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THE EFFECT OF CONCENTRATION ON THERMAL AND OPTICAL BEHAVIOURS OF ALUMINIUM NANOFLUIDS

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The present study reports measurements of the effective thermal effusivity and refractive index of nanofluids using photoacoustic spectroscopy and minimum deviation methods. Ethylene glycol, ethanol, and distilled water were used as standard liquids to optimize the experimental set up. In this study, the effective thermal effusivity and the refractive index of Aluminium nanofluids, in ethylene glycol, were measured and effects of mass fractions were clarified. The results showed that nanoparticles significantly enhance the thermal effusivity and refractive index of the investigated nanofluids.

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Keywords: Thermal Effusivity; Refractive Index; Aluminium; Nanofluid; Photoacoustic Spectroscopy; Minimum deviation

1. Introduction

The light energy can be converted to the acoustic wave that is known as the photoacoustic effect. For the first time, Alexander Graham Bell (1880) discovered photoacoustic effect, Vengerov (1938) applied this effect in gas analysis [1], then Rosencwaig and Gersho (1976), extended the applications of photoacoustic technique to liquids and solids [2], which can be used for nanofluids as a liquid sample. Nanofluid can be prepared by dispersing an appropriate amount of nanoparticles (NPs) in a base fluid. So there are three most important factors in any nanofluids; type of NP, base fluid, and NP concentration. Based on the literature reviews, different properties of the nanofluids were changed in compare with the base fluid [3, 4]. Metal based NPs such as aluminium, cadmium, silver and so on, due to surface plasmon resonance, have strong absorption in the visible range [5]. This property got much attention from the researchers due to the unique properties such as high thermal conductivity [6], thermal collector [7], and antibacterial activity [8]. Thermal effusivity is a measure of nanofluid’s ability to exchange heat with its surroundings. Thermal effusivity of various metal based nanofluids were reported in recent years [4, 9]. The majority of nanofluid thermal conductivity information stated in liquid literatures reveals that increasing the NP mass fraction causes an increase in nanofluid’s conductivity which announces a linear relationship between the mass fraction of NPs and nanofluid’s thermal conductivity [10, 11]. The thermal conductivity and thermal effusivity relation is given as [12, 13]

$$\varepsilon = \sqrt{k\,\rho\,C} \tag{1}$$

where ε is the thermal effusivity, k is the thermal conductivity, ρ and C are respectively density and the specific heat capacity. Since conductivity, density and thermal effusivity are in direct relationships as shown by Eq.1, it is expected that thermal effusivity increases by an increase in the mass fraction concentration of NPs. Refractive index is another essential quantity

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which has various applications in different fields, for instance, it is used in photonic. Since the thermal effusivity and refractive index need to be measured for particular applications of nanofluids [14]. In this work, ethylene glycol was chosen as base fluid for Al nanofluids. The thermal and optical characterizations were carried out to verify the dependency of thermal effusivity and refractive index on mass fraction concentration of Al nanofluid, using photoacoustic spectroscopy and minimum deviation method.

2. Theory

Rosencwaig - Gersho theory known as R-G theory adequately explains the photoacoustic signal generation in a cell resulting from the absorbed light energy [15]. When a chopped laser beam passing through the cell's window and illuminates solid sample, the heat intensity is generated at depth x, for PA cell in the presence of liquid samples, a modulated laser beam is focused on the Al foil in which it contacts with the liquid sample and air in the PA cell. Using Rosencwaig and Gersho model δp that is the air pressure can be calculated as it was expressed well in papers published previously by Delgado-Vaesallo and Marin [16] and Delgado-Vaesallo et.al [17].

