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Flow and heat transfer characteristics of magnetic nanofluids: A review

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ABSTRACT

Magnetic nanofluids (MNFs) are suspensions which are comprised of a non-magnetic base fluid and magnetic nanoparticles. In this modern set of suspensions which can be called smart or functional fluids, fluid flow, particles movement and heat transfer process can be controlled by applying magnetic fields. Regarding unique characteristics of MNFs, studies in this field have witnessed a phenomenal growth. This paper reviews and summarizes recent investigations implemented on MNFs including those conducted on thermophysical properties, natural convection, forced convection, boiling as well as their practical applications. Moreover, this review identifies the challenges and opportunities for future research.

1. Introduction

Recent technological advancements in the field of electronics and thermal systems have led to an ever increasing demand for heat transfer systems with higher efficiencies. Thus far, numerous studies have been carried out on heat transfer augmentation using both active and passive methods. In active methods such as mechanical agitating, rotating and vibration, there is a need to apply external energy, while passive ones include methods such as improvement of fluid thermal properties and surface geometry. One of the passive methods that has attracted the attention of many researchers in recent years is application of nanofluids. After Choi [1] who introduced the novel idea of adding nanoparticles to base fluid in order to improve thermal characteristics, many researchers applied nanofluids for heat transfer enhancement in various thermal systems [2–8].

Among investigations in the field of nanofluids, some studies have focused on MNFs. MNFs or ferrofluids are suspensions of a non-magnetic base fluid and magnetic nanoparticles which are coated with surfactant layers such as oleic acid to provide proper stability [9,10]. Magnetic nanoparticles used in MNFs are usually prepared in different sizes and forms from metal materials (ferromagnetic materials) such as iron, nickel, cobalt, as well as their oxides such as spinel-type ferrites, magnetite (Fe_3O_4), and so forth.

The main feature of this type of nanofluids is that apart from improvement of thermal properties, they possess both magnetic properties similar to other magnetic materials and flowability like other fluids. Such unique characteristic makes it possible to control fluid flow, heat transfer and particles movement by applying magnetic fields and consequently, they have a great potential for being used in various fields such as bioengineering, electronics as well as thermal engineering [11–13]. Moreover, there is a specific type of MNFs, called temperature-sensitive magnetic fluids, whose magnetization is considerably dependent on temperature and hence, they are considered as a promising fluid in miniature energy conversion and heat transport systems [14,15].

In the field of heat transfer, using MNFs has attracted the attention of many researchers in recent years because of their capability to be controlled under magnetic fields. The objective of this paper is to present an overview of literature dealing with recent investigations on MNFs in different fields of thermal engineering. It is expected that this in-depth review will provide a framework for not only investigating the current status but also specifying the future direction of studies on MNFs.

2. Properties of MNFs

Beyond doubt, flow and heat transfer characteristics of a fluid are profoundly affected by its properties such as thermal conductivity and viscosity. In this regard, numerous studies in the field of nanofluids assessed their properties [16–18]. As far as MNFs are concerned, some investigations evaluated their rheological behavior and thermophysical properties in the absence and presence of magnetic fields, which are assessed in this section.

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2.1. In the absence of magnetic field

Investigations on MNFs in the absence of magnetic fields demonstrate that the their thermophysical properties are affected by various parameters such as particle size, volume fraction of nanoparticles, base fluid properties, chemical composition of magnetic nanoparticles, temperature, particle coating layer, and so forth.

In a great deal of the conducted studies, the effects of temperature and concentration of nanoparticles on the properties of MNFs have been assessed. Syam Sundar et al. [19] investigated the effective thermal conductivity and viscosity of Fe_3O_4/water MNF experimentally. Experiments were conducted in the concentration range of 0 to 2% and the temperature range of 20 °C to 60 °C. They concluded that the thermal conductivity enhances with increase in particle concentration and temperature. It was also demonstrated that the nanofluid exhibits Newtonian behavior under the tested concentration range. They proposed models of effective thermal conductivity and viscosity of the MNF as below:

$$k_{nf} = k_{bf}(1+10.5\varphi)^{0.1051} \quad (1)$$

$$\mu_{nf} = \mu_{bf}\left(1+\frac{\varphi}{12.5}\right)^{6.356} \quad (2)$$

where subscripts *nf* and *bf* respectively refer to nanofluid and base fluid, k is thermal conductivity, μ is viscosity and φ represents volume concentration. In order to consider the effect of temperature, thermal conductivity and viscosity of the base fluid should be substituted in the correlations at that particular temperature.

Thermal conductivity of Fe_3O_4 nanoparticles in ethylene glycol was determined experimentally as a function of temperature and concentration by Pastoriza-Gallego et al. [20]. They found that the enhancement of the thermal conductivity increases almost linearly with the concentration while it is nearly temperature-independent.

