

Determination of thermal effusivity of solids by a photoacoustic scanning technique

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MS received 22 May 1996; revised 19 August 1996

Abstract. A new method is proposed to determine the thermal effusivity of solid samples using a one dimensional photoacoustic scanning technique. The method employs a sample configuration in which the backing for a good light absorber layer is changed from a reference sample to the unknown sample by scanning the absorber surface with an incident modulated light beam. From the measured phase difference or amplitude ratio one can determine the thermal effusivity of the unknown sample, knowing the effusivity of the reference sample. The Rosencwaig–Gersho theory of photoacoustic effect has been extended to the present experimental situation and expressions have been derived for photoacoustic phase difference and amplitude ratio as the backing is changed. Values calculated using these expressions are found to agree well with measured values for different sample combinations except in amplitude ratio values when the thermal effusivities of the samples differ very widely. The reason for this disagreement is discussed.

Keywords. Photoacoustic effect; thermal effusivity; scanning technique.

PACS Nos 44·50; 43·85; 66·90

1. Introduction

The photoacoustic (PA) technique has emerged as a very powerful technique to study optical and thermal properties of solid samples [1]. It is now the best alternative analytical technique for samples in which conventional absorption spectroscopic techniques often fail. The technique has proved its power over a very wide variety of samples ranging from human blood to superlattices. A number of review articles have appeared in literature on this subject [1–3]. Since the amplitude and phase of the PA signal ultimately depend upon material parameters such as optical absorption coefficient, thermal conductivity, heat capacity and density, it has proved its ability to detect and measure thermodynamic changes such as phase transitions in solids [4]. In photoacoustic effect, since optically generated thermal waves propagate through the sample causing pressure variations in the surrounding gas medium, it finds application in thermal wave depth profiling, microscopy and nondestructive testing of materials [5–7].

A number of papers have appeared in literature on the determination of thermal parameters such as thermal diffusivity (α) and effusivity (e) of solid samples using PA technique. Measurement of thermal diffusivity and effusivity lead to the determination of thermal conductivity (k) and heat capacity (C). The PA technique belongs to the category

of periodic heat flow methods of measuring thermal diffusivity in contrast to the conventional transient heat-flow methods. A number of different methods have been developed to measure the thermal diffusivity of solids by the photoacoustic technique. The most popular among these involves a chopping frequency analysis of the PA amplitude or phase and determination of the critical frequency, f_0 , at which the sample goes from a thermally thick to a thermally thin regime [8–10]. Adams and Kirkbright [11] calculated α for different samples coated with a thin layer of absorber by measuring the variation of the phase φ of the PA signal obtained from a rear illumination with frequency. For a thermally thick sample, $l_s a_s \gg 1$, where l_s is the sample thickness and a_s is the thermal diffusion coefficient defined by $a_s = (\omega/2\alpha)^{1/2}$. For a thermally thick sample, the PA phase ceases to vary beyond the critical frequency corresponding to $l_s a_s = 1$ so that $\alpha = f_0^2 l_s^2$. An equivalent procedure is to measure the variation of the PA amplitude with frequency and obtain the critical frequency at which there is a distinct change in slope. Determination of f_0 is rather straightforward here because, for a thermally thick sample the Rosencwaig–Gersho (R–G) theory [12] predicts an ω^{-1} dependence for the PA amplitude. So, when a sample with a definite thickness changes over from a thermally thin to a thermally thick regime with increase in frequency, the slope of the PA amplitude versus $\omega^{1/2}$ plot changes from -2 to -3 from which the critical frequency can be determined and thermal diffusivity evaluated.

An alternative to the above method is to vary the distance between the point where the heat is generated and the point at which the thermal oscillations are detected. Cesar *et al* [13] have adopted this method by varying the position of a laterally incident laser beam on a transparent sample. A plot of the photoacoustic amplitude and phase against the distance x provides α by a data fit to expression with an exponential and linear dependence on $-a_s x$. A related technique has been adopted to determine the thermal conductivity and specific heat of an opaque sample by measuring the variations in photoacoustic phase with frequency for different sample thicknesses [14]. By adopting the R–G theory to specialized experimental conditions and analyzing the generated PA signal amplitude and phase, different authors have determined thermal diffusivity [15] or thermal conductivity and specific heat simultaneously [16] of a variety of samples.

