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Thermal and hydraulic characteristics of a minichannel heat exchanger operated with a non-Newtonian hybrid nanofluid

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ABSTRACT

In this study, thermal and hydraulic characteristics of a non-Newtonian hybrid nanofluid are investigated in a double-tube minichannel heat exchanger. The nanofluid contains two different nanoparticles, namely Tetra Methyl Ammonium Hydroxide (TMAH) coated Fe_3O_4 nanoparticles and Gum Arabic (GA) coated Carbon Nanotubes (CNTs). The nanofluid and water flow in the tube side and annulus side of the heat exchanger, respectively. Variable thermal conductivity and viscosity are applied in the simulations. Numerical solutions are performed based on both Reynolds number and mass flow rate, and the heat transfer rate in the heat exchanger, overall heat transfer coefficient, effectiveness, pressure drop, pumping power, and performance index are evaluated under different conditions. The results show that adding the nanoparticles causes a further increment in heat transfer rate at lower Reynolds numbers, such that the increase in heat transfer rate of the nanofluid compared with water at Reynolds numbers 500 and 2000 is 53.8% and 28.6%, respectively. The findings obtained show a promising view for use of this hybrid ferrofluid in mini heat exchangers.

1. Introduction

The device that is employed to exchange heat between two fluids with different temperatures while keeping them from mixing with each other is called “heat exchanger”. Heat exchangers are utilized in many applications such as nuclear reactors, air conditioning systems, power plants, electronics cooling, chemical processing, and aeronautical applications. They are designed to achieve maximum heat transfer rate, minimum volume and weight, small pressure drop, great effectiveness, and also low cost. In many situations, the weight and size of heat exchangers are very important parameters especially in devices related to aerospace and electronics.

The use of fins is one of the common methods to improve heat transfer rate in heat exchangers. However, in addition to intensifying pressure drop, this method increases the weight and volume of heat exchangers and therefore, its application has many limitations.

Other than changes in geometry of heat exchangers, improving the properties of working fluids can enhance the heat transfer rate in heat exchangers. Using nanofluids, which are suspensions composed of nanoparticles and a base fluid, in heat exchangers has been highly attended by researchers in recent years [1–3]. Bahrehmand and Abbassi [4] investigated heat transfer of Al_2O_3 nanofluid flow inside a shell and helical tube heat exchanger. The results indicated that the presence of 0.2% and 0.3% volume concentration increases the heat transfer rate by approximately 14% and 18%, respectively. The results also showed that the coil-side, shell-side and overall heat transfer coefficients enhance with the concentration increment. It was found that for the same mass flow rate, the heat transfer rate of nanofluid enhances noticeably compared to water. Shahrul et al. [5] evaluated the performance of a heat exchanger operated with different nanofluids. The convective heat transfer coefficient was found to be 2–15% higher than that of water. In addition, energy effectiveness improved about 23–52% for the nanofluids. Maximum effectiveness was obtained for the ZnO–water nanofluid and lowest one for the SiO_2–water nanofluid. Khajeh Arzani et al. [6] investigated heat transfer enhancement of graphene nanoplatelet-based water nanofluids including non-covalent nanofluid (GNP-SDBS-based water nanofluid) and covalent nanofluid (GNP-COOH-based water nanofluid) in an annular heat exchanger. The suspended GNP-SDBS and GNP-COOH nanoparticles significantly enhanced the heat transfer performance of the base fluid. At constant concentration, the higher Reynolds number caused the higher Nusselt number. In addition, the friction factor was also declined as the Reynolds number increased.

A modern category of nanofluids is the set of magnetic nanofluids that are produced, in fact, by suspending magnetic nanoparticles in a base fluid. Magnetic nanofluids or ferrofluids,

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Nomenclature

C	heat capacity rate (W/K)
C_{min}	minimum heat capacity rate (W/K)
c_p	specific heat capacity (J/kgK)
k	thermal conductivity (W/mK)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
q	heat transfer rate (W)
Re	Reynolds number
T	temperature (K)
U	overall heat transfer coefficient (W/m^{2}K)
V	velocity (m/s)
$\dot{V}$	volumetric flow rate

Greek symbols

ε	effectiveness
η	performance index (W/Pa)
μ	viscosity (kg/ms)
ρ	density (kg/m^3)
φ	concentration (%)

