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Thermohydraulic performance analysis of a spiral heat exchanger operated with water–alumina nanofluid: Effects of geometry and adding nanoparticles

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ABSTRACT

This paper examines thermohydraulic performance of a spiral heat exchanger operated with the water–alumina nanofluid under turbulent flow regime. The hot water flows in one side while the cold nanofluid flows inside the other side of the heat exchanger. The effects of Reynolds number, mass flow rate, nanoparticle concentration and gap between the plates on the convective heat transfer coefficient, pumping power, overall heat transfer coefficient as well as effectiveness of the heat exchanger are evaluated. The average heat flux enhances with the increase of concentration and Reynolds number, while reduces by increasing the gap magnitude. Moreover, convective heat transfer coefficient and overall heat transfer coefficient enhance with increasing Reynolds number and concentration. Thereby, the convective heat transfer coefficient increases about 134.4% with increase of Reynolds number from 4000 to 11,000 at concentration of 2%, while it enhances almost 26.3% with increment of the concentration from 0 to 5% at Reynolds number of 10,000. The pumping power intensifies by increasing either concentration or Reynolds number, and at higher Reynolds numbers, the effect of concentration on the pumping power becomes more noticeable. Moreover, the pumping power intensifies by decreasing the gap, and this augmentation is more significant at higher concentration. Based on constant mass flow rate, however, an optimum concentration is obtained in which maximum heat transfer occurs. Meanwhile, the pumping power decreases by increasing the concentration at a constant mass flow rate. Furthermore, the effectiveness enhances by increasing the Reynolds number and reducing the gap.

1. Introduction

Nanofluids, i.e. suspensions of solid nanoparticles dispersed in conventional fluids, have attracted attention of many researchers due to their various applications in different industries such as thermal engineering [1]. In fact, they are introduced as the promising thermal fluids owing to their excellent thermal attributes [2]. So far, many studies have been performed in this area, and several scholars have also reviewed and categorized the investigations carried out in this field [3]. There are some contradictions among the results reported in the relevant literature. For instance, Nebbati and Kadja [4] reported noticeable enhancements in the case of employing nanofluids instead of base fluids while some other researchers such as Lelea and Laza [5] mentioned that using nanofluids does not improve thermal characteristics. Although there are such contradictions in some of the studies, most of investigations conducted in this area show that nanofluids improve heat transfer attributes considerably in different thermal devices [6].

Heat exchanger is a device in which energy is transported from one fluid to another fluid through a solid wall [7]. Heat exchangers are nearly the most utilized devices in industries related to thermal engineering and management such as power plants, petrochemical industries, refineries, drug industries, air conditioning, and so on. Heat transfer in heat exchangers can be carried out in arrangements of liquid-gas, liquid-liquid, and gas-gas. Heat exchangers are employed for warming a cold fluid or cooling a hot fluid or both together [8].

Due to extraordinary features of nanofluids, many researchers have examined application of them in different heat exchangers. Karimi and Afrand [9] studied a heat exchanger under an external flow. Air was chosen as the external fluid while water and MgO-CNT/EG hybrid nanofluid were chosen as the radiator fluids. The results showed that radiators having vertical pipes possess superior efficacy up to 10% higher than radiators with horizontal pipes. Bahiraei et al. [10] assessed the performance and hydrothermal attributes of a biological nanofluid in a miniature counter-flow double-tube heat exchanger considering

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Nomenclature

C_{min}	minimum heat capacity rate, W/K
c_p	specific heat, J/kg K
D_h	hydraulic diameter, m
d_p	particle diameter, nm
G_k	generation of turbulent kinetic energy, W/m^3
k	thermal conductivity, W/mK
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
q	heat transfer rate, W
q''	heat flux, W/m^2
Re	Reynolds number
T	temperature, K
v	velocity, m/s
$\dot{V}$	volumetric flow rate, m^3/s

Greek symbols

ε	effectiveness
κ	turbulent kinetic energy, J/kg
μ	dynamic viscosity, Pa·s
μt	turbulent viscosity, m^2/s
ρ	density, kg/m^3
$\sigma\varepsilon$	Prandtl number for rate of dissipation
φ	volume concentration