Another technique to measure the thermal diffusivity of a solid sample involves determination of the amplitude ratio or phase lag of the photoacoustic signal between the front and rear surface illuminations at a single chopping frequency. This method is attractive in the sense that the measurement is independent of the sample thickness and chopping frequency. Measurement of the amplitude ratio was adopted by Yasa and Amer [17], but phase lag measurements are found to give better results. For phase lag measurement, Pessoa *et al* [18] have used two beams of light derived from the same source to illuminate the front and rear surfaces of the sample simultaneously, whereas Thomas *et al* [19] have adopted the technique of illuminating the front surface and then rotating the PA cell by 180° to illuminate the rear surface of the sample with the same light beam.

All the techniques described above suffer from the limitation that the measurement accuracy is dependent on photoacoustic cell calibration. Measurements involving variations in sample thickness or chopping frequency can cause errors in measurement. Measurement of amplitude ratio or phase lag between front and rear surfaces also depend

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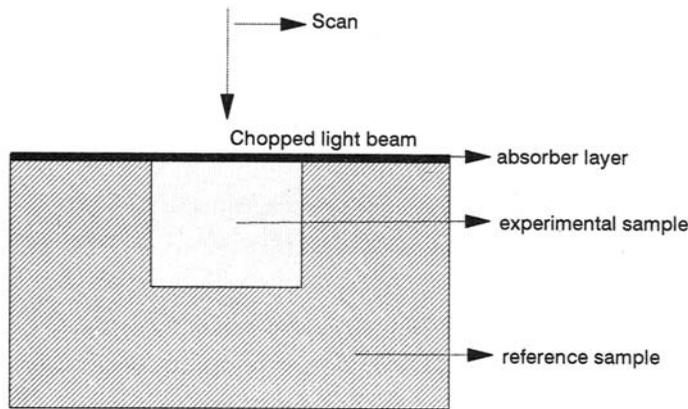


Figure 1. Sample configuration used in the experiment.

on the experimental conditions. Moreover, these measurements are laborious and difficult to automate.

In this paper we describe a convenient technique to measure thermal effusivity of solid samples using a photoacoustic scanning method. Principle of the method, adaptation of the R-G theory to this experimental situation, experimental details, results obtained and discussion of the results analyzing the advantages and limitations of this technique, are given in the following sections.

2. Principle of the technique

Consider the experimental configuration shown in figure 1. The experimental sample, whose thermal parameters are to be determined, is inserted inside a reference sample, whose thermal parameters such as thermal conductivity, k , and heat capacity, C , are known. The experimental sample is tightly inserted into the reference samples in such a way that the top of both the samples are flat and are at the same level. A thin layer of a highly light absorbing material such as carbon black is coated over the top surface. The top surface can be irradiated with a chopped beam of light and the light beam can scan the surface in a step by step fashion. The sample configuration can be kept in a photoacoustic cell and the PA amplitude as well as phase can be measured. In this configuration the absorber layer acts as the thermally thin photoacoustic sample and the thermally thick backing medium is changed from the reference sample to the experimental sample and back to the reference sample as the absorber surface is scanned with the chopped beam of light in a step by step fashion.

If the samples are made in such a way that they have thickness larger than their thermal diffusion lengths at the chopping frequency used, one can apply the one dimensional R-G theory to this configuration and evaluate the ratio of the PA amplitude as the backing is changed from the reference to the experimental sample. An expression for the corresponding difference in PA phase can also be obtained. Once the thermal effusivities of the reference sample and absorber layer are known, we show that the effusivity of the

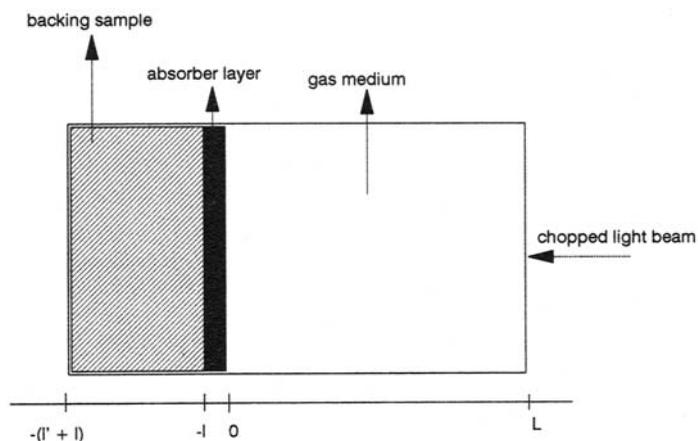


Figure 2. Sample geometry with the absorber layer on a backing sample.

experimental sample can be determined without involving any of the cell parameters and experimental conditions.

