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THERMAL DIFFUSIVITY DETERMINATION OF LIQUID TROUGH THERMAL DIFFUSION LENGTH MEASUREMENT

M. Noroozi, B.Z. Azmi, Z.A. Wahab, M.M. Moksin and M.H. Mamat

Department of Physics, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor.

ABSTRACT

A new Optical Fiber Thermal Wave Resonance Cavity (OF-TWRC) technique was used to determine thermal diffusivity of liquids from the thermal diffusion length obtained from the curve of pyroelectric amplitude exponential decay with respect to cavity length and compared with the linear fitting of pyroelectric phase signal. The average thermal diffusivity of water obtained by this calculated method gives the value for water as $1.472\times10^{-3}\ \mathrm{cm^2/s}$. The thermal parameters for water and for other liquids agree with reported values in the literature.

INTRODUCTION

Thermal wave (TW) is generated by thermal expansion due to absorption of optical energy of a pulsed or modulated laser beam. Various facilities based on the same working principle were subsequently proposed, above all for nondestructive testing of metals [1]. In a thermal wave resonance cavity (TWRC) technique, a cavity consists of two parallel walls: one wall acts as TW generator, thus no optical properties of sample influences the signal; other wall is a pyroelectric (PE) transducer [4]. This technique allowed the signal to be scanned on cavity length, instead of only that on frequency modulation. The disadvantageous of the conventional TWRC technique are; the generated TW strongly depends on the thermal characterization of metal foil, and secondly the inconsistency of light beam intensity thus the TW generation resulted from variation of surface illuminated area on the foil due to laser beam divergence, as the cavity length (L) varies.

The optical fiber has been used for photothermal technique in detection of trace compound in water using the deflection of water meniscus [6], as position sensitive detector of photothermal deflection [7], and mostly as merely channeling the modulated light from laser diode to the foil in particular TWRC technique. Azmi *et al*. (2007) have modified the TWRC set up by using the optical fiber for both that are to channeling the modulated laser beam and to generate the TW by coating one of the fiber end with silver paint.

For a very small area of TW generator the actual signal should be represented by a three dimensional model but for a the laser beam diameter large compare to the thermal diffusion length of sample the temperature field or the amplitude signal from liquid can

Corresponding Author: monir.noroozi@gmail.com

be represented by a 1-[D] model [3]. The PE signal detected in the TWRC configuration at a fixed TW oscillation frequency $f = \omega/2\pi$ can be represented in 1-[D] model as [8]

$$V(L,\alpha_l,\omega) = Const(\omega)\left[\frac{e^{-\sigma_l l}}{1-\gamma_{ls}\gamma_{pl}e^{-2\sigma_l l}}\right] \qquad (1)$$

The subscripts *s, p*, and *l* refer to the plane metallic light absorber, the PE material, and the liquid sample, respectively. σ_j is the complex TW diffusion coefficient $\sigma_j = (1+i)/\mu_j$, $\mu_j = (\alpha_j/\pi f)^{1/2}$ is the thermal diffusion length, and subscript j is the material *s, p*, or *l*. Considering that for typical cavity lengths in liquid media $\left|e^{-2\sigma_l l}\right| << 1$ then Eqn. (1) can be written more simply as [4],

$$V(\omega, L) = \text{constant}(\omega)\, e^{-\sigma_l L} \;, \qquad (2)$$

It follows that the amplitude and the phase with respect to *L*, respectively, can be written as [4],

$$|V(f,L)| = \text{constant}(f) \times e^{-\sqrt{\frac{\pi f}{\alpha}}L} \;, \quad (3a)$$

$$\phi(f,L) = \text{constant}(f) - \sqrt{\frac{\pi f}{\alpha}}L \;, \quad (3b)$$

Eqn. (3a) describes the exponential decay of TW amplitude as a function of *L* the distance between TW generator and PE detector. Through PE amplitude signal, the thermal diffusivity can be obtained by many ways; among them is by measuring thermal diffusion length or the relative *L* at which the PE amplitude has a value of *1/e* (≈ 37 %) of the value at *L* = 0, and following the liquid sample thermal diffusivity can be calculated from relationship of $\alpha = \pi f \mu^2$. From PE phase signal, the thermal diffusivity can be obtained by linear fitting the plot of phase versus *L*, and use its gradient in Eqn.(3b) to obtain the value. [4]

In this paper we present the OF-TWRC technique to measure thermal diffusivity of water and other liquids determined from the curve of PE amplitude versus *L*, and then compare its value with that obtained from the phase method.