$$\delta p = \frac{\beta I_o \gamma\, P_o}{2\sqrt{2}\, k_S l \alpha T_o\, (\beta^2 - \sigma_{Al}^2)}\, F \tag{2}$$

where γ is the specific heat ratio, ε, α and k are respectively thermal effusivity, thermal diffusivity and conductivity of Al. I_o and T_0 are the intensity and temperature, P_0 and β are ambient pressure and optical absorption efficient of the solid respectively and σ_{Al} is the complex thermal diffusion coefficient. F is the pressure fluctuation made by the Al foil absorber that for liquids if B << 1, then:

$$F = \frac{2r}{\sigma_{Al} l_{Al}\left(1 + \frac{2B}{\sigma_{Al} l_{Al}}\right)} \tag{3}$$

where p_1 and p_2 are constants, the reference signal can be measured when the sample holder is empty and given as:

$$|\delta P_{Al}| = \frac{P_1}{f^{P_2}} \tag{4}$$

while in the presence of a sample the amplitude of Eq.2, can be expressed as

$$|\delta P| = \frac{P_1}{f^{P_2}\left(1 + \frac{P_3}{\sqrt{f}} + \frac{P_3^2}{2f}\right)^{1/2}} \tag{5}$$

where P_3 is also constant. Finally, solution thermal effusivity (ε_s) can be simply calculated by fitting based on the below equation.

$$\varepsilon_S = \frac{P_3 \varepsilon_{Al} l_{Al}}{2} \left(\frac{\pi}{\alpha_{Al}}\right)^{\frac{1}{2}} \tag{6}$$

3. Materials and methods

3.1 Preparation of sample

For preparing the Al NPs with average diameter of 40 nm, from Nano Structured and Amorphous Materials Inc (USA), and the base fluid Ethylene Glycol from Aldrich (Germany) were used. NPs were suspended in ethylene glycol by sonication technique to prepare six samples with different mass fraction concentrations of 0.036, 0.072, 0.090, 0.181, 0.272, and 0.381 % (w/w). The mixtures were kept and mixed in an ultrasonic bath for about 6 hours using Acetyl Trimethyl Ammonium Bromide (CTAB) as surfactant to produce uniform and homogeneous nanofluids.

3.2 Experimental set ups

The experimental set up of the photoacoustic spectroscopy is presented in Fig.1. It consists of He-Ne laser (Melles Griot, 632.8 nm), detector, optical chopper (Stanford Research system, SR540), low-noise preamplifier (Stanford Research system, SR560) and a lock-in amplifier (Stanford Research system, SR350) that amplifies detected photoacoustic signals.

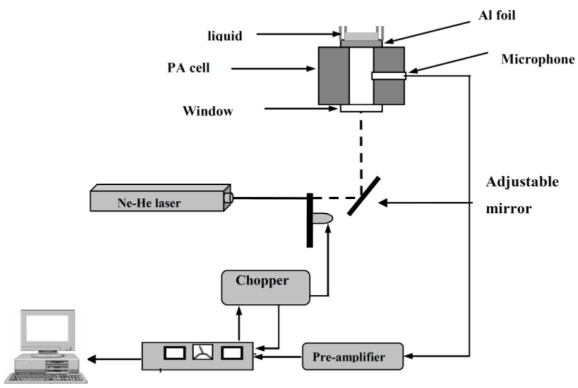

Fig.1: The experimental set up of open photoacoustic spectroscopy for liquid samples.

In the present study, photoacoustic cell was constructed using Aluminium rod with a diameter of 76 μm and a Quartz plate was applied as the optical window. When the laser illuminated the sample placed on sample holder with chopped laser beam, the heat transferred to Al foil and heats the air in the cell, so it generated pressure its variations were detected by sensitive a microphone. Pre and lock-in amplifiers amplified the pressure variations which were displayed and recorded using a personal computer.

For measuring refractive index the minimum deviation method was used by application of a laser (Melles Griot, 632.8 nm), rotation stage, and a hollow prism. By measuring the x and y distances, refractive index (n) can be calculated using the following equation:

$$n = \frac{sin\frac{1}{2}(\alpha + D)}{sin\left(\frac{\alpha}{2}\right)} \tag{7}$$

where D is deviation angle and α which is the angle of the hollow prism was equal to 60˚ in present study. The experimental set up of minimum deviation method is presented in Fig.2. All the measurements were carried out at room temperature about 25˚C.

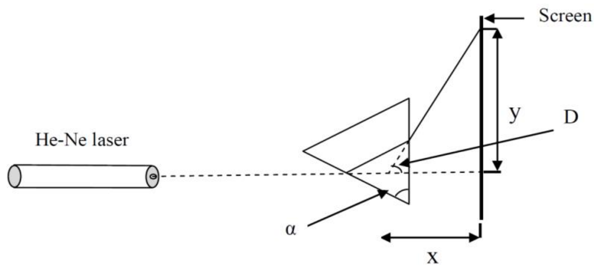

Fig.2: The experimental set up for measuring refractive index of liquids.

