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Thermal transfer in mixtures of ethylene glicol with carbon coated iron nanoparticles under the influence of a uniform magnetic field

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ABSTRACT

In this work, the study of the heat transfer enhancement induced by aligning iron nanoparticles in an ethylenglicol fluid matrix is presented. In particular the effect of the interface is studied by analyzing the cases in which the nanoparticles are coated with carbon and comparing with uncoated ones. Results indicate that the coating acts as a thermal barrier making thermal conductivity to decrease. Moreover, the magnetic field creates aligned columns that enhance the heat transfer. Effective models are used to determine the role of the coating as well as of the aligning of the nanoparticles.

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1. Introduction

Thermal conductivity of randomly suspended spheres in a matrix material has been the focus of a large number of investigations [1]. The thermal conductivity of fluids, developed for heat exchangers, plays a vital role in the development of energy-efficient heat transfer equipment. The thermal conductivity of most of the fluids is generally small. Applications in diverse fields, especially in heat exchangers demand the development of fluids with enhanced thermal conductivity [2,3]. One of the simplest configurations, helpful in reaching this objective, is to insert metallic particles in the fluids. If those metallic particles have a high magnetic moment they can get aligned with an external magnetic field. Heat transfer is expected to grow preferentially along the direction of the magnetic field, allowing in some way to manipulate the direction in which the heat is transferred. However, heat transfer from particle to particle could be affected by the thermal interface resistance. According to Maxwell model, the effective thermal conductivity of materials that contain spherical particles can be determined by simply considering the volume fraction concentration and the thermal conductivity of matrix and suspended particles. Nevertheless, effects of microstructural features of these composites as well as the interface thermal resistance play a determinant role on their macroscopic properties. In recent years, a lot of effective conductivity models have been developed in which particle interactions, size and form have been taken into account. However the experimental evaluation of the effects of the thermal interface resistance, among the nanoparticles and the fluid, are hard to evaluate. In this paper it is shown that, preparing ferrofluids with coated nanoparticles and comparing with ferrofluids with non-coated nanoparticles can be useful in the understanding of the role of thermal interface resistance in heat transfer.

2. Materials and methods

2.1. Sample preparation

Iron Nanoparticles (Fe, 99.5%, passivated) with an average particle size of 25 nm and Iron nanoparticles carbon coated (Fe, 99.6%) with an average particle size of 25 nm and an average carbon thickness of 2 nm (Nanostructured and Amorphous Materials) and ethylene glycol as carrier fluid were used to develop the studied samples. TEM images of the nanoparticles, supplied by the manufacturer, are shown in Fig. 1. The samples were prepared by one-step technique, at different nanoparticles volume fraction concentrations of 0%, 0.25%, 0.5%, 1%, 2.5%, 5% and 10%. The nanoparticles were added to the ethylene glycol and then this mixture was sonicated with an ultrasonic processor working at 20 kHz.

2.2. Experimental set up

The thermal diffusivity was measured as a function of nanoparticles content. The samples were inserted inside a pair of Helmholtz coils and measurements were made when a magnetic field is turned off and compared with measurements with the magnetic field at 300G in the direction of the heat transport, using the Thermal Wave Resonator Cavity (TWRC). This is a very useful technique because it provides simple, versatile and accurate measurements of thermal properties of fluids [4]. We verify that the pyroelectric sensor is insensitive to the applied magnetic field by measuring the thermal diffusivity of non-magnetic fluids and we found no-difference when the field is on and off. The experimental setup for the measurement of the thermal diffusivity is shown in Fig. 2.

After determining the thermal diffusivity α of the samples, the effective thermal conductivity k was obtained using the relation

$$k = \alpha\left(\rho_m C_m(1-\phi) + \rho_p C_p \phi\right), \qquad (1)$$

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where C_m and C_p are the specific heat capacity and ρ_m and ρ_p are the density of the matrix and nanoparticles respectively and the values of these parameters are shown in Table 1.

3. Results and discussion

Fig. 3 illustrates the images of the samples at different nanoparticle concentration. Fig. 3a and c are samples of ethylene glycol at 0.25% and 1% of carbon coated Fe nanoparticles, respectively. It is easy to observe agglomeration of the particles in the sample, due to the hydrophobic behavior of the carbon coating [1]. However, for samples at the same concentration of non-coated Fe nanoparticles, the samples did not show such degree of agglomeration (Fig. 3b and d).

Thermal conductivity of the analyzed samples as a function of the nanoparticle concentration is shown in Fig. 4, for the cases in which the particles have a random spatial distribution and a chain-like structure in presence of the applied magnetic field (300G). It can be seen that the increment of the volume concentration of nanoparticles causes an increasing in thermal conductivity. This could be expected due the fact that the thermal conductivity of the nanoparticles is larger than the thermal conductivity of the matrix [8]. At zero magnetic field and for a concentration of 5% of Fe nanoparticles, the increment in thermal conductivity is around 29%, whereas for samples of carbon coated nanoparticles, the coating reduces the increment of the thermal conductivity, such that for the same concentration of nanoparticles, the increment observed is only 9.3%.