In the following section we adapt the one dimensional R–G theory to the sample configuration shown in figure 1.

3. Theoretical background

Consider the sample geometry shown in figure 2 where we have a good light absorber such as carbon black coated over a backing medium enclosed in a cylindrical photoacoustic cell. Let us apply the Rosencwaig–Gersho (R–G) one-dimensional theory for the production of photoacoustic signal to this configuration. The backing material has thermal conductivity k_b , density ρ_b and specific heat C_b and the corresponding parameters for carbon black are k_c , ρ_c and C_c respectively. The parameters for the air medium in front of the absorber layer are k_a , ρ_a and C_a respectively. For the three media, the thermal diffusivity is $\alpha = k/\rho C$, the thermal diffusion coefficient is $a = [\omega/2\alpha]^{1/2}$ and the thermal diffusion length is $\mu = 1/a$, with the corresponding subscripts as before. Here ω is the modulation frequency of the light beam. Assume that a sinusoidally chopped monochromatic beam of light of wavelength λ is incident on the absorber sample so that the modulated intensity of the light can be written as

$$I = (1/2)[I_0(1 + \cos \omega t)], \quad (1)$$

where I_0 is the incident light flux. If β is the optical absorption coefficient of the absorber sample, then the heat produced at any point x due to the absorbed light is given by

$$(1/2)[\beta I_0 e^{\beta x} (1 + \cos \omega t)],$$

where x is negative as per figure 2. Now, one can write the thermal diffusion equation for the absorber sample, backing sample and the air medium in front, and follow the algebra

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as has been done by Rosencwaig and Gersho [12] and obtain an expression for the complex amplitude of the periodic temperature at the absorber layer–air boundary. This periodic temperature variation within the absorber sample produces a corresponding heating of the boundary layer which in turn causes a corresponding expansion and contraction of the boundary layer of air, which in turn causes a corresponding periodic pressure variation which is detected by a microphone as the photoacoustic signal. One can apply the gas laws and show that the complex envelope of the sinusoidal pressure variation is of the form [1]

$$\delta P = A e^{-i\varphi}, \quad (2)$$

where A and φ are the amplitude and phase of the generated PA signal. This expression can be written more explicitly as

$$\delta P = Y \left[\frac{(r-1)(b+1)e^{\sigma l} - (r+1)(b-1)e^{-\sigma l} + 2(b-r)e^{-\beta l}}{(g+1)(b+1)e^{\sigma l} - (g-1)(b-1)e^{-\sigma l}} \right], \quad (3)$$

where

$$\begin{aligned} b &= \frac{k_b a_b}{k_a a_a}, \\ g &= \frac{k_c a_c}{k_a a_a}, \\ r &= \frac{(1-i)\beta}{2a_a}, \\ \sigma &= (1+i)a_a \end{aligned} \quad (4)$$

and l is the thickness of the absorber sample.

For a good absorber such as carbon black, optical absorption coefficient β is very high. Moreover, the absorber sample is thermally thin at the chopping frequencies used. Under these physically realistic assumptions, the magnitude of the PA amplitude term simplifies to

$$A = Y \left[\frac{b^2(g+b)^2}{4a_a^2[(g^2+b^2)^2 + 4gb[(g+b)^2 - gb]]} \right]^{1/2}, \quad (5)$$

where

$$Y = \frac{\beta I_0 \gamma P_0}{2\sqrt{2} T_0 k_c l_a a_a}$$

is a constant. Here P_0 , T_0 and γ are the ambient pressure, temperature and ratio of specific heats respectively. Substituting for b and g and defining thermal effusivity as $e = (\rho C k)^{1/2}$, one finds that the amplitude term can be expressed in terms of thermal effusivity. In one dimensional photoacoustic scanning, as one changes the backing from the reference sample to the experimental sample, the ratio between the amplitudes, after algebraic simplifications, works out to be

