Thermal wave interferometry of gas-liquid using optical fibre thermal wave resonator cavity technique

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Abstract. The optical fibre thermal wave resonator cavity (OF-TWRC) technique was used to measure thermal diffusivity of a two-layer sample; air-liquid. The thermal waves were generated by transmitting the modulated laser beam through one end of optical fibre and illuminating the other fibre end surface that metalised with silver paint. The cavity length scan was done by moving the fibre end surface towards the pyroelectric detector continuously through air and then into the liquid. A good linear relationship of pyroelectric amplitude with respect to cavity length was obtained in thermally thick region in both media; air and liquid. The thermal diffusivity of air, glycerol and water obtained were close to the literature values.

1. Introduction
Thermal wave (TW) is a phenomenon of temperature fluctuation in a medium as a result of the nonradiative de-excitation process that takes place following absorption of intensity-modulated radiation. Conventionally the pyroelectric (PE) technique for measuring thermal properties of material involves the detection of these TW’s over the scanning of the modulation frequency1-4. To ascertain that only the thermal properties of sample, with no optical properties and internal heat source contribute to the PE signal, the sample is usually coated with a very thin layer of an optically opaque and thermally thin material1,3. In a thermal wave resonator cavity (TWRC) technique, a cavity consists of two parallel walls; one wall acts as TW generator while the other wall is a PE transducer itself5,6. The cavity acts as a resonator as the temperature rise at the PE surface due to the thermal wave generated in the cavity will be partially reflected and interference between the reflected and incident wave trains will set in. TWRC technique allows the signal to be scanned on cavity length, instead of only frequency modulation. Beside the major advantages of cavity-length scans on the improvement of signal-to-noise ratio and doing away with instrumental transfer function normalization, the thermo-optical parameters of the sensor can be isolated in PE signal expression for appropriate thermal thickness of sample. Simplification has been done by incorporating optical fibre to guide light beam as well as to generate TW at fibre tip7.

One of the most important advantages of TW interferometric approach in analysing the PE signal is that the propagating wave-field can be described and manipulated directly under a great variety of thermal conditions and geometry. The amplitude and the phase signal can conveniently be modeled as representing the addition of forward- and backward-propagating TW’s in the spatial region of an excited sample8. Azmi et al.9 has adopted this approach to two-layer fluid (gas-liquid) using conventional TWRC technique to measure thermal diffusivity of air and water.
In this paper, we present an optical fibre-TWRC or simply OF-TWRC set-up to measure two fluid thermal diffusivities in a two-layer or gas-liquid configuration in a thermally thick condition.

2. Experimental procedure

The treatment for the two media in contact of solid-air in 1-[D] configuration using PE technique has been done by Azmi et al.\textsuperscript{10} We can apply the similar treatment for air-liquid in contact in the conventional TWRC technique using metal foil as the TW generator. The propagating of TW within air \((a)\), liquid \((s)\), and PE detector is partially reflected and transmitted upon striking at the air-liquid and at the liquid-PE detector interfaces, Fig. 1. The PE signal is detected when the TW generator moved through air and liquid towards PE detector.

\[ \theta_p(f, x) = \frac{Q_{T_{m}T_{a}}e^{-(\sigma_{j}L_{j}+\sigma_{a}L_{a})}}{2k_{j}\sigma_{j}}\left[1-R_{p}R_{m}e^{-2\sigma_{j}L_{j}}\left(1-R_{m}R_{a}e^{2\sigma_{a}L_{a}}\right)\right], \]  

\[ V(f, L_{a}) = \frac{Q_{T_{m}T_{a}}e^{-(\sigma_{j}L_{j}+\sigma_{a}L_{a})}}{2\varepsilon_{j}k_{j}\sigma_{j}}\left[1-R_{p}R_{m}e^{-2\sigma_{j}L_{j}}\left(1-R_{m}R_{a}e^{2\sigma_{a}L_{a}}\right)\right], \]