4. Results and discussion

Optical absorption of prepared samples was characterized using UV-Vis spectroscopy, as shown in Fig.3a. This figure reveals that the absorption peaks appeared at 304 nm as it was expected for Al NPs [18, 19]. The intensity of absorption peaks increases by increasing the concentration of Al NP in the base fluid (0.036 % to 0.381 %). The homogeneous distribution of Al NPs in ethylene glycol after 6 hours sonication in presence of CTAB was verified using transmission electron microscopy (TEM). Fig.3b is a typical TEM image of the 0.090% nanofluid. TEM images reveal that the Al NPs dispersed homogeneously in ethylene glycol.

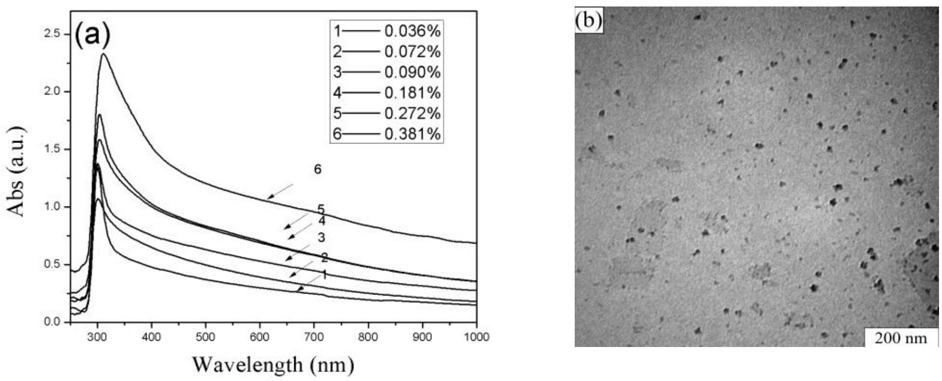

Fig.3: (a) UV-Vis spectra of Al nanofluids in different mass fraction concentrations.
(b) TEM image of 0.090 % (w/w) Al NP suspended in ethylene glycol.

The measurement of refractive index by minimum deviation method was verified by measuring the refractive indexes of standard liquids. The refractive index of distilled water, ethanol, and ethylene glycol were measured and the values are respectively equal to 1.327, 1.359 and 1.427 which agreed well with the reported values [20-23]. In photoacoustic setup the sample holder made by Al foil. Regarding to Eq.6 first of all, it needs to measure the thermal diffusivity of Al using photoacoustic spectroscopy. The obtained value was 0.939 cm^2/s that is in good agreement with literature values [24, 25]. Using the measured thermal effusivity of empty sample holder, the constant parameters (p_1, p_2) were calculated. Before measuring the thermal effusivity of nanofluids and for calibrating the photoacoustic spectroscopy set up, the thermal effusivity values of Di water, ethanol, and ethylene glycol, as standard samples, were measured and the obtained values are 0.163, 0.054 and 0.093 $Ws^{1/2}/cm^2K$ respectively. The measured values for standard samples also are in good agreement with the reported values [26, 27]. After ensuring the accuracy of the data, Al nanofluids were thermally characterized using the photoacoustic spectroscopy. Generally, the thermal effusivity and refractive index of nanofluids are higher than those of the base fluids [28]. Fig. 4a and Fig. 4b show the PA intensity signal as function of frequency for two nanofluids with the Al mass fractions of 0.036 and 0.090 % (w/w), respectively. The solid curve represents the best fit of the theoretical data.