EXPERIMENTAL METHOD

In the set up, a 200 mW continuous diode pumped solid state laser (MGL(10)) of wavelength 532 nm modulated at 6.73 Hz was transmitted through an inlet of 1 mm diameter single core polymer fiber (RS 368-047) of about 1 m length, Figure 1. The 2.25 mm optical fiber tip or "free" end diameter was finely polished then coated with very thin layer silver conductive paint so that it does not contribute significantly to

Corresponding Author: monir.noroozi@gmail.com

the slope of the PE response. The paint also was applied to the side about 3 cm from the tip upward to prevent light from escaping the fiber end side that would introduce noise to the detecting signal. The *L* scan was done by moving this optical fiber free end with respect to PE detector. The PE signal is sent to a lock-in amplifier for analysis to give PE amplitude and phase and the detail procedure can be found elsewhere [Azmi *et al*., 2007]. The recorded experimental data was analyzed by using Origin 7.5 software. The main liquid used was distilled water since it can be considered as standard to ensure the reliability of the thermal diffusivity measurement by the set up, and others were olive oil and sun flower oil. The liquid thermal diffusivity values were obtained by the methods as mentioned above and all measurements were made at room temperature, 25^{o}C.

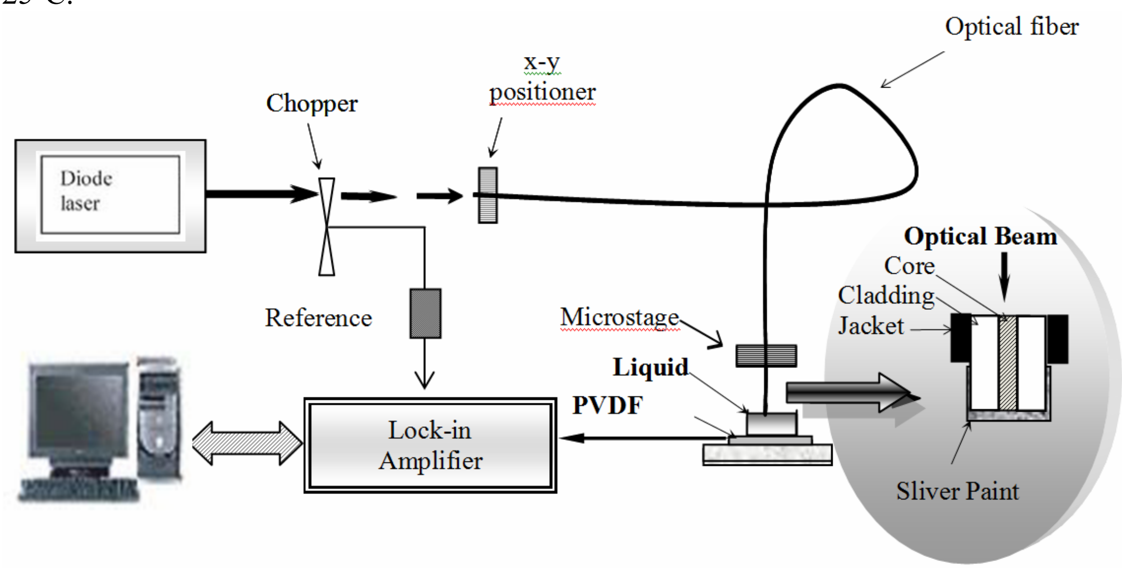


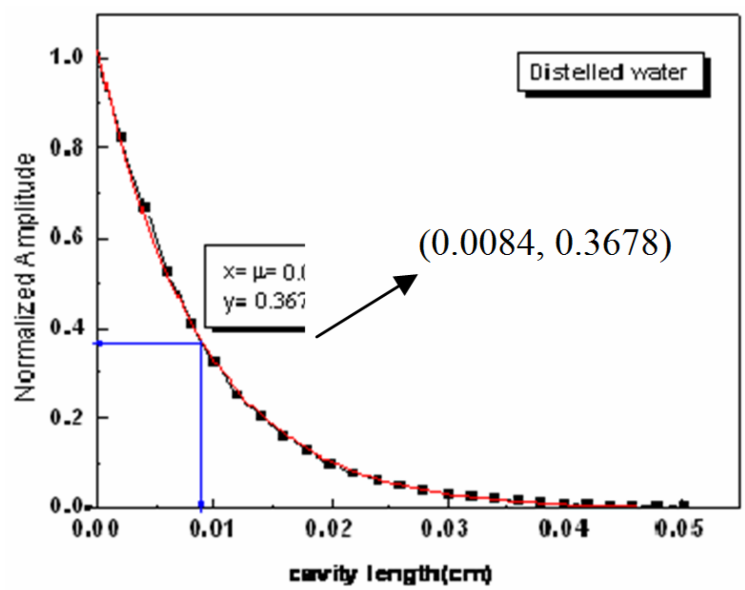
Figure 1: Schematic diagram of TWRC technique with optical fiber tip coated by silver paint as the TW generator

RESULTS AND DISCUSSION

The 1-D model on TW response of the cavity is only valid when the laser beam diameter is larger than the thermal diffusion length, μ, of liquid sample [8]. Figure 2 shows the experimental plot of normalized PE amplitude of distilled water that decays exponentially with respect to increasing cavity length, *L,* suitable to the Eqn. (3a). The amplitude was normalized by dividing all PE amplitude signals to that of its maximum value. From the exponential fitting curve through the experimental points, and moving the pointer along the curve at 1/e (or 36.78%) of the relative PE amplitude at *L*=0, the thermal diffusion length obtained is 0.084 mm, it can be see in figure 2. This thermal diffusion length value is smaller than the TW generator diameter or polymer fiber diameter, 2.25 mm, which is a necessary to the validity of using the temperature field expression of 1-[D] in the simplification that of 3-[D] [3]. Hence from $\alpha=\pi f \mu^2$ relation the thermal diffusivity of water is 1.491×10^{-3} cm^2/s. The lock-in amplifier noise is

Corresponding Author: monir.noroozi@gmail.com

around 0.15 mV and from fitting error, the experimental error is around 0.056×10^{-3} cm^2/s or 3.7%.



