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Thermal conductivity of a diamond magnetite composite fluid under the effect of a uniform magnetic field

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ABSTRACT

We study the thermal diffusion through a fluid made of diamond microparticles immersed in a ferrofluid. A thermal conductivity enhancement is observed when a magnetic field is applied to the fluid; this phenomenon is due to a better heat propagation through a tridimensional chain-like structuring formed by the diamond particles in the direction of the field; additionally the thermal conductivity of the material could be controlled in a switchable way and moreover with the intensity and direction of the field. This thermal improvement shows a strong dependence on the diamond volume fraction, presenting a maximum of 76% when the diamond volume concentration is 15% and as the concentration increases, the relative thermal conductivity enlargement decreases, becoming zero at the maximum diamond volume fraction. This complex behavior could be modeled with the use of the Lewis–Nielsen effective thermal conductivity model, with a form factor that depends on the diamond particle concentration.

1. Introduction

One of the great challenges in materials science is to devise working materials whose thermal properties can be tuned at will in a certain range. This is hard to achieve with homogeneous materials; however, this objective could be reached when working with composites [1,2].

In particular, electronics, computing and systems for energy saving and generation are among the most demanding and require the development of flexible and versatile composites which confront the challenges of controlling the dissipation of heat, not only at the micro- but also at large scale [3]. New kinds of materials are needed in order to solve the increasing demands in diverse applications. An innovative way of improving the thermal conductivities of working media is to suspend ultrafine metallic or nonmetallic solid powders in traditional fluids, taking into account that the thermal conductivities of most solid materials are higher than those of liquids [4–6]. Those kinds of materials can exploit the physical properties of the liquids, which are their high heat capacity, the tendency to take the form of the system of interest, and those that can be a good option when a suitable thermal contact is desirable.

Among the most promising composite materials are smart fluids, which are those whose properties can be changed by applying external stimuli (electric or magnetic fields, heat, mechanical force, light, etc.) [7,8]. Ferrofluids are colloidal stable suspension of ferromagnetic particles of tenths of nanometers in a liquid carrier. The nanoparticles are coated with adsorbed surfactant layers to keep the suspension state stable. In the absence of magnetic field, the particles are randomly oriented and the fluid has no net magnetization. However, in the presence of an external magnetic field, the magnetic nanoparticles become aligned in the direction of the field, and thus forming chain-like structures [9–11]. The analysis of the thermal properties and the viscosity of ferrofluids among other features have attracted greatest attention of diverse research groups in the last years [12–16]. On the other hand, it is well known that diamond has excellent physical properties. Its thermal conductivity is higher than any of the metals, and offers a wide variety of applications when large heat transfer rates are required [17,18].

In this work, the ability of a magnetic field to induce the formation of chain-like structures in a suspension of a non-magnetic diamond microparticles in a carrier ferrofluid, called negative magnetophoresis [19,20], is used to control heat transport. The thermal analysis of the samples was performed using the thermal wave resonator cavity (TWRC), which has become, in the last few years, an attractive technique, in the thermal characterization of liquids and gases, due to its simplicity, versatility and accuracy [21–23]. This technique provided the thermal diffusivity of the samples, which is the physical property that measures how fast a material is heated or cooled, and rules the heat transfer under dynamic conditions. Additionally, the thermal wave cavity has been successfully used to study heat transfer in mixtures of liquids [24]. In this work we are going farther proposing to use the TWRC to measure stable mixtures of solid particles in liquids under the influence of magnetic fields.

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2. Materials and methods

2.1. Preparation of samples

Diamond microparticles with a Gaussian size distribution with 3.2 μm mean diameter and standard deviation of 0.6 μm were purchased from Diamond Tech Quality; and ferrofluid (Ferrotec EMG 900 @ 3% magnetite volume fraction, Gaussian particle size distribution with 10 nm mean diameter and standard deviation of 1 nm) was used to obtain the samples. The fluids were prepared by a one-step technique, which consists in the mixing of the diamond microparticles with the ferrofluid matrix, at different diamond particle volume concentrations of 0%, 5%, 10%, 15%, 20%, 35% and 48%. The diamond powder was added to the ferrofluid and then it was sonicated with an ultrasonic processor working at 20 kHz by 5 min. Micrographs of the diamond microparticles (Fig. 1a, b and c) and diamond microparticles coated with Fe_3O_4 nanoparticles (Fig. 1d, e and f) were obtained using a Field Scanning Electron Microscope (SEM JEOL JSM-7600F).

2.2. Photothermal setup

The samples were inserted inside a Helmholtz coils, and measurements were made when a magnetic field is turned off and turned on (at 175 G) (see Fig. 2). We verify that the pyroelectric sensor is insensitive to the applied magnetic field by measuring the thermal diffusivity of non-magnetic fluids.

