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High accuracy photopyroelectric investigations of dynamic thermal parameters of fluids

D. DADARLAT, C. NEAMTU, M. STREZA, D. CHICEA[a*], A. PASCA[a]
National R&D Institute for Isotopic and Molecular Technologies, Cluj-Napoca, 400293, Romania
[a]Physics department, "Lucian Blaga" University, Str. Dr. Ion Ratiu 5-7, Sibiu, 550012, Romania

The photopyroelectric calorimetry, in two detection configurations, was applied in order to accurately measure the thermal diffusivity and effusivity of several liquid samples. The thermal diffusivity was investigated in a back PPE configuration using a thermal-wave-resonator-cavity. The thermal effusivity was measured by making use of a frequency scan in a front PPE detection configuration. In both configurations, the pyroelectric sensor and sample were thermally thick and the incident layer optically opaque. The selected particular PPE detection schemes, allowing for high accuracy results (error within ±1%), are used in the paper for some applications on $CoFe_2O_4$ ferrofluid.

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1. Introduction

In the photopyroelectric (PPE) technique, the temperature variation of a sample, exposed to a modulated radiation, is measured with a pyroelectric sensor. In the last years, the two PPE calorimetric configurations (i.e. "back" and "front", respectively) have been used in investigating the behaviour of static (specific heat) and dynamic (thermal conductivity, diffusivity, effusivity) thermal parameters of condensed matter samples [1,2].

In order to find the *thermal diffusivity* of a given sample, in the *back* configuration, the phase of the PPE signal can be measured, by performing either a frequency or a thickness scan [3]. Recently, it has been demonstrated that the methodology based on sample thickness scan leads to very accurate and reproducible values for the thermal diffusivity, due to the possibility of precisely controlling the sample's thickness variation [4].

The *front configuration*, with opaque sensor and thermally thick sensor and sample, was recently used to measure the *thermal effusivity* of some (semi)liquids. The experimental conditions (chopping frequency, number and geometrical thickness of the layers of the detection cell) were set up in such a way that the information (the value of the thermal effusivity) is contained in the phase of the signal [5].

In the work reported this paper we intend to test the limits of the two PPE configurations mentioned above in detecting small variations of the thermal parameters of nanofluids. The nanofluid notion is a relatively new one and was first mentioned by Choi in 1995 [6] as he noticed that a small amount of nanoparticles, added to a fluid, considerably enhanced the heat transfer properties [7].

The nanoparticles have a continuous, irregular motion in nanofluids, which is the effect of several factors such as gravity, Brownian force, Archimede's force and friction force between fluid and the particles. The irregular nanoparticle motion in the fluid is the cause the remarkable enhancement of heat transfer properties of the nanofluids [8-11]. In the paper, two samples with different concentrations from the same type of magnetic nanofluid, having $CoFe_2O_4$ nanoparticles in suspension, were selected for investigations. The reason of selecting this type of material was the lack in the literature of thermal data about the ferrofluids.

2. Theoretical aspects and experimental setup

The theory of the two configurations (including the approximations for each particular detection case), together with the schematic diagrams of the detection cells, were largely presented elsewhere [1-5]. We will present here only the results.

2.1 The back configuration

In the particular case when the sample and the sensor are thermally thick and, additionally, the sample is optically opaque, the phase θ of the PPE signal is given by [2]:

$$\theta = \theta_0 - L_s \left(\frac{\omega}{2\alpha_s} \right)^{\frac{1}{2}} \qquad (1)$$

where θ_0 is an instrumental, frequency independent, phase offset, L_s and α_s are the sample's thickness and thermal diffusivity, respectively, and ω is the angular modulation frequency of the incident radiation.

An inspection of Eq. (1) leads to the conclusion that, in order to find the thermal diffusivity, one can perform either a frequency or a thickness scan of the phase.

