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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

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