Abareshi et al. [21] prepared MNFs by dispersing the Fe_3O_4 nanoparticles in water in the presence of tetramethyl ammonium hydroxide as a dispersant and measured the thermal conductivity of the nanofluid as a function of volume fraction and temperature. The highest value of enhancement in thermal conductivity was reported to be 11.5% for the nanofluid with 3 vol% of nanoparticles at 40 °C.

Regarding the importance of the size of suspended magnetic nanoparticles in the base fluid on the MNFs properties, some researchers have investigated the effect of nanoparticle size as well as cluster size of the nanoparticles. The result which has been reported in most of such studies is the reduction of the thermal conductivity of ferrofluids with particles enlargement. Wang et al. [22] performed an experimental study to examine the effect of Fe_3O_4 nanoparticle size on the thermal conductivities of heat transfer oils. The results showed that the MNFs exhibit higher thermal conductivity than heat transfer oils, and the values of enhancement increase with reducing the particle size. In addition, they found for the first time that the viscosities of all nanofluids are remarkably lower than that of the base fluid.

Hong et al. [23] focused on the effect of the clustering of nanoparticles on the thermal conductivity of MNFs. The thermal conductivity increased nonlinearly as the volume fraction of nanoparticles increased. The nonlinearity was attributed to the rapid clustering of nanoparticles in condensed nanofluids.

In addition, the effect of base fluid on ferrofluids properties has been evaluated in some studies. For instance, Tsai et al. [24] performed an experimental study to investigate the effect of viscosity of the base fluid on the thermal conductivity of nanofluids in which Fe_3O_4 nanoparticles are suspended in the base fluid composed of diesel oil and polydimethylsiloxane. Viscosity of the base fluid was varied by changing the volumetric fractions between both fluids. They observed that thermal conductivity of nanofluids gradually approaches the value predicted by the Maxwell equation by increasing the viscosity of the base fluid. This means that at high viscosities, the experimental results obtained for thermal conductivity of nanofluid become very close to those predicted by the Maxwell model. In fact, Maxwell model does not consider the role of Brownian motion and therefore, at low viscosities, due to high intensity of Brownian motion, the results obtained from experiments on nanofluids show higher values in comparison with those obtained from the Maxwell model. However, with viscosity increment, due to decrease in the effect of Brownian motion, the role of Brownian motion in the value of thermal conductivity diminishes. It was observed that the viscosity around 100 cP is a critical value of demarcation. In other words, below 100 cP of viscosity, the Brownian motion is active, so the thermal conductivity of nanofluids increases and consequently, the Maxwell model underpredicts the experimental results. Over 100 cP of viscosity, the Brownian motion becomes inactive and the thermal conductivity of nanofluids obeys the Maxwell theory.

In Fig. 1, a comparison between the values of enhancement in thermal conductivity obtained by different researchers for various MNFs has been depicted in the absence of magnetic field. The enhancement parameter is defined as below:

$$Enh. = \frac{k_{nf}-k_{bf}}{k_{bf}} \times 100 \quad (3)$$

It can be observed from the figure that adding magnetic nanoparticles increases the thermal conductivity of the base fluid and in some cases, the value of enhancement has non-linear relation with volume fraction of particles. The reason is that clustering is more intense at higher concentrations and therefore, the average size of clusters increases with concentration increment and this causes a change in the increasing trend of thermal conductivity. It means that with enlargement of clusters, the slope of variations in thermal conductivity in terms of concentration decreases. Other studies in which the relation between thermal conductivity and concentration is linear even at high concentrations indicate that the prepared nanofluids have proper stability even at great concentrations such that clustering occurs lately in them. This can be due to applying appropriate surfactants or correct use of ultrasonic waves. Therefore, the value of concentration above

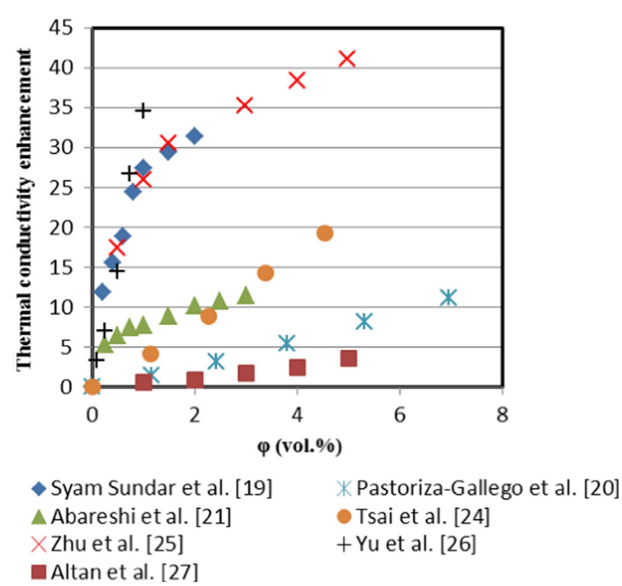

Fig. 1. Comparison between the values of enhancement in thermal conductivity obtained by different researchers for various MNFs in the absence of magnetic field.

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