2.2 The front configuration

In the front configuration, with opaque sensor and thermally thick sensor and sample, the phase θ of the PPE signal is given by [4-5]:

$$\tan\theta = \frac{\left(1+R_{sp}\right)\cdot\sin\left(\frac{L_p}{\mu_p}\right)\cdot\exp\left(-\frac{L_p}{\mu_p}\right)}{1-\left(1+R_{sp}\right)\cdot\cos\left(\frac{L_p}{\mu_p}\right)\cdot\exp\left(-\frac{L_p}{\mu_p}\right)} \qquad (2)$$

From Eq. (2), for a given frequency, one can calculate R_{sp} and then derive the sample's effusivity e_s, according to the following relationship:

$$\frac{e_s}{e_p} = \frac{\left(1+R_{sp}\right)}{\left(1-R_{sp}\right)} \qquad (3)$$

In eqs. (2) and (3) R_{ij} represents the reflection coefficient of the thermal waves at the interface of two media and it is given by:

$$R_{ij} = \frac{\left(b_{ij}-1\right)}{\left(b_{ij}+1\right)} \qquad (4)$$

where $b_{ij} = e_i/e_j$. The symbols "p" and "s" refer to the pyroelectric sensor and substrate (sample), respectively. The thermal diffusion length is:

$$\mu = \left(\frac{\alpha}{\pi f}\right)^{\frac{1}{2}} \qquad (5)$$

where f is the modulation chopping frequency and α is the thermal diffusivity, related to the other thermal parameters (the volume specific heat C, thermal conductivity k and thermal effusivity e) by:

$$k = C\cdot\alpha; \quad e = \left(C\cdot\alpha\right)^{\frac{1}{2}} \qquad (6)$$

3. Experimental results

A standard PPE calorimetric line was used for investigations [2]. The schematic of the experimental setup is presented in Fig. 1.

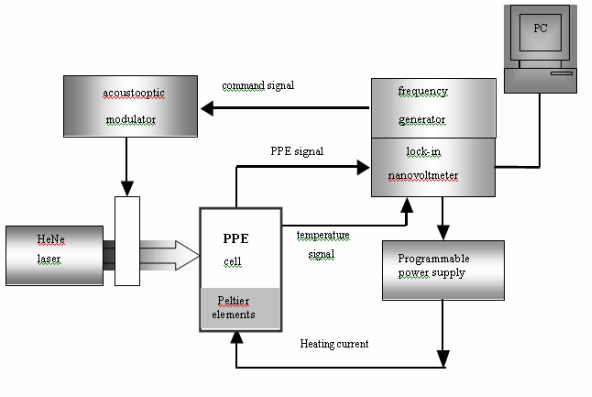

Fig. 1. The experimental setup.

The radiation source was a 30 mW HeNe laser, chopped by an acousto-optical modulator. The signal from a 500 μm thick $LiTaO_3$ pyroelectric sensor was processed with a SR 830 lock-in amplifier. The design of the detection cells in both front and back configurations, and experimental details were largely presented in [4,5].

In both configurations, a computer was used for data acquisitions. The signal/noise ratio was better than 1000.

The experiment was conducted with different concentrations from the same type of ferrofluid, with $CoFe_2O_4$ nanoparticles in suspension. Typical frequency scans for the normalized phase of the PPE signal are presented in Fig.2, and the corresponding results for the thermal effusivities in Fig.3.

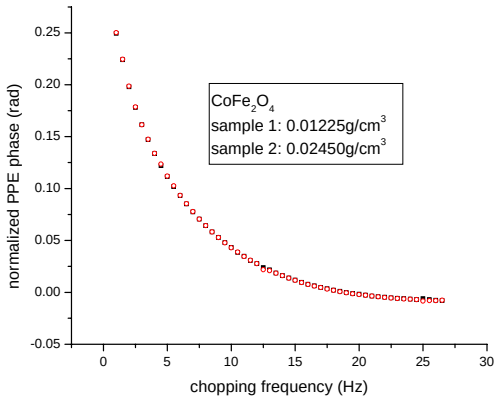

Fig. 2. Normalized PPE phase as a function of the chopping frequency for two samples of $CoFe_2O_4$ nanofluid with different concentrations of nanoparticles.

The value of the thermal effusivity was obtained by optimizing the fit performed on the experimental data with Eq. (2), using the thermal effusivity of the sample as a fit parameter.