When the magnetic field has a direction along the axis of the thermal wave cavity cylinder, an enhancement of the thermal diffusivity and conductivity is observed. This may be associated to the fact that the particles form chain-like structures aligned in direction of the magnetic field, which facilitates the heat conduction along the direction parallel to the magnetic field [9]. The increment of the thermal conductivity due to the magnetic field for samples depend of the volumen concentration. The enhancement for the samples of Fe nanoparticles is about 4.6% for the higher concentration, while for carbon coated Fe nanoparticles at same concentration, the change is around 1.5%, compared to the measurements without the magnetic field.

Two models are used to interpret the experimental data for the normalized thermal conductivity of a two-phase system. The models consider the effects of the microstructures of the samples, maximum packing fraction of the dispersed phase, interfacial thermal resistance and the ratio of the thermal conductivity of the nanoparticles with respect to the thermal conductivity of the matrix, among others.

3.1. Model for particulate composites with oriented particles

Let us consider a composite made up of spherical particles forming chain-like structures with a random orientation, as shown in Fig. 1. The overall thermal conductivity k of this composite can therefore be modeled in two steps: First, we consider each chain-like structure with a straight shape as a single cylindrical particle and calculate its effective thermal conductivity k_{pe}. The random distribution of these effective particles is then used to determine k, in the second step. Given that the spherical particles are touching each other within the chain-like structures, k_{pe} is given by the well-known series rule, as follows

$$\frac{2a}{k_{pe}} = \frac{2a}{k_p} + \frac{1}{R}, \tag{2}$$

where a and k_p are the radius and thermal conductivity of the particles and R is the particle-particle interface thermal resistance.

For a low volume fraction f of particles ($f < 15\%$), as is the case of interest in the present work, the thermal conductivity k of the composite with a random distribution of cylindrical particles is then given by [10,11]

$$\frac{k}{k_m} = \frac{3 + (A+B)f}{3 - Af} \tag{3}$$

where k_m is the thermal conductivity of the matrix and

$$A = 2\frac{1-\lambda}{1+\lambda}, \qquad B = \frac{k_{pe}}{k_m} - 1, \qquad \lambda = \frac{k_m}{k_{pe}} + \frac{a_K}{a} \tag{4}$$

being $a_K = \rho k_m$ the so-called Kapitza radius (12.8 nm for Fe and 28.5 nm for C) and ρ the interfacial thermal resistance among the matrix and particles.

3.1.1. Coating effect

If the spherical particles are coated with a coating of thickness δ, Eqs. (2)–(4) still hold provided that the thermal conductivity k_p of the uncoated particle is replaced by the effective thermal conductivity k_{cp} of the coated spheres ($k_p \rightarrow k_{cp}$), which can be written as [10,11]

$$\frac{k_{cp}}{k_c} = 1 + \frac{3v(k_p - k_c)}{3k_c + (1-v)(k_p - k_m)} \tag{5}$$

where $v = (a/(a+\delta))^3$ and k_c is the thermal conductivity of the coating. Given that the thickness δ might be much smaller than the mean free path l of the energy carriers within the coating, the thermal conductivity k_c should take into account the boundary scattering of these carriers (size effects), as follows

$$k_c = \frac{K_c}{1 + l/(\delta + a/2)}, \tag{6}$$

where K_c is the bulk thermal conductivity of the coating material and it has been assumed that $\delta \ll a$ as is usually the case of practical interest.

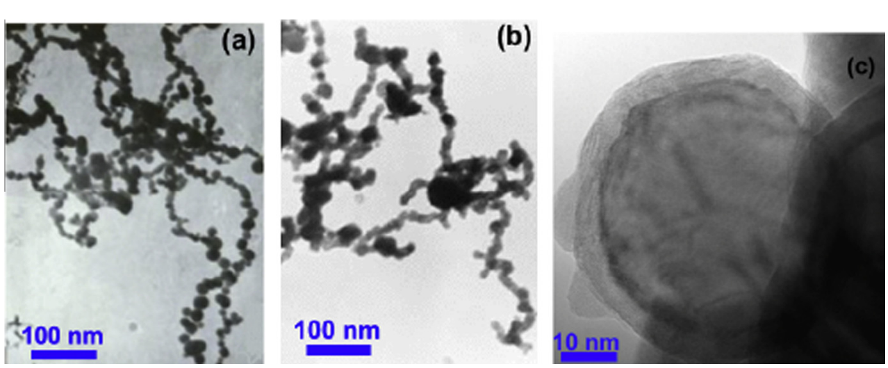

Fig. 1. TEM images of (a) Fe nanoparticles and (b and c) carbon coated Fe nanoparticles.

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