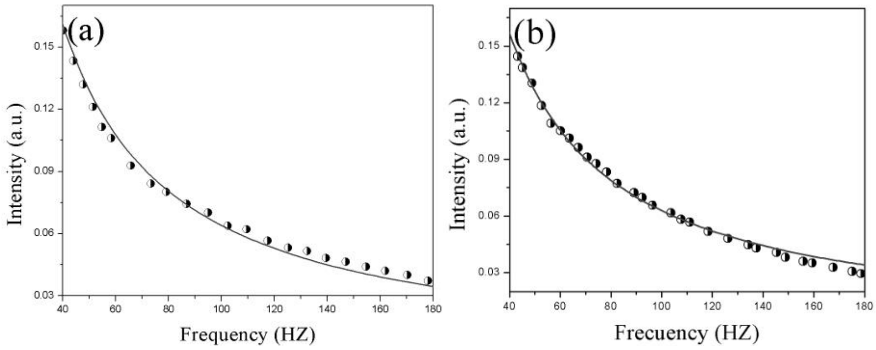

Fig.4: Intensity dependent on the frequency variations obtained by photoacoustic spectroscopy for (a) 0.036 % and (b) 0.090 % (w/w) Al NPs suspended in EG.

Fig. 5 shows the variation of thermal effusivity as function of mass fraction of Al NPs. This figure reveals that thermal effusivity of ethylene glycol (0%) slightly increase from 0.093 to 0.095 ($Ws^{1/2}/cm^2$ K) by adding of 0.036% Al NPs. Thermal effusivity increases slightly by adding more NPs up to 0.09%. The figure shows a considerable increase in thermal effusivity by adding more than 0.09% NPs. These results show an 84% increase in thermal effusivity of ethylene glycol by turn it into an Al nanofluid of 0.381%.

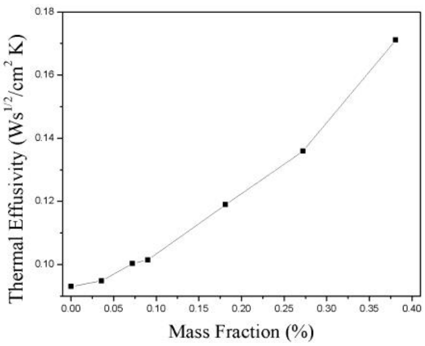

Fig.5: Variation of thermal effusivity versus mass concentration of Al NPs.

Fig. 6 reveals the refractive index of Al nanofluid as function of mass fraction concentration. Refractive index, almost linearly, increases from 1.427 to 1.697 by increasing the mass fraction from 0 to 0.381%.

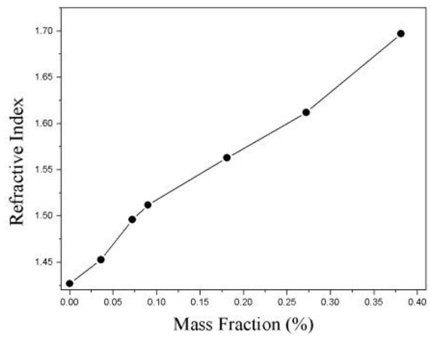

Fig.6: Variation of refractive index versus mass concentration of Al NPs.

Thermal effusivity and refractive index show higher values in Al nanofluids in compare with the base fluid. It is obviously clear due to the presence of more NPs in nanofluids. Table 1 shows the thermal effusivity and refractive index values for all nanofluids.

Table.1: Thermal effusivity and refractive index of Al NPs suspended in Ethylene Glycol.

Mass fraction of Al NP (%)	Thermal effusivity ($Ws^{1/2}/cm^2$ K)	Refractive index
0	0.093	1.427
0.036	0.095	1.453
0.072	0.100	1.496
0.090	0.101	1.512
0.181	0.119	1.563
0.272	0.136	1.612
0.381	0.171	1.697

5. Conclusions

Al NPs with average diameter of 40 nm were suspended in ethylene glycol to prepare six Al nanofluids with different mass fraction concentrations of 0.036, 0.072, 0.090, 0.181, 0.272, and 0.381% (w/w). Thermal effusivity and refractive index of Al nanofluids in ethylene glycol were successfully measured using photoacoustic spectroscopy and minimum deviation methods respectively. Thermal effusivity of Al nanofluids increased from 0.095 to 0.171 $Ws^{1/2}/cm^2$ K and the refractive index values roughly linearly increased from 1.453 to 1.697 by increasing the mass fraction concentration. This research revealed that tuning the thermal effusivity and refractive index of Al nanofluids are possible by varying the mass fraction concentration of Al NPs.

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