Research Article

Photoacoustic Method for Measurement of Thermal Effusivity of Fe_3O_4 Nanofluid

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Photoacoustic (PA) sensor was designed and developed to evaluate thermal effusivity of Fe_3O_4 nanofluid. The PA sensor is based on open cell mode (OPC) to measure acoustic signals from low concentration of nanoparticulate suspensions in ethylene glycol (EG). Spherical Fe_3O_4 nanoparticles (NPs) were obtained by chemical precipitation method in powder form. The obtained NPs were stabilized by acetylacetone (acac) in EG. Thermal conductivity estimation was carried out with the help of transient hot wire method. The developed PA sensor was calibrated by measuring thermal effusivity of standard samples. The acoustic signals of the PA experiments have been analyzed with a simple Rosencwaig-Gersho theoretical model.

1. Introduction

Metal oxide NPs dispersion in liquids are of fundamental as well as technological interest pertaining to nanofluidic and other applications including antibacterial medical treatment and thermal management systems because of transport property enhancement [1]. Recently, there has been significant interest in studying different thermophysical properties of nanofluids such as thermal conductivity, diffusivity, and effusivity [2]. The two dynamic thermal parameters, that is, thermal diffusivity α and effusivity ε is connected with other thermal parameters, that is, thermal conductivity k and volumetric specific heat c_p by $\alpha = k/\rho c_p$ and $\varepsilon = \sqrt{k\rho c_p}$ where ρ is the density of sample. The thermal effusivity measures essentially the thermal impedance of sample or the ability of sample to exchange heat with environment [3]. To completely characterize the nanofluid out of three, two parameters are required. Reported studies on thermal properties of nanofluids are mostly based upon the thermal conductivity measurement. Exact determination of thermal effusivity of such nanoparticulate dispersed phase would be complementary to the thermal conductivity obtained by hot wire method.

Photoacoustic methods are known to be useful tools for investigation of thermal parameters for gases, liquids, thin films, and powder materials [4–11]. There has been considerable amount of work based on experimental techniques related to PA spectroscopy [12–15]. For NPs dispersions at very low concentrations or solid particle loading the sample were effectively treated as transparent one, and Rosencwaig-Gersho (RG) theory could be applied [16]. The single most important parameter that characterizes the PA system is pressure variations, induced by samples surface temperature which are detected by a microphone coupled to PA cell [17]. However, in a closed configuration of PA setup both the expansion of gas and liquid sample contributes to signal [17]. To overcome this problem open methods has been introduced. To measure the PA signal of liquid sample, OPC technique has been proved to be a powerful tool both in terms of the low cost and easy data analysis.

Previously, OPC has been successfully applied for evaluating liquid thermophysical properties comprising suspension of very low concentration or transparent liquids [18]. The application of OPC to higher dense colloids suspension is limited due to unavailability of theory. In this work, the thermal effusivity and conductivity were investigated for EG based Fe_3O_4 NFs.

FIGURE 1: Photoacoustic setup for determination of effusivity of Fe_3O_4 nanofluid (a) design (b) top view.

FIGURE 2: SEM pictures of Fe_3O_4 NPs after self-assembly.

2. Experimental

The experimental setup for OPC is shown in Figure 1. In a typical open cell PA experiment, the excitation beam is used to generate the thermal waves in the sample which are transferred to microphone as an acoustic signal via Al foil coupled to sample as well as gas beneath. A beam of monochromatic light from helium neon (He-Ne 632 nm, 10 mW) laser is used as an excitation source. The light beam was focused with the help of lens and passed through chopper. The whole PA cell is made within acrylic body with the chamber beneath aluminium foil having 3 mm depth as well as diameter. Owing to absorption of laser radiations, the sample temperature rises and heat generated diffuses through aluminium foil into PA gas chamber. Pressure modulation also occurs within the PA cell. Acoustic waves induced by light were detected by a microphone transducer

(PCB 130D20) consisting of a built-in preamplifier. Output signals of PA transducer were again amplified with signal conditioner and acquired with the help of lock in amplifier (SR 7265).

The change in pressure of gas was calculated by using RG Theory Algorithm [17],

$$\delta P_\epsilon = \frac{\gamma P_0 I_0 (1 + i)}{\sqrt{2 l_g \sigma_g k_{Al}^2 l_{Al} \sigma_{Al}}} \frac{1}{1 + (2 \epsilon_s / e_{Al} l_{Al} \sigma_{Al})}, \quad (1)$$

where γ specific heat ratio for air, I_0 is intensity of incident radiation, l represents the sample thickness, ϵ is the effusivity, k is thermal conductivity, and P_0 is ambient pressure. The thermal diffusion length $\mu = [\alpha / (\pi f)]^{1/2}$ related to

TABLE 1: Thermal parameters for EG, water, and Fe₃O₄ nanofluid.