where \(\varepsilon\) and \(\varepsilon_{0}\) are the dielectric constant of PE detector and the permittivity in vacuum, respectively, \(\varepsilon\) is the PE coefficient, \(Q_{T}\) is the TW source intensity at the generator, \(\sigma=(1+i)/\mu_{j}\) is the complex wave number, \(\mu_{j}=(\alpha_{j}/\pi f)^{1/2}\) is the thermal diffusion length at modulation frequency \(f\), \(T_{m}\) and \(R_{m}\) are the transmission and the reflection coefficients of TW, respectively, at interface \((j-k)\). The other parameters are defined as; \(\alpha_{j}\) is the thermal diffusivity, and \(L_{j}\) is the medium thickness. The subscript \(j\) refers to TW generator \((m)\), air \((a)\);
liquid (s), and PE detector (p). From Eq. 2, in the first stage of probing in air, by varying $L_a$, the thermal properties of liquid and PE transducer can be regarded as constant, hence for a thermally thick case of air, $e^{-2\sigma_s L_a} \approx 0$, the average PE voltage can simply be written as,

$$V(f, L_a) = \text{constant}(f) \times e^{\left(\frac{\pi f}{\alpha_s}\right)^2 L_a}$$

(3)

This equation is similar to that of reported for a single fluid sample of TWRC technique\textsuperscript{6}, even though involving two-layer fluids.

2.2 The thermal wave source is in liquid:

The following, when the TW generator is in liquid the temperature distribution in PE film transducer should have no dependence on air thermal property. Hence, the parameters $L_a$ and $\sigma_a$ can be removed from Eq.’s (1) and (2), and therefore the expressions for the temperature distribution in PE film transducer and its average voltage can be simplified, respectively, to\textsuperscript{6}

$$\theta_s(f, x) = \frac{Q_s T_p e^{-(\sigma_s L_a + \sigma_p x)}}{2k_s \sigma_s (1 - R_p R_m e^{-2\sigma_s L_a})}$$

(4)

$$V(f, L_s) = \frac{Q_s T_p p(1 - e^{-\sigma_p L_s}) e^{-(\sigma_s L_s)}}{2\varepsilon e_k \sigma_s \sigma_p (1 - R_p R_m e^{-2\sigma_s L_s})}$$

(5)

In a thermally thick case of liquid or $e^{-2\sigma_s L_s} \approx 0$ the average PE voltage simply can be written as

$$V(f, L_s) = \text{constant}(f) \times e^{\left(\frac{\pi f}{\alpha_s}\right)^2 L_s}$$

(6)

Hence, the Eq.’s (3) and (6), the fluids thermal diffusivity can be obtained from the slope fitting parameter $(\pi f/\alpha_s)^{1/2}$ of plot ln(PE signal amplitude) versus cavity length $L_j$ in thermally thick case where subscript $j$ is referring to air and liquid. In the case of using optical fibre as TW generator where laser spot diameter, controlled by fibre core diameter, is relatively large compare to that of cladding diameter that resemble TW generator diameter, the temperature field or TW in 3-[D] case produced by the generator can be approximated to that of 1-[D] case\textsuperscript{11}.

