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Efficacy of an eco-friendly nanofluid in a miniature heat exchanger regarding to arrangement of silver nanoparticles

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ABSTRACT

The performance and hydrothermal characteristics of a biologically produced nanofluid in a miniature counter-flow double-tube heat exchanger are investigated considering particle migration. Hot water flows in the annulus side, and the nanofluid is employed as the coolant in the tube side. The particles used are silver nanoparticles synthesized through plant extract method from green tea leaves. Particle migration disturbs particle concentration distribution, and a more non-uniform concentration is developed by increasing either Reynolds number or mean concentration. The results reveal that at great concentrations and Reynolds numbers, particle migration possesses a significant effect on efficacy of the heat exchanger. Particle migration increases the heat transfer rate while decreasing pumping power. As concentration and Reynolds number increase, the overall heat transfer coefficient and heat transfer rate enhance. The effectiveness and number of transfer units decrease by increasing Reynolds number, and augment with concentration increment. Pumping power significantly intensifies by increasing Reynolds number, but it reduces by augmenting concentration, which is a very positive finding. In addition, the ratio of heat transfer rate to pressure drop increases with concentration increment and therefore, the nanofluid has greater merit to be applied in the heat exchanger at higher concentrations. Moreover, the overall heat transfer coefficient enhances by increasing the water temperature in annulus side inlet, which is due to an increase in convective heat transfer coefficient of the tube side because of the nanofluid thermal conductivity augmentation.

1. Introduction

Water, ethylene glycol, and engine oil have low thermal conductivities, and this issue limits the enhancement of the efficiency and compactness of devices related to electronic, automotive and aerospace industries. Improvement of thermal conductivity by suspension of fine solid particles in liquids is one of the solutions to prevent this disadvantage. Thermal conductivity is a key property in enhancing thermal performance of a heat transfer fluid. Since thermal conductivity of solid particles is greater than that of fluids, suspended particles are expected to be able to augment thermal conductivity and thermal performance. Many academics have carried out studies on thermal conductivity of these suspensions. Some of problems such as abrasion and clogging are observed due to size of suspended particles that are of millimeter or micrometer order. Therefore, these types of large particles are not appropriate for heat transfer improvement. Newly, advancements in manufacturing technologies have made synthesis of particles in the nanometer scale possible. A two-phase mixture composed of continuous liquid and dispersed nanoparticles is called ‘nanofluid’.

Many researchers have performed studies on different nanofluids and have reported that nanofluids possess superior thermal characteristics [1]. Singh and Gupta [2] carried out a review on heat transfer augmentation using nanofluids, and mentioned that nanofluids have been proved as superior heat transfer fluids despite of various contradictions in results by different research groups. Wang et al. [3] utilized a carbon-nanotube nanofluid for high efficient solar steam generation, and reach evaporation efficiency up to 46.8%. Malvandi et al. [4] investigated the effect of temperature-dependent thermophysical properties on nanoparticle migration, and showed different modes of nanoparticle migration induced by asymmetric heating. Sheikholeslami et al. [5] studied magnetic field influence on free convection of nanofluid in a porous media, and stated that increasing Hartmann number leads to reduce Nusselt number. Imani-Mofrad et al. [6] evaluated effect of filled bed on performance of a cooling tower with ZnO nanofluid, and claimed that the nanofluid improves effectiveness of the cooling tower.

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In the examinations reported so far, a nanofluid was often assumed to be a homogeneous liquid, and its properties were considered to be constant throughout the system [7]. These assumptions are not realistic, and can lead to misunderstandings in the phenomena related to nanofluids [8]. Even if nanoparticles are in a stationary matrix, they can possess Brownian motion resulting from their small mass and size. Taking into account the effects of particle migration is one of the important approaches which can be efficient to better recognize the behavior of nanofluids. Nanoparticle migration might lead to the non-uniform concentration in nanofluids and so, can alter distribution of thermophysical properties such as thermal conductivity and viscosity.

Very few studies have been carried out about particle migration effects on features of nanofluids [9]. Ding and Wen [10] investigated the motion of nanoparticles in laminar pressure-driven pipe flows for dilute suspensions. It was found that concentration near the wall is significantly lower than concentration at the pipe center. Bahiraei [11] evaluated flow and heat transfer of the suspensions containing Fe_3O_4 nanoparticles in turbulent regime. The effects of Brownian motion, shear rate and viscosity gradient on nanoparticle migration were considered. The concentration value at the vicinity of the wall was lower than that at the tube center.