$$\frac{A_R}{A_E} = \left[\frac{e_R^2(e_c + e_R)^2[(e_c^2 + e_E^2)^2 + 4e_c e_E(e_c + e_E)^2 - e_c e_E]}{e_E^2(e_c + e_E)^2[(e_c^2 + e_R^2)^2 + 4e_c e_R(e_c + e_R)^2 - e_c e_R]} \right]^{1/2}, \quad (6)$$

where e_R, e_E and e_c are the thermal effusivities of the reference sample, experimental sample and the absorber sample respectively. Under the same assumptions, as one changes the backing material from the reference sample to the experimental sample, the difference in PA phase works out to be

$$\varphi_R - \varphi_E = \tan^{-1}\left(1 + \frac{e_R}{e_c}\right) - \tan^{-1}\left(1 + \frac{e_E}{e_c}\right). \quad (7)$$

If R_R and R_E are the thermal wave reflection coefficients at the absorber-backing boundaries defined by

$$R_R = (1 - e_R/e_c)/(1 + e_R/e_c)$$

and

$$R_E = (1 - e_E/e_c)/(1 + e_E/e_c),$$

one can consider three cases depending upon whether both R_R and R_E are negative or both are positive or one of them positive and the other negative. When both R_R and R_E are negative, (6) simplifies to

$$\frac{A_R}{A_E} = \left[\left(\frac{e_R}{e_E} \right) \frac{e_E + 4e_c - (e_c/e_E)/(1/e_E)}{e_R + 4e_c - (e_c/e_R)/(1/e_R)} \right]^{1/2}. \quad (8)$$

When both R_R and R_E are positive, (6) simplifies to

$$\frac{A_R}{A_E} = \left[\left(\frac{e_R}{e_E} \right) \gamma_1 \left[\frac{m_2 + e_c(4P_2 - 1)}{m_1 + e_c(4P_1 - 1)} \right] \right]^{1/2}, \quad (9)$$

where

$$m_1 = \frac{(e_c^2 + e_R^2)^2}{e_R},$$

$$m_2 = \frac{(e_c^2 + e_E^2)^2}{e_E},$$

$$P_1 = (e_c + e_R)^2,$$

$$P_2 = (e_c + e_E)^2,$$

and

$$\gamma_1 = (e_c + e_R)^2/(e_c + e_E)^2.$$

Similarly, when R_R is positive and R_E negative, (6) simplifies to

$$\frac{A_R}{A_E} = \left[\left(\frac{e_R}{e_E} \right) \left[\frac{(m_2/P_2) + e_c(4 - 1/P_2)}{e_R + e_c(4 - 1/e_R^2)} \right] \right]^{1/2}. \quad (10)$$

An inverse relation results when R_R is negative and R_E is positive. Once the thermal parameters of the absorber and the reference samples are known, the above equations can be used to determine the thermal effusivity and related parameters of the experimental sample. The values of φ_E and φ_R in (7) cannot be separated and treated independently because one does not know the absolute phase in the experiment.

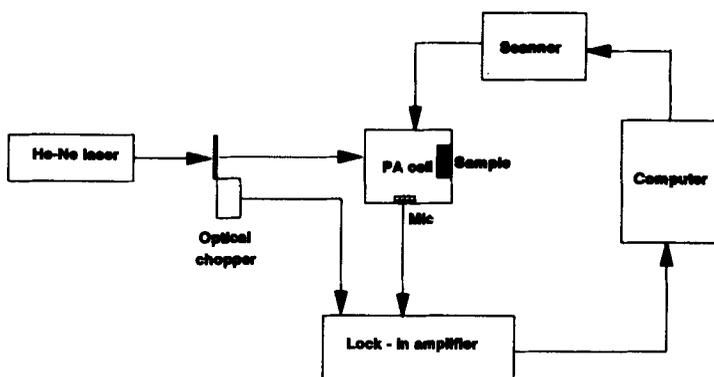


Figure 3. Block diagram of the experimental set up.