The schematical set up of OF-TWRC technique can be seen in Fig. 2. The optical fibre “free” end or tip surface was used as TW generator instead of the usual metal foil by finely polished to a reasonable flatness, coated with a very thin matt black paint (less than 10 micron) to act as good light-to-heat converter, and then coated with a very thin layer of silver conductive paint. Here, a 200 mW continuous wave diode pumped solid state laser (MGL 150(10)) was modulated at 6.52 Hz using an optical chopper (SR540) and then focused onto an inlet of 2.25 mm diameter single core polymer fibre (RS 368-047) of 1 mm core diameter. The modulated laser light was guided through fibre to the tip to illuminate the inner side of the silver metalised layer. The cavity length scan was done by moving this tip, firstly in air and then into liquid, with respect to a polyvinylidene difluoride PE detector in scanning range less than 5 mm. The generated PE signal was analyzed by using a lock-in amplifier (SR 530). In the experiment two set of standard samples are used, that are air-glycerol and air-water since measuring thermal diffusivity of pure glycerol and water can be considered as a standard in stating the degree of accuracy and sensitivity on the thermal diffusivity measuring technique.
3. Results and discussion
Fig. 3 shows the variation of PE amplitude signal with respect to cavity length for the two layer fluid: air-glycerol. When the fibre end or TW generator is in air at 4 mm, far from the detector, the PE signal is in the thermally thick regime while at 1 mm also it is also in the thermally thin regime as evidence from straight line even though the air thermal diffusion length is around 1 mm. It clearly shows two distinct straight lines, the first line is the best fit to Eq. (3) for air on longer cavity length, the second line is the best fit to similar equation for liquid or glycerol on shorter cavity length. Also from Fig. 3, there is no sudden jump in PE amplitude at air-fluid interface as in the conventional TWRC set up. This is due to a very small fibre tip or TW generator area as such it only contact with liquid when it is so close to the air-liquid interface. The smallest signal in Fig. 3 is around 6 microvolt while the noise level also is around this value.

![Figure 2. Schematic diagram of OF-TWRC set-up.](image)

![Figure 3. The PE amplitude versus cavity length for a two-layer fluid sample; air-glycerol](image)
Table 1. Thermal diffusivities of two-layer sample measured and compared with literature values

| Sample          | $A_{\text{slope}}$ (cm⁻¹) | $\alpha$ (cm²/s)       | $\alpha_{\text{Literature}}$ (cm²/s) | Deviation (%) |
|-----------------|---------------------------|------------------------|---------------------------------------|---------------|
| Glycerol        | 150.700±0.967            | (0.913±0.010)×10⁻⁵     | 0.922×10⁻³ a                          | 1.0           |
| Air             | 9.840±0.043               | 0.213±0.002            | 0.211 b                               | 0.9           |
| Distilled water | 120.503±0.967            | (1.427±0.020)×10⁻⁵     | 1.434×10⁻³ c                          | 0.5           |
| Air             | 9.770±0.042               | 0.216±0.002            | 0.211 b                               | 2.3           |

a(Balderas-Lopez and Mandelis, 2000)  b(Shen and Mandelis, 1995)  c(Dadarlat et al., 2002)

The feature of different slope lines can be understood from the clear difference of air and liquid thermal diffusivity, e.g. one can expect to obtain lower value of thermal diffusivity from greater magnitude of slope. For air, the best-fit line of Fig. 3 in longer cavity lengths gives the slope ($\pi f/\alpha A$)¹/² = 9.840±0.057 cm⁻¹ hence the measured thermal diffusivity is (0.213±0.002) cm²/s. While for glycerol, the best-fit line in shorter cavity lengths gives slope of 150.700±0.967 cm⁻¹ hence the thermal diffusivity is (0.913±0.010) ×10⁻³ cm²/s. The thermal diffusivity values measured in thermally thick condition for air-glycerol and air-water are summarized in Table 1. The values obtained from the PE amplitude signal for air, glycerol and water differ only between 0.9 to 2.3%, hence are closed to literature values. For application, since the technique can be used to measure thermal diffusivity of gas layer without any physical contact with liquid layer, it has potential use to monitor the liquid vaporization rate and thus determining its chemical reaction rate in small volume.

4. Conclusion

In the cavity length scanning process the determination of top fluid (air) thermal diffusivity is not affected by the bottom fluid (liquid). The thermal diffusivity of pure glycerol and water obtained by the OF-TWRC set up is in good agreement to that of literature value derived from the conventional TWRC set up. This implies that the optical fibre of a reasonable core diameter is suitable to produce appropriate TW in gas-liquid, hence to measure gas and liquid thermal diffusivities.

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