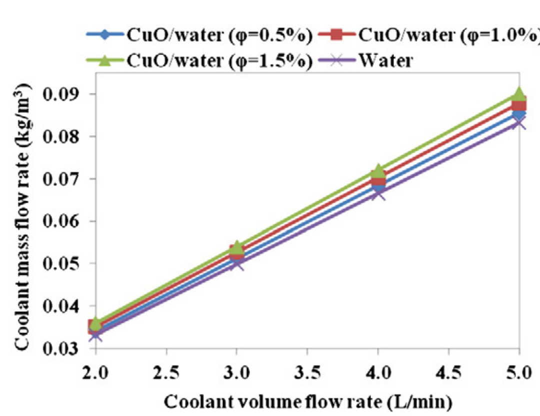

Fig. 3. Effect of coolant volume flow rate on mass flow rate.

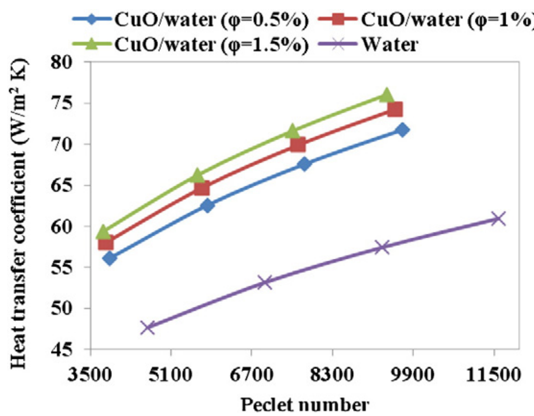

Fig. 4. Variation of heat transfer coefficient of the coolant with Peclet number.

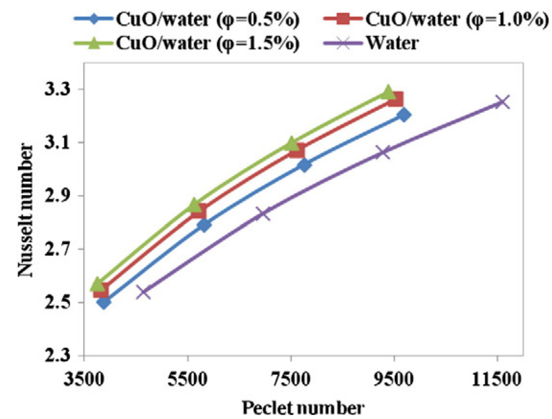

Fig. 5. Variation of Nusselt number of the coolant with Peclet number.

Fig. 6 illustrates the effect of the coolant volume flow rate on heat transfer rate of a plate heat exchanger at 2 L/min volumetric flow rate of hot water. Improved heat transfer rate is observed for a higher volume fraction of CuO/water nanofluids. On the other hand, lower heat transfer rate is noticed in case of water. From Figs. 3 and 5, expanding the nanoparticle percentage increases the mass flow rate and Nusselt number of nanofluids. This exhibit that growing the molecular thermal diffusion due to raising the nanoparticles concentration is the foremost purpose of the heat transfer improvement. From the previously conducted literature review, it can be concluded that the mass flow rate and Nu are responsible mostly for the heat transfer performance of a fluid. Heat transfer rate was calculated from the Eq. (14). The heat transfer rate is directly proportional to the temperature difference and it is obvious that the higher output temperature is found for 1.5 vol.% of nanofluids. The specific reason for higher output temperature is the more nanoparticles in base fluid. As we know, specific heat is defined as, "The heat required to increase the temperature of a unit mass of a substance by one unit of temperature." It is clear from the definition that any substance, which has a lower specific heat, should provide more temperature difference for equal heat flow.

3.2. Friction factor, pressure drop and pumping power

Fig. 7 illustrates the effect of the Peclet number on friction factor. In this analysis, the Darcy friction factor (Eq. (15)) for turbulent flow through a plate heat exchanger was used to determine the friction factor. Considering this equation, basically the value of friction factor depends on the Peclet number as well as the volume fraction of the nanoparticle. The friction factor decreases with the rise in Peclet number. The findings are completely matched with the results of Tiwari et al. [29] and Jamshidi et al. [30].

The sample of nanofluids with different nanoparticles volume percentages are employed in the pressure drop computation. Fig. 8 illustrates the pressure drop as a function of the volume fraction and the volume flow rate for the turbulent flow respectively. The pressure drop increases with the increase of the coolant flow rate and nanoparticles volume concentration. At a given coolant flow rate, the pressure drop is minimum of water and it rises with the increase of vol.% of nanoparticles. The pressure drop is a function of friction factor, density, volume flow rate, viscosity, and also the geometry of the heat exchanger. The higher pressure drop is observed for nanofluids due to its higher density. Results are agreed with Kabeel et al. [26] and Tiwari et al. [29].