4. Experimental method

A photoacoustic spectrometer has been set up around a small volume PA cell in which the light beam can scan the surface of the absorber sample. Scanning is done under computer control in a step by step fashion so that photoacoustic amplitude and phase can be measured at different points on the absorber surface as the backing is changed. The scanner is designed in such a way that one step corresponds to a distance of 0.25 mm. A block diagram of the experimental set up is shown in figure 3. A 10 mW He-Ne ($\lambda = 632.8$ nm) laser is used as the radiation source and a chopping frequency of 40 Hz has been chosen to correspond to the best performance of the PA cell. An electret microphone (Knowles model BT 1759) has been used to detect the PA signal and the PA amplitude and phase, as usual, are measured with a lock-in amplifier.

The PA cell is mounted over a movable platform which moves step by step in one dimension. Range of movement, interval between steps etc. are software controlled. During measurements, the experimental parameters such as chopping frequency as well as the PA cell parameters remain unaltered as the light beam scans the absorber surface changing the backing from one to the other. PA signal amplitude and phase from each point are recorded after ensuring that the readings are stabilized. The changes in PA amplitude or phase due to change in distance between the acoustic source point and the detector as a consequence of PA cell movement are negligibly small as this distance is extremely small compared to the wavelength of the acoustic wave with frequency 40 Hz.

The sample configuration shown in figure 1 is so designed that it is circular with a reference sample diameter of 12 mm and experimental sample diameter of 4 mm. So we can go from backing boundary to the other in 16 steps. Obviously, it is ensured that the thickness of the backing sample is more than the thermal diffusion length at the chopping frequency used. Moreover, the thickness of the absorber layer is very small, of the order of a few microns, so that it is much smaller than its thermal thickness. The absorber layer used in our experiment is carbon black with thickness of a few tens of microns which is applied by keeping the backing samples in a benzene flame. The set up has been tested several times by having the reference and experimental samples the same, in which case the system just senses the boundaries without causing any change in PA phase or amplitude as the backing is changed.

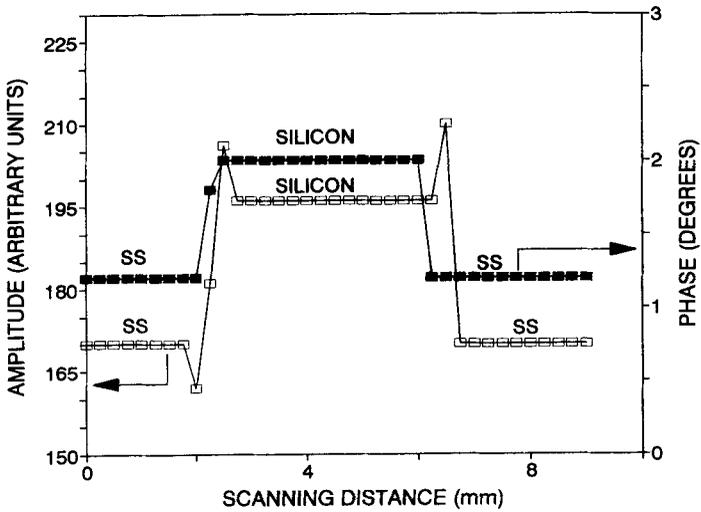


Figure 4. Variation of PA amplitude and phase with distance for a sample configuration with stainless steel (SS) as reference sample and silicon as experimental sample.