Subscripts

bf	base fluid
c	cold
CNT	carbon nanotube
h	hot
i	inlet
LMTD	logarithmic mean temperature difference
M	magnetite
nf	nanofluid
o	outlet
w	water

in addition to great thermal properties, have important magnetic properties as well. Due to having magnetic properties alongside flowability, many researchers have been attracted to this class of nanofluids in recent years. Magnetic nanofluids can have many applications in different areas such as bioengineering, electronic packing, and heat transfer [7–9]. In the field of thermal engineering, the ability to control heat transfer process and flow of magnetic nanofluids by applying an external magnetic field has opened up new horizons in the applications of heat transfer enhancement, and various studies have been conducted in this area. Aminfar et al. [10] applied the mixture model to investigate the hydrothermal characteristics of a ferrofluid in a vertical rectangular duct under a non-uniform magnetic field generated by an electric current. The results showed that applying this magnetic field causes the velocity gradient to increase near the walls so that the local Nusselt number is enhanced. They also demonstrated that the magnetic field creates a pair of vortices which can improve the heat transfer rate and prevent sedimentation of nanoparticles. Some researchers have employed magnetic nanofluids as coolant in different heat exchangers. Mousavi et al. [11] evaluated the effect of magnetic field on a magnetic nanofluid flow inside a sinusoidal double-tube heat exchanger. They focused on the effect of variable magnetic field in the heat transfer of heat exchanger. The inner tube was sinusoidal while the outer tube was considered smooth. The nanofluid containing Fe_3O_4 nanoparticles flowed in the internal tube as hot fluid and air flowed counter currently as cold fluid in external tube. Nusselt number and heat transfer increased and this enhancement intensified at great Reynolds numbers. Shakiba and Vahedi [12] investigated the hydrothermal characteristics of a magnetic nanofluid (water and 4 vol.% Fe_3O_4) in a double-pipe heat exchanger, which was exposed to a non-uniform magnetic field with different intensities. The magnetic field was generated by an electric current going through a wire located parallel to the inner tube. The results showed that applying this kind of magnetic field causes kelvin force to be produced perpendicular to the flow, changing axial velocity profile and creating a pair of vortices which lead to an increase in Nusselt number, friction factor and pressure drop. Bahiraei et al. [13] examined irreversibilities caused by heat transfer and friction for a magnetic nanofluid flow in a double-tube heat exchanger with the aid of entropy generation rates. The results showed that heat transfer is the main cause in entropy generation at low concentrations while friction is the main factor at high concentrations.

Recently, hybrid nanofluids have received increasing interest since they can significantly enhance thermophysical properties and heat transfer characteristics. Hence, some academics have been motivated to evaluate the hydrothermal characteristics of hybrid nanofluids in different thermal devices. In fact, for the production of hybrid nanofluids, two or more different nanoparticle materials are employed, and one of hybrid nanofluids contains CNTs and magnetic nanoparticles. Functionalizing CNTs utilizing magnetic nanoparticles can combine the features of magnetic nanoparticles and CNTs, which can prepare materials with new chemical and physical properties. In reality, the magnetic particles attach to the wall of CNTs *via* hydrophobic interactions. Consequently, the ferromagnetic property is added to the CNTs without alteration in the great yield of tube formation.

Very few studies have been conducted on hybrid ferrofluids. Baby and Sundara [14] investigated the thermal conductivity of Fe_3O_4/CNT hybrid nanofluid. It was shown that the thermal conductivity augments in the presence of magnetic field. The thermal conductivity enhancement was attributed to the chain formation of magnetic nanomaterials under the magnetic field. Hong et al. [15] studied thermal conductivity of the hybrid nanofluid containing CNT and Fe_2O_3 nanoparticles in water under various magnetic field strengths. The authors stated that the thermal conductivity can be enhanced *via* external magnetic fields. They mentioned that the Fe_2O_3 nanoparticles create aligned chains under magnetic field and help to attach the CNTs, which causes thermal conductivity increment. In addition, some researchers have employed hybrid nanofluids as coolants in heat exchangers. Aghabozorg et al. [16] applied a hybrid nanofluid containing Fe_2O_3–CNT nanoparticles inside a horizontal heat exchanger. The nanoparticles with 30 nm diameter and distilled water as base fluid were utilized. It was found that the Fe_2O_3–CNT hybrid nanofluid demonstrates greater heat transfer coefficient in comparison with the base fluid.

In the current study, thermal and hydraulic characteristics of a minichannel heat exchanger operated with the CNT/Fe_3O_4–water hybrid nanofluid are investigated. A review of the relevant literature reveals that hybrid ferrofluids have been considered so far as Newtonian fluids, while the ferrofluid under study here is taken into account as a non-Newtonian nanofluid, such that the effect of shear rate on viscosity is considered. To our knowledge, this contribution is the first research in which a non-Newtonian hybrid ferrofluid is employed as coolant in a heat exchanger. The main objective is to evaluate the hydrothermal attributes of the mini heat exchanger by employing the hybrid magnetic nanofluid as the working fluid. In addition, the effects related to each of the nanoparticles (*i.e.* CNT and Fe_3O_4) on the heat exchanger characteristics including the heat transfer rate, overall heat transfer coefficient, effectiveness, pressure drop, pumping power, and performance index are reported and discussed.

2. Definition of the heat exchanger and nanofluid

In this study, flow and heat transfer characteristics of a hybrid ferrofluid are investigated in a double-pipe counter-flow

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