Fig. 9 demonstrates the variation of pumping power as a function of coolant volumetric flow rate. Pumping power increases with the increase of the nanoparticles volume fraction, and minimum pumping power is obtained from water. Pumping power was calculated from Eq. (17). According the pumping power equation, the variation of pumping power is associated with the mass flow rate, pressure drop and density of working fluids. The enhancement of vol.% of CuO nanoparticles guides to increase in mass flow rate, density and pressure drop, which is shown in Fig. 3, Table 2 and Fig. 8, respectively. Consequently, the pumping power increases with the increase of nanoparticles volume fraction. Pantzali et al. [9] and Kabeel et al. [26] found the same results.

3.3. Exergy loss and exergetic heat transfer effectiveness

Fig. 10 illustrates that the effect of coolant volume flow rate on exergy loss. Water shows approximately 24%, 16.25% and 8% higher exergy loss compares to nanofluids for volume faction 1.5, 1.0 and 0.5% respectively. It is expected that entropy generation number might be decreased to gain exergy. When using nanofluids as agent fluid, it is known that, by adding different nanoparticles to the water, the entropy generation number is reduced [31]. Exergy loss was calculated from Eq. (21). It can be described that the addition of nanoparticles in base fluids leads to enhance the effective heat transfer surface area. Thermal conductivity increases due to the hydrodynamic effect of Brownian motion of nanoparticles, molecular level layering of the liquid at liquid particle interface, effect of nanoparticle clustering and the

Table 2
Thermophysical properties of the CuO/water nanofluids at different volume concentrations.

Fluid	Thermal conductivity, k(W/m K)	Density, ρ(kg/m^3)	Specific heat, c_p (J/kg K)	Viscosity, μ(mPa s)	Thermal diffusivity, α (m^2/s) $\times 10^6$
0.5% CuO/water	0.72	1026	4066	1.012	0.1748
1.0% CuO/water	0.73	1053	3957	1.025	0.1776
1.5% CuO/water	0.74	1081	3853	1.037	0.1437

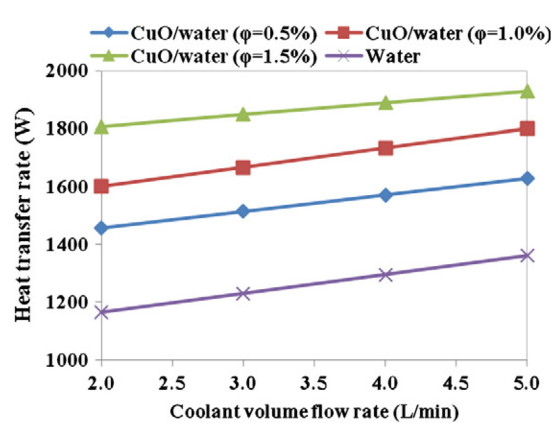

Fig. 6. Effect of coolant volume flow rate on heat transfer rate.

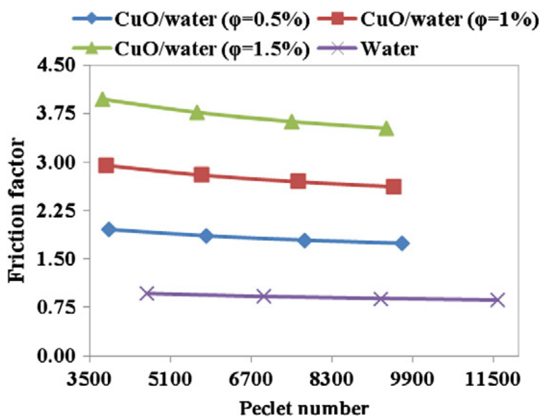

Fig. 7. Variation of friction factor of the coolant with Peclet number.

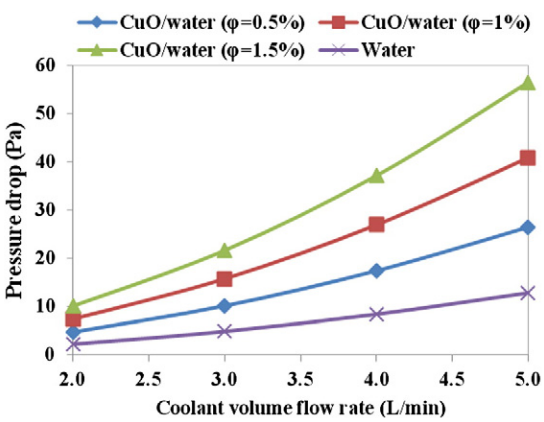

Fig. 8. Effect of coolant volumetric flow rate on pressure drop.

nature of the heat transport in nanoparticles. Alternatively, with a growth in nanoparticles volume fraction, the useful viscosity of the nanofluids buildups and successively the fluid friction involvement in the entropy generation rise. Nevertheless in whole, entropy generation decreases in the gap. The above reasons might be causing an improvement in exergy efficiency and reduce the exergy loss. CuO/water with 1.5 vol.% of nanoparticles may be a good choice for heat transfer fluid because of their exergy efficiency is higher than the water and other vol.% of nanoparticles.