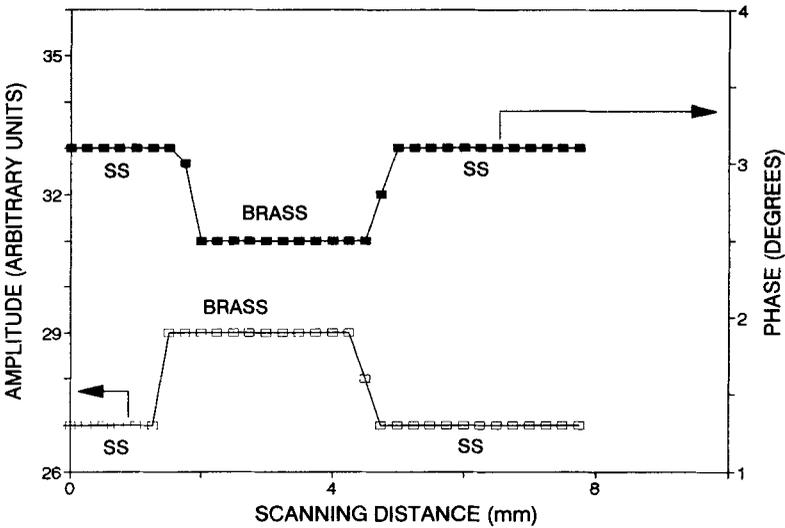


Figure 5. Variation of PA amplitude and phase with distance for a sample configuration with stainless steel (SS) as reference sample and brass as experimental sample.

5. Results

The PA amplitude ratio and phase difference have been recorded for a series of sample combinations with varying thermal parameters. They include copper, brass, stainless

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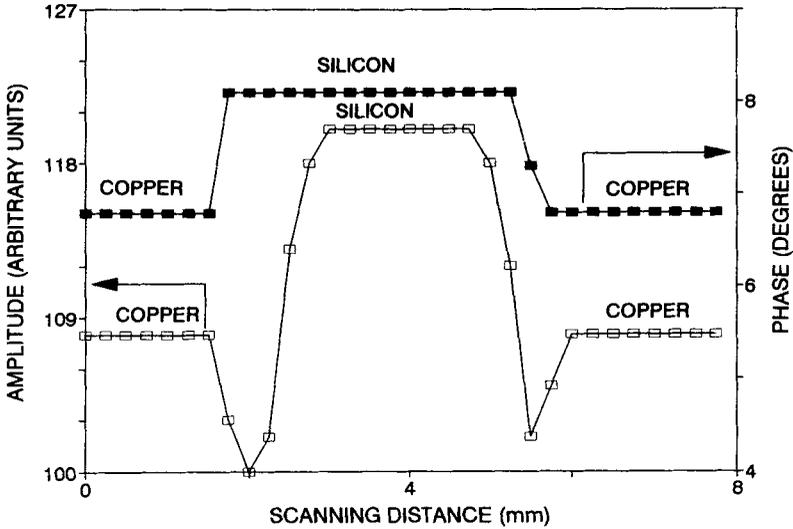


Figure 6. Variation of PA amplitude and phase with distance for a sample configuration with copper as reference sample and silicon as experimental sample.

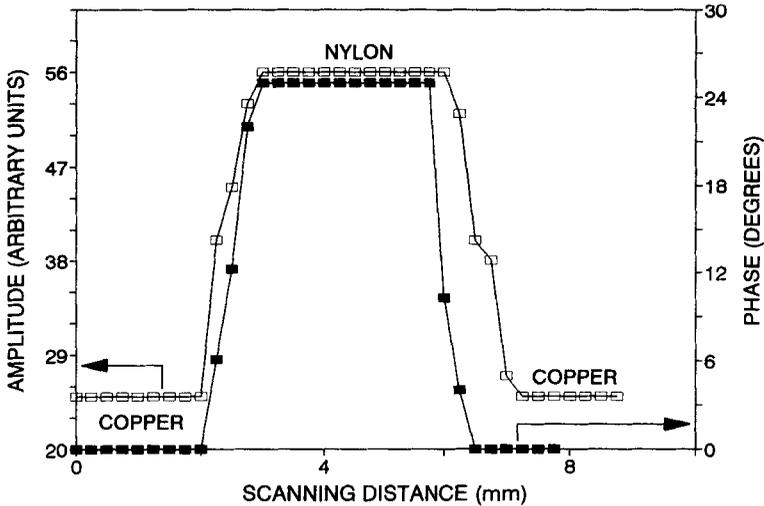


Figure 7. Variation of PA amplitude and phase with distance for a sample configuration with copper as reference sample and nylon as experimental sample. This is a case where the R values have opposite signs. Consequently there is large difference between measured and calculated amplitude ratio values.

steel, silicon, nylon, and teflon. A few plots are shown in figures 4–7. The sharp changes in amplitude and phase as a function of distance correspond to the boundaries. The direction in which the PA amplitude or phase vary in the experimental sample relative to the reference sample clearly indicates whether the experimental sample has a higher or lower thermal effusivity compared to the reference sample. Obviously, there is no

Table 1. Measured and calculated values of phase difference and amplitude ratios for different sample configurations.

