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Heat transfer enhancement by magnetic nanofluids—A review

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ABSTRACT

Magnetic nanofluids (MNF) constitute a special class of nanofluids that exhibit both magnetic and fluid properties. The interests in the use of MNF as a heat transfer medium stem from a possibility of controlling its flow and heat transfer process *via* an external magnetic field. This review presents recent developments in this field with the aim of identifying major affecting parameters and some novel applications. This review emphasizes on thermal conductivity enhancement and thermomagnetic convection in devices using MNFs as heat transfer media.

Contents

1. Introduction

Dispersion of nano-sized particles of different materials (metals, metal oxides, etc.) in a carrier fluid known as nanofluids has been a subject of intensive investigations over decades due to their potential applications in heat transfer and electronic cooling [1–6]. Magnetic nanofluids (or ferrofluids), which consist of

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colloidal mixtures of *superparamagnetic* nanoparticles suspended in a nonmagnetic carrier fluid, constitute a special class of nanofluids that exhibit both magnetic and fluid properties [7–9]. To prevent the aggregation (due to London-van der Waals interaction and magnetic interaction between the particles), the suspended nanoparticles are coated by a surfactant layer such as oleic acid [10–12], tetramethylammonium hydroxide [13], etc. A wide range of carrier fluids are used, and some magnetic nanofluids are commercially available to satisfy different applications [14]. Theoretically, it should be possible to produce dispersion in any liquid thereby being able to tailor the requirements of viscosity, surface tension, temperature and oxidative stability, vapor pressure, stability in hostile environments [15]. However, the choice of a carrier fluid for MNF suitable for heat transfer applications needs some additional requirements such as high conductivity, high heat capacity, high thermal expansion coefficient, etc. Conventional heat transfer fluid (such as water, oils, ethylene glycol, etc.) could be a superior option for advanced applications. Magnetic nanoparticles used in magnetic nanofluids are usually prepared in different sizes and morphologies from metal materials (ferromagnetic materials) such as iron, cobalt, nickel as well as their oxides (ferrimagnetic materials) such as magnetite (Fe_3O_4), spinel-type ferrites, etc.

MNF has been used as an advanced functional material to position the colloids at a certain part of devices by means of magnetic forces. For this reason, the main aspects for research involve the increase of fluid magnetization, the specific properties of free magnetic nanofluid surfaces in the presence of an external magnetic field and the magnetoviscous and magnetorheological effects [15]. The use of MNF as transfer media becomes of importance in applications [16–18]. In particular, a possibility to induce and control the heat transfer process and fluid flow by means of an external magnetic field opened a window to a spectrum of promising applications including magnetically controlled thermosyphons for technological purposes, enhancement of heat transfer for cooling of high power electric transformers, and magnetically controlled heat transfer in energy conversion systems [15]. The heat transfer enhancement using MNF in the presence of magnetic field can be classified as a compound heat transfer technique with the additives (i.e., magnetic nanoparticles) and an external magnetic field to increase the heat transfer process [19]. Compared to the conventional nanofluids (nonmagnetic nanofluids), the use of MNF affected by external applied magnetic field for heat transfer enhancement offers the following advantages [20]:

a) The possible absence of any moving parts necessary for making the fluid to flow in commonly energy conversion and cooling devices. The current of MNF is generated by temperature difference and non-uniform magnetic field, which can be formed by means of a permanent magnet system. The configuration of this system determines the direction and the type of the fluid flow. As a result, the thermomagnetic convection is readily handled;
b) The thermomagnetic convection is much more intensive than the gravitation one;
c) The possibility of tuning thermophysical properties (thermal conductivity and viscosity) of MNF using external magnetic fields [21,22].

2. Preparation of MNF

MNF is prepared *via* the dispersion of nano-sized superparamagnetic particles into a nonmagnetic carrier fluid such as water, ethylene glycol, hydrocarbon oil, etc. [23]. MNF used in heat transfer applications is subjected to a magnetic field, magnetic field gradient and/or gravitational field, which may contribute to the particle sedimentation in the fluid. Since the interaction range of magnetic nanoparticles in the applied fields is directly related to the particle size/size distribution of magnetic nanoparticles [21], it is obvious that the later plays a vital role in the particle sedimentation, thus affecting the stability of MNF. The stability against the particle sedimentation may be ensured when the thermal energy of the particles becomes greater than that of magnetic and gravitational energies, respectively. the maximum particle size was determined by Odenbach [21] to be $d<(6k_BT/\mu_0M_0\pi H)^{1/3}$ for MNF used in the presence of magnetic field and $d<(k_BT/\Delta\rho gh\pi)^{1/3}$ for MNF in the presence of gravitational field, where k_B, T, M_0, $\Delta\rho$, g, d, H and μ_0 denote the Boltzmann constant, temperature, spontaneous magnetization of the magnetic material, density difference between magnetic particle and the carrier fluid, gravitational acceleration, the height of the sample, the magnetic field and the vacuum permeability, respectively. In addition, the aggregation of magnetic nanoparticles during the synthesis has to be avoided at all costs. In principle, the aggregation of particles increases their active diameter and thus causes a destabilization of the suspension by sedimentation. The maximum particle diameter (d), in this case, was estimated as $d<\left(144k_BT/\mu_0M_0^2\right)^{1/3}$ corresponding to the maximum interaction energy when two interacting particles come into contact [21]. Recent efforts have been made to synthesize metal and metal oxide magnetic nanoparticles with the desired size/size distribution [24]. Metallic nanoparticles such as Ni, Fe and Co were prepared *via* the techniques like simple reduction of metal-salts, gas-phase reduction of metal complexes, thermolysis of metal–polymer complexes, thermal decomposition of metal–carbonyl complexes and submerged arc nanoparticle synthesis system (SANSS) [24,25]. Magnetic nanoparticles of metal oxide such as Fe_3O_4, γ-Fe_2O_3 and spinel-type ferrites of the formula MFe_2O_4 (with M = Mn, Co, Zn, Ni, etc.) are mostly used in MNF due to their chemical stability. Metal oxide magnetic nanoparticles are usually prepared by chemical co-precipitation, micro-emulsion and recently phase transfer [14,24,26].

The use of the required superparamagnetic particles in MNF is not a definitive requirement of magnetic nanofluid stability [8]. A suspension with magnetic nanoparticles in carrier fluids will not be stable due to the presence of London-van der Waals and magnetic forces, leading to the irreversible aggregation of the particles and their subsequent sedimentation. Therefore, the preparation of stable MNF requires an introduction of repulsive forces between magnetic nanoparticles to counteract the London-van der Waals and the dipole–dipole magnetic interactions. The repulsive mechanism between the particles can be achieved, either by coating the particles with a polymer surfactant, which produces an entropic repulsion, and/or by charging the surface of the particles, producing a coulombian repulsion [8,14]. It is interesting to note that the selection of the mechanism to be used should depend mainly on the properties of the carrier fluids and the particles. The dispersion process is usually performed in the presence of a polymer surfactant by ultrasonic equipment and/or a high speed homogenizer.

3. Thermal conductivity of MNF

The original idea of using a suspension for heat transfer application was a possibility of enhancing the thermal conductivity of common heat transfer fluids by the addition of nanoparticles with a higher thermal conductivity [4]. For this reason, some previous investigations on thermal conductivity of nanofluids were dominated by nanofluids prepared with metallic or metallic oxide nanoparticles such as TiO_2, Al_2O_3, Cu, CuO, Ag, carbon