Subscripts

bf	base fluid
c	cold
h	hot
i	input
LMTD	logarithmic mean temperature difference
m	mean
nf	nanofluid
o	output
p	particles
w	wall

particle migration. The results showed that at high concentrations and Reynolds numbers, particle migration has a significant effect on effectiveness of the heat exchanger. Bahmani et al. [11] investigated heat transfer characteristics for turbulent flow of the water–alumina nanofluid in a counter-flow double-pipe heat exchanger. The results revealed that increase of the nanoparticle concentration or Reynolds number results in increment of Nusselt number and convection heat transfer coefficient. In addition, with increasing the nanoparticle concentration, the outlet temperature of nanofluid as well as the wall temperature increased. Rabbani Esfahani and Mohseni Languri [12] conducted exergy analysis of graphene oxide nanofluids in a shell and tube heat exchanger. The results showed that applying graphene oxide nanofluids as the hot fluid leads to lower exergy loss in the heat exchanger under both laminar and turbulent flow conditions. Pourhoseini et al. [13] investigated the effect of employing a silver–water nanofluid on overall heat transfer coefficient of a plate heat exchanger. The results indicated that the overall heat transfer coefficient enhances by increasing either nanofluid concentration or volume flow rate. Bhattad et al. [14] performed numerical and experimental evaluations on a plate heat exchanger using hybrid nanofluid (Al_2O_3 + carbon nanotube/water) as the coolant for investigating the effect of nanoaprticle concentration on pressure loss and heat transfer attributes. It was shown that with employing this nanofluid, heat transfer coefficient increases by 39.16% with a minor increment in pumping power. Khoshvaght-Aliabadi et al. [15] investigated hydrothermal features of an agitated-vessel U tube heat exchanger. The authors utilized two passive enhancement methods, namely spiky twisted tapes and water based metallic nanofluids to enhance the heat transfer rate. A significant enhancement in the heat transfer amount was observed with employing these techniques. Esfe et al. [16] carried out a Pareto optimal design of COOH-carbon nanotube nanofluid in a heat exchanger to decrease pressure loss and enhance the heat transfer coefficient. The optimum results indicated that to achieve the lowest pressure drop, the relative nanoparticle concentration should be at the minimum interval, and to reach the highest heat transfer coefficient, the relative nanoparticle concentration should be at the maximum interval.

Among various kinds of heat exchangers that are employed for cooling and heating the fluids in different industries, Spiral Heat Exchanger (SHE) has a remarkable significance. A SHE includes two sheets that are rolled around a central rod and thus, two separate concentric ducts are developed. SHEs have many advantages over other kinds of heat exchangers. The flow in them can be arranged as countercurrent that is a key point to reach an efficient heat transfer between two fluids. Moreover, the convective heat transfer of spiral flows is great with a moderate pressure drop. Furthermore, SHEs typically have great area-to-volume ratios, which is very important for installation and shipping. Another interesting feature of SHEs is low tendency to fouling. This is owing to their specific geometry that causes a constant alteration in direction and therefore, intensifies local turbulence and reduces fluid stagnant zones. The advantages of these heat exchangers such as great heat transfer effectiveness, small pumping power and low fouling make them excellent candidates for utilization in thermal applications.

Although several investigations have been conducted on spiral heat exchangers operated with ordinary fluids, the studies performed on these heat exchangers is very minimal compared with other heat exchangers. Segundo et al. [17] carried out optimization of a spiral heat exchanger through wind-driven optimization and a new variant of this algorithm with the inserting a statistic distribution to self-adapting of the evolution variables. The parameters adopted for the optimization were the width, length and thickness of the heat exchanger as well as the space between the channels for cold and hot flows. Two cases were introduced in which minimizing the cost and maximizing the overall heat transfer coefficient were considered. Decreases almost 4.46 and 23% were achieved for the cost and increments approximately 18.8 and 16.4% were obtained for the overall heat transfer coefficient for each

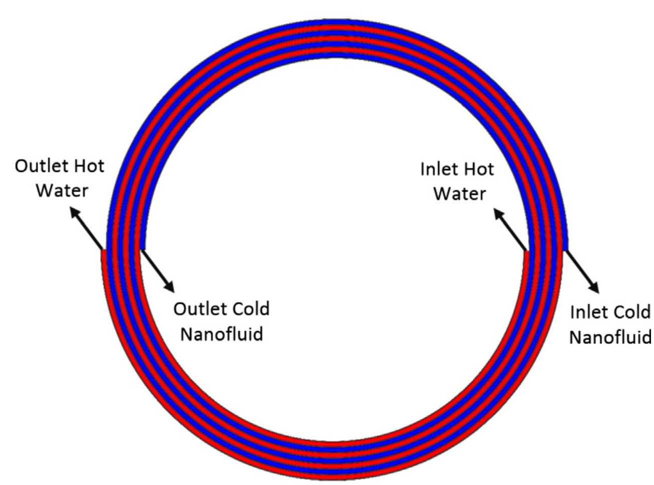

Fig. 1. The locations of inlet and outlet of each flow (hot water and cold nanofluid).