The experimental setup for the measurement of the thermal diffusivity is shown in Fig. 3, it was obtained at room temperature (near 297 K). The thermal wave resonant cavity is a 7 mm aluminum cylindric container of variable length in which the liquid sample is placed. The upper cover of the cavity is a 500 μm thick circular silicon wafer; the bottom cover is a PZT acting as pyroelectric sensor. A laser diode (Mitsubishi ML120G21 658 nm, 80 mW) was used as the excitation source. The laser beam was electronically modulated at a frequency f = 0.5 Hz by the internal sine oscillator of the lock-in amplifier (SR-830) and controlled by a laser diode driver (IP500). The laser light impinges on the outer surface of the silicon wafer, which acts as an optical-to-thermal power converter (thermal-wave generator) [25,26]. As a consequence, the fluid is heated periodically at the fix modulation frequency of the incident laser beam. The temperature oscillations can be measured with the PZT sensor. The output of the detector is connected to a low noise preamplifier (SR-560), used to improve the signal to noise ratio, and then sent to a lock-in amplifier in which the complex voltage of the PZT sensor is evaluated in its magnitude and phase. Cavity length scans were performed with a stepper motor coupled to a translation stage with a resolution of 10 μm. All data acquisition and cavity length scans were automated using a home-made LabView™ program.

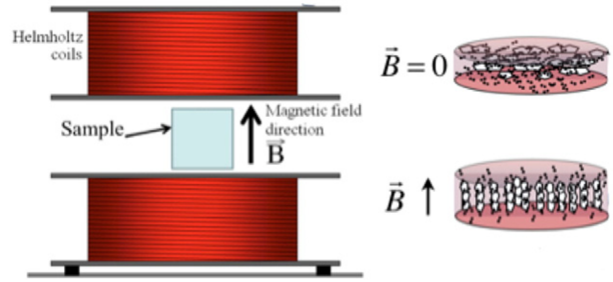

Fig. 2. Scheme of the Helmholtz coils setup to generate a uniform magnetic field to obtain samples with different kinds of particle structuring: (a) Random distribution of particles and (b) parallel chain-like structure.

In the configuration used in this work, the signal measured by a thermally thick pyroelectric sensor (sensor thermal diffusivity of 0.39×10^{-2} cm^2 s^{-1} [27], and 0.05 cm thickness), for a thermally thick sample of thermal diffusivity α and thickness L (a material is thermally thick when $L > \sqrt{\alpha/\pi f}$), follows the equation

$$V(L, \alpha, f) = F(f) \exp\left[-L(i+1)\sqrt{\pi f/\alpha}\right]. \quad (1)$$

The natural logarithm of the signal amplitude becomes $\ln|V| = c_V - m_V L$ and the pyroelectric signal phase is $\Phi = c_\Phi - m_\Phi L$. Where constants c_V and c_Φ are not relevant in the calculation of the thermal diffusivity of the sample, and $m_V = m_\Phi = \sqrt{\pi f/\alpha}$. Fig. 4 shows the typical behavior of the amplitude and of the phase as a function of the thickness of the sample. As can be seen in this figure a change in the slope of the sample with 15% of diamond powder occurs as a consequence of the magnetic field. It is important to mention that measurements with the thermal wave cavity with a non-magnetic sample do not show any evidence of change when the magnetic field is turned on and off, therefore the changes observed in the voltage signal are only due to the effects induced by the field on the samples with embedded magnetic particles.

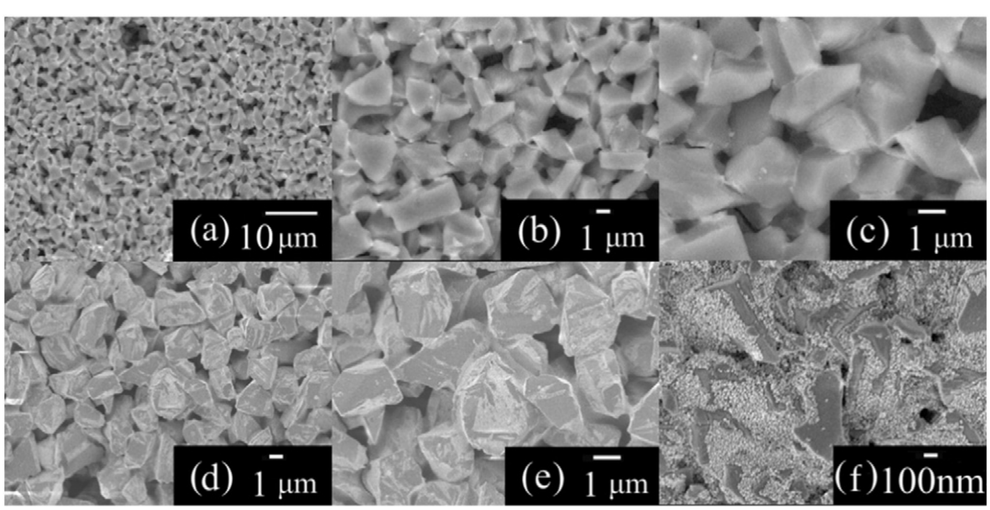

Fig. 1. SEM images (a), (b) and (c) correspond to the diamond powder, shown in a magnification sequence from less to a higher augmentation to clarify the geometry and size of the diamond particles. Micrographs (d), (e) and (f) show a dry ferrofluid with 15% of diamond powder; these images illustrate the significant size difference of the diamond particles and magnetite nanoparticles.