Sample	P_1	P_2	P_3	ε_{exp} (Ws ^{1/2} /cm ² K)	ε_R (see [18])	k_{exp} (W/cmK)	α_{exp} (cm ² /s)	α_R (see [19])
EG	0.0034	1.2824	1.9045	0.081	0.0817	0.0025	9.53×10^{-4}	9.66×10^{-4}
Water	0.0034	1.2824	3.4056	0.158	0.1593	0.0058	1.35×10^{-3}	1.43×10^{-3}
Fe ₃ O ₄ NPs in EG	0.0034	1.2824	2.1237	0.093	—	0.003	1.04×10^{-3}	—

FIGURE 3: DLS result for Fe₃O₄ nanofluid.

parameter σ , that is, $\sigma = (1 + i)/\mu$. In the absence of sample, the above equation reduces to

$$\delta P_{\text{Al}} = \frac{\gamma P_0 I_0 (1 + i)}{\sqrt{2l_g \sigma_g k_{\text{Al}}^2 l_{\text{Al}} \sigma_{\text{Al}}^2}}. \quad (2)$$

The amplitude of reference signal can be expressed as

$$|\delta P_{\text{Al}}| = \frac{P_1}{f^{P_2}}, \quad (3)$$

where

$$P_1 = \frac{\gamma P_0 I_0 \alpha_g^{1/2} \alpha_{\text{Al}}}{[(\pi^{3/2}) T_0 l_g l_{\text{Al}} k_{\text{Al}}]}, \quad (4)$$

$$P_2 = \frac{3}{2},$$

where P_1 and P_2 are constants. In the presence of sample, the above equation is written as

$$|\delta P_{\text{e}}| = \frac{P_1}{f^{P_2} \left(1 + \left(\frac{P_3}{\sqrt{f}} \right) + \left(\frac{P_3^2}{2f} \right) \right)^{1/2}}, \quad (5)$$

where

$$P_3 = \frac{2\varepsilon_s}{\varepsilon_{\text{Al}} l_{\text{Al}}} \left(\frac{\alpha_{\text{Al}}}{\pi} \right)^{1/2}. \quad (6)$$

Colloidal Fe₃O₄ NPs were prepared using a method described by Khan [19]. Prepared NPs were suspended in EG with the help of ultrasonication and acac. Thermal conductivity of samples has been measured by transient hot wire (platinum wire, $\phi = 30 \times 10^{-6}$ m) technique with data acquisition (Datataker dt80) system.

3. Results and Discussion

The prepared Fe₃O₄ NPs have been characterized by scanning electron microscopy (SEM) (Figure 2). The test sample was prepared by placing drop of colloidal solution on glass substrate and heated slightly to evaporate EG. The SEM observations show that the particles are organized in a chain-like structure. Evidence of the occurrence of aggregates in the absence of magnetic field was found also by direct visual inspection (chain length up to 3 mm and width up to 500 nm) [20]. This aggregate has been formed under self-assembly process [21]. Figure 3 shows dynamic light scattering analysis having particle size around 200 nm with uniform distribution.

The laser irradiation of deionised (DI) water sample, EG, and blank yields acoustic signal as shown in Figures 4(a), 4(b), and 4(c). The irradiation of the NPs suspension yields acoustic signal as shown in Figure 4(d). The light impingement frequency was varied from 5 Hz to 100 Hz in steps of 2.5 Hz. The data from each sample can be fitted as indicated by equation. P_1 and P_2 fitting parameters were evaluated for each sample according to equations to fit the signal amplitude versus frequency data points, taking P_3 as adjustable parameter. The curve fitting was done and parameter P_3 evaluated from which effusivity of sample was calculated from (5). As it can be seen from Figure 4(d), the amplitude value of an acoustic signal in suspension differs from that in EG. The analysis of the form of a signal shows relative increase of acoustic signal from suspension. The obtained value for parameter ($P_2 \approx 1.28$, Table 1) shows that the obtained PA signal has inverse frequency dependence in accordance with RG theory. George et al. [22] used log-log plot to analyze the thermal diffusivity of GaAs semiconductor layer, and various mechanisms responsible to generate the signal have been discussed. Since the data and applied model are the same, residual error remains the same in normal and log-log scale (inside Figures 4(c) and 4(d)). All efforts have been made to minimize the noise but microphone, placed beneath chopper, picks up the noise generated by the slotted chopper blades during experiment producing some scatter in PA signal data.

Results for different samples are shown in Table 1. Suspension of Fe₃O₄ NPs produces change in thermal properties of EG as can be seen from enhancement of PA signal (Figure 4(d)) and effusivity (Table 1). Measured thermal conductivity values for Fe₃O₄ nanofluid shows 20% enhancement. The measured effusivity and estimated diffusivity values for water and EG are in close agreement with values reported in the literature with an error of maximum $\pm 5\%$ [23, 24]. Enhancement in thermal diffusivity can be explained due to Brownian motion, nanoconvection, and

FIGURE 4: OPC signal amplitude as a function of modulation frequency for: (a) water, (b) EG, (c) blank (inside: log-log plot), and (d) Fe_3O_4 (inside: log-log plot) nanofluid.

heat diffusion on addition of nanoparticles to the fluid [2, 25].

4. Conclusions

The described OPC technique can be effectively applied to evaluation of thermal properties of dilute NPs suspensions. Results show that PA signal changes significantly with inclusion of Fe_3O_4 NPs in EG.

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