Figures 2: The plot of PE amplitude versus cavity length of distilled water

Figure 3 shows the linear variation of phase versus *L* for distilled water. Fitting the plot gives the plot gradient *A*=120.632 cm^{-1}, thus from Eqn.(3b) that yield relation $A=(\pi f/\alpha)^{1/2}$ the corresponding thermal diffusivity is 1.453×10^{-3} cm^2/s.

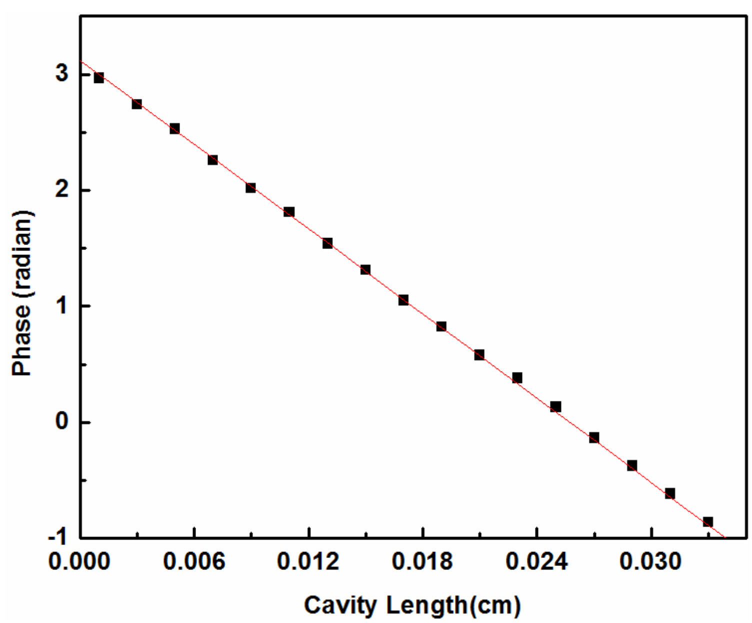


Figure 3: The plot of PE phase signal versus cavity length of distilled water

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The error in gradient is 1.250 cm^{-1} therefore the experimental error is about 0.038×10^{-3} cm^2/s or 2.6%. The reported literature value is 1.456×10^{-3} cm^2/s [4], hence the value obtained from PE phase fitting indeed gives a very close value to that of the literature by difference of only (0.2%), compared to that from PE amplitude fitting (2.4%). The slight high value obtained from PE amplitude fitting is due to less precision in determining thermal diffusion length in the PE amplitude decay curve. The other average thermal diffusivity values for commercial olive oil and sun-flower oil are 0.869×10^{-3} and 0.940×10^{-3} cm^2/s, respectively, see Table 1. The slight different values than the reported values are due to unknown additives in the commercial olive oil and sun flower oil.

Table 1: Thermal diffusivity of various liquids

Sample	**Thermal diffusivity** $\times 10^{-3}\ cm^2/s$				Difference from literature
	Thermal diffusion length	Fitting the phase plot	Average	Literature value	
Water	1.491	1.453	1.472	1.456[4]	1.1%
Olive oil	0.833	0.906	0.869	0.881[4]	1.4%
Sun-flower oil	0.922	0.958	0.940	0.904[4]	3.9%

[4]Balderas-Lopez *et al*., 2000.

The distilled water can be regarded as a standard liquid in determining the accuracy of any thermal diffusivity measuring technique. Hence the good value obtained for water implies that the optical fiber of this diameter size suitable to produce appropriate TW in liquid. This is also means that the OF-TWRC technique using optical fiber of diameter slightly bigger than maximum scanning range should yields the result close to conventional technique that use metal foil. However, the limitation to its applicability is that the fiber core diameter must be at reasonable size with respect to fiber external diameter in order to have good temperature field response in front of TW generator so that the TW can be optimally detected by PE detector [2]. This OF-TWRC system has a potential to be used in small volume detection rather than in big volume as in that of the conventional system.

CONCLUSION

The water thermal diffusivity value obtained by fitting the phase plot gives a very good value (1.453×10^{-3} cm^2/s) compared to that obtain by fitting the PE amplitude plot (1.491×10^{-3} cm^2/s). This good water thermal diffusivity value implies that the optical

Corresponding Author: monir.noroozi@gmail.com

fiber of the current diameter size is suitable to produce appropriate TW in liquid. Therefore it has a potential to be used in determining the liquid thermal diffusivity in a small liquid volume.

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Corresponding Author: monir.noroozi@gmail.com