In the evaluations performed on nanofluids, different materials have been used as nanoparticles [12]. In recent years, silver nanoparticles have extensively been employed in many applications such as medical devices, thermal systems, and clothing due to their unique properties. Usually, the techniques for the synthesis of silver nanoparticles involve the reduction of silver ions in the solution or at high temperatures inside gaseous environments [13]. However, the reducing reagents, such as sodium borohydride, can intensify the environmental toxicity or biological hazards [14]. Furthermore, the production costs enhance at high temperatures. Thus, development of green preparation techniques for silver nanoparticles by applying eco-friendly solvents and nontoxic reagents is very important. Sun et al. [15] presented a simple, environmentally friendly, and cost-effective method to synthesize silver nanoparticles utilizing tea leaf extract. The silver nanoparticles were synthesized using silver nitrate and tea extract, and the reaction was conducted at room temperature for two hours. Sarafraz and Hormozi [16] used this process to prepare the nanofluid containing silver nanoparticles. They studied convective heat transfer of this biological nanofluid inside a heat exchanger. The results revealed a significant enhancement of heat transfer coefficient up to 67% for concentration of 1%.

Assessment of the related literature reveals that there is no study about using nanofluids in heat exchangers considering nanoparticle migration. As mentioned before, nanoparticle migration can cause non-uniform concentration and so, can change the distribution of thermophysical properties. This alters temperature and velocity profiles and therefore, affects the characteristics of nanofluids in heat exchangers. It should be noted that the heat exchanger under study is a miniature heat exchanger and therefore, particle migration can affect flow and heat transfer characteristics significantly. This is due to the fact that particle migration is more significant in smaller geometries according to Ref. [8]. In addition, silver nanoparticles have a superior thermal conductivity and particularly those prepared by green methods can enhance performance of heat exchangers without environmental toxicity intensification. Hence, in the present contribution, an effort is made to investigate thermal and hydraulic characteristics of a biological nanofluid flow containing Ag nanoparticles in a miniature heat exchanger regarding to particle migration. To our knowledge, this research is the first investigation on efficacy of nanofluids in a heat exchanger considering particle migration.

2. Definition of the nanofluid and heat exchanger

The numerical simulation using the control volume approach is performed on a biological nanofluid containing Ag nanoparticles with the diameter of 55 nm. The base fluid is ethylene–glycol/water (50:50 by volume). The technique to synthetize this nanofluid has been completely introduced in [16]. This technique is a green and simple method to prepare nanofluids containing silver nanoparticles by tea extract. The nanoparticles possess functional groups from the tea extract capped on the surface including amides, carboxyl, and phenols. Sun et al. [15] have proved that the silver ion release from nanoparticles synthesized via this technique is lower in comparison with the other methods. Additionally, this approach demonstrates a good stability resulting from the functional groups from the tea extract capped on the nanoparticles.

The miniature heat exchanger under investigation is a double-tube counter-flow one according to Fig. 1. The length of the heat exchanger, diameter of the inner tube, and diameter of the outer tube are respectively 1 m, 1 mm and 2 mm. Also, the wall has a thickness of 0.2 mm, and its material is copper. The hot water flows in the annulus side, and the nanofluid is employed as the coolant in the tube side. The flow directions of both hot water and nanofluid in the heat exchanger are illustrated in Fig. 1.

3. Theory of particle migration

Three mechanisms, i.e. non-uniform shear rate, viscosity gradient and Brownian diffusion, affect particle distribution in shear flows, which have different effects on particle migration.

For a steady-state and fully developed nanofluid flow through a horizontal tube, establishing mass balance for the particle phase will give [10]:

$$J + r\frac{dJ}{dr} = 0 \tag{1}$$

where r is the radial coordinate and J is the total flux of particles in r direction. As mentioned above, the total flux of particle migration contains three terms:

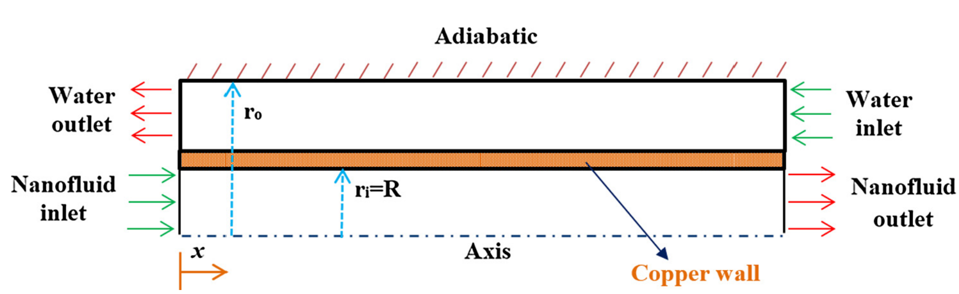

Fig. 1. Miniature heat exchanger under study.