Fig. 11 illustrates the effect of coolant volume flow rate on exergetic heat transfer effectiveness at various volume concentrations of nanoparticles. Exergetic transfer effectiveness is evaluated from Eq. (22).

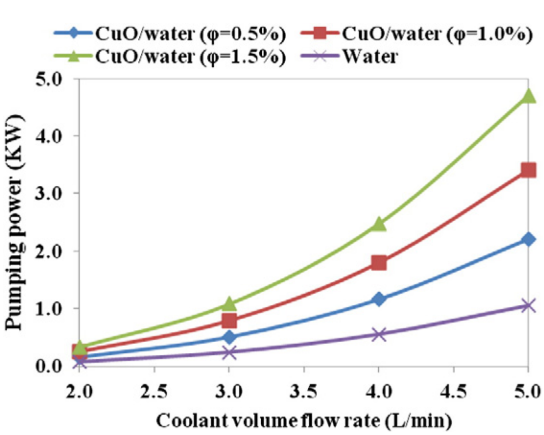

Fig. 9. Effect of coolant volume flow rate on pumping power.

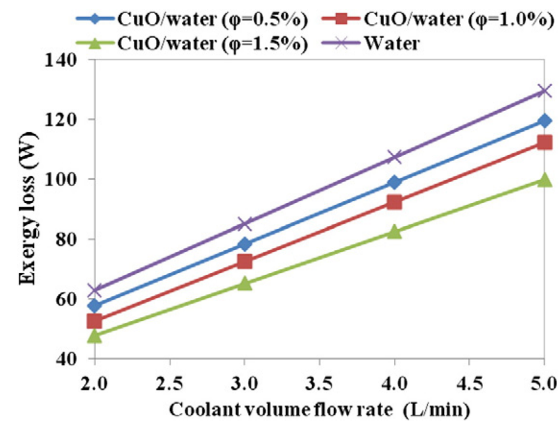

Fig. 10. Effect of coolant volume flow rate on exergy loss.

Nanoparticles with 1.5 vol.% shows 34% higher exergetic heat transfer effectiveness compare to water. Besides, 1 vol.% and 0.5 vol.% of nanoparticles indicate higher effectiveness 22% and 12%, respectively. Exergetic transfer effectiveness is discussed when heat exchangers operate above/below the environmental temperature. Increasing the nanoparticles in base fluid will enhance the heat transfer rate (Fig. 6) and decrease the exergy loss (Fig. 10). Hence, the exergetic heat transfer effectiveness in PHE increases by using nanofluids [29].

4. Conclusion

In the present study, we have focused on the benefits of using CuO/water nanofluids in a corrugated plate heat exchanger. We have studied the effects of volume flow rate, nanoparticles volume fraction, mass flow rate, density, thermal conductivity, Reynolds number and Nusselt number on heat transfer coefficient, heat transfer rate, friction factor, pressure drop, pumping power and exergy loss of the heat exchanger. Analytical outcomes revealed that, CuO/water nanofluids at 0.5%, 1.0% and 1.5 vol.% could increase the heat transfer coefficient about 17.70%, 21.80% and 24.7%, respectively with compared to water. Besides, significant heat transfer rate is noticed for nanofluids. The study also remarked that the increment of particle volume fraction and volume flow rate of nanofluids could enhance the friction factor which will result in a higher pressure drop and pumping power. Analytical results reveal that, CuO/water nanofluids could reduce the exergy destruction by 24%, 16.25% and 8% for 1.5 vol.%, 1.0 vol.% and 0.5 vol.% of nanoparticles, respectively compared to water. Therefore, average 34%, 22% and 12% enhanced exergetic heat transfer effectiveness is found for 1.5 vol.%, 1.0 vol.% and 0.5 vol.% of nanoparticles compare to water.

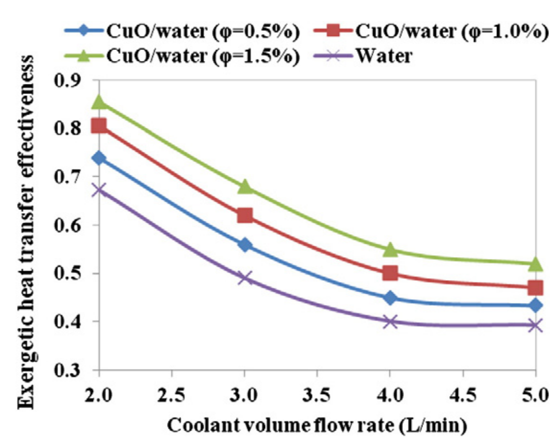

Fig. 11. Effect of coolant volume flow rate on exergetic heat transfer effectiveness.

For equal volume flow rate, mass flow rate could be increased by injecting nanoparticles in a base fluid only which will represent the higher heat transfer coefficient. Density and thermal conductivity are the most important parameters for efficiency improvement of a heat exchanger. From this study, it may be concluded that the performance of a heat exchanger can be enhanced by converting the working fluid with nanofluids.

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