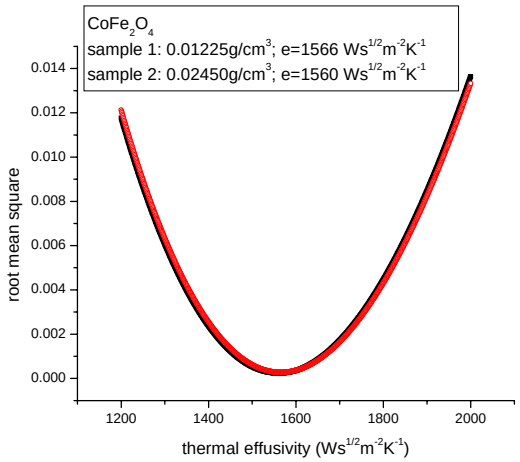

Fig.3. The relative error of the fit performed with Eq. (2) having the thermal effusivity of the sample as a parameter.

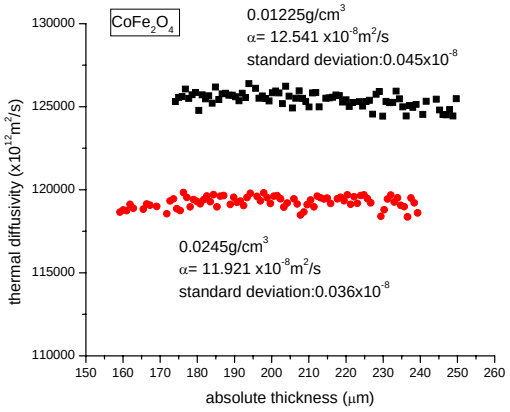

Fig.5 Typical thickness scan (in the linear region) of the thermal diffusivity (as calculated with Eq. (1)) for $CoFe_2O_4$ ferrofluid with two different concentrations of nanoparticles.

Fig. 4 displays a typical behaviour of the thermal diffusivity as a function of absolute thickness of the sample (as calculated with Eq. (1)).

It is the linear (horizontal) part of the curve that is used in assessing the value of the thermal diffusivity (see Fig. 5). The above mentioned value was obtained by using a fitting procedure: the best fit was selected by minimizing the relative error of thermal diffusivity found with Eq. (1), as compared to the best fit value of the linear part of the curve, having the absolute thickness of the sample as a fit parameter.

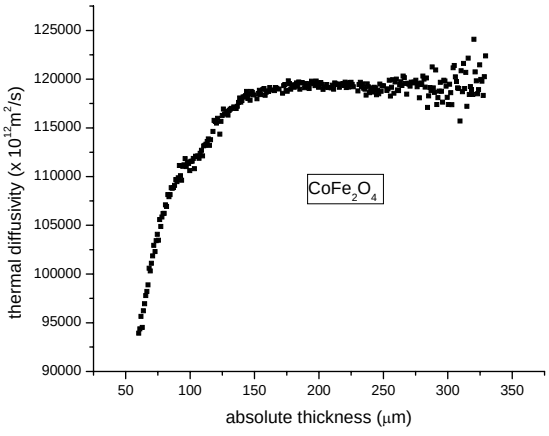

Fig. 4. Typical thickness scan of the thermal diffusivity, as calculated with Eq. (1), for $CoFe_2O_4$ ferrofluid with 0.0250g/cm^3 concentration of nanoparticles.

4. Discussion and conclusions

Two PPE detection configurations were used to measure the thermal diffusivity and effusivity of some $CoFe_2O_4$ ferrofluid samples. Both methods present an accuracy and reproducibility better than 98%. The high accuracy of the methods allows for the detection of small changes in the values of the dynamic thermal parameters. In the paper, the changes in the thermal parameters were induced by changing sample's composition. Concerning the sensitivity, it seems that the thermal diffusivity is more suitable for such type of investigations. Work is in progress with investigations of static and dynamic thermal properties of the magnetic nanofluids as a function of the relevant parameters of the nanofluid (carrier liquid, type of surfactant, type, size and concentration of nanoparticles).

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*Corresponding author: dan.chicea@ulbisibiu.ro