Sample configuration E-experiment sample R-reference sample	Thermal wave reflection coefficients	Phase difference (degrees)		Amplitude ratio	
		Measured	Calculated	Measured	Calculated
E-Brass	$R_E = -0.91$	1.2	1.2	0.87	0.93
R-Copper	$R_R = -0.96$	± 0.05		± 0.04	
E-Stainless steel	$R_E = -0.93$	0.6	0.62	0.97	0.98
R-Copper	$R_R = -0.96$	± 0.04		± 0.05	
E-Silicon	$R_E = -0.91$	1.3	1.4	0.9	0.92
R-Copper	$R_R = -0.96$	± 0.05		± 0.05	
E-Nylon	$R_E = +0.08$	26	27.5	large difference as	
R-Copper	$R_R = -0.96$	± 1.2		R_E is +ve and R_R is -ve	
E-Brass	$R_E = -0.91$	0.7	0.62	0.93	0.95
R-Stainless steel	$R_R = -0.93$	± 0.04		± 0.05	
E-Copper	$R_E = -0.96$	26	27.5	large difference as	
R-Nylon	$R_R = +0.08$	± 1.3		R_E is -ve and R_R is +ve	
E-Nylon	$R_E = +0.08$	24.5	26.9	large difference as R_E is	
R-Stainless steel	$R_R = -0.93$	± 1.2		+ve and R_R is -ve	
E-Silicon	$R_E = -0.91$	0.75	0.77	0.9	0.93
R-Stainless steel	$R_R = -0.93$	± 0.04		± 0.04	
E-Teflon	$R_E = +0.05$	0.6	0.64	0.96	0.95
R-Nylon	$R_R = +0.08$	± 0.03		± 0.06	
E-Brass	$R_E = -0.91$	24	26.3	large difference as R_E is	
R-Nylon	$R_R = +0.08$	± 1.2		-ve and R_R is +ve	
E-Teflon	$R_E = +0.05$	23.6	26.5	large difference as R_E is	
R-Copper	$R_R = -0.96$	± 1.2		+ve and R_E is -ve	

An estimated value of $e_c = 0.02 \text{ cal cm}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ has been used in these calculations.

variation in amplitude or phase, except for variations at the boundaries, when the same material is used in places of the reference and experimental samples leading to a value zero for the phase difference in equation (7) and unity for the amplitude ratio in equations (8), (9) or (10). For a sample in two different experiments the measured PA phases need not be the same as the initial phases in the two situations could very well be different. This is why the phases for the same sample in different figures show difference in values.

In table 1 we tabulate the results obtained from a series of sample combinations with different thermal effusivity values. The measured phase difference and amplitude ratio values along with the corresponding values calculated using (7) and (8), (9) or (10) using data taken from handbooks are tabulated in this table for comparison. The thermal effusivity of carbon black layer used as absorber is estimated by measuring the amplitude ratio and phase difference in one experiment in which both backings used have known thermal properties. It can be noted from the table that the agreement between calculated and experimental phase difference values is good irrespective of the thermal effusivity values of the backings. Again, the agreement between calculated and experimental ratios is very good when both the backings have higher or lower thermal effusivities compared

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Table 2. Values of thermal effusivity determined for a few selected samples.

Experimental sample	Reference sample used	Effusivity values determined experimentally $\text{cal cm}^{-2} \text{K}^{-1} \text{s}^{-1/2}$		Calculated effusivity of the experimental sample available data $\text{cal cm}^{-2} \text{K}^{-1} \text{s}^{-1/2}$
		Phase difference method	Amplitude ratio method	
Brass	Stainless steel	0.42 ± 0.01	0.41 ± 0.01	0.44
Silicon	Copper	0.4 ± 0.01	0.38 ± 0.01	0.37
Stainless steel	Copper	0.59 ± 0.02	0.54 ± 0.02	0.585
Teflon	Nylon	0.018 ± 0.001	0.018 ± 0.001	0.018

to that of the absorber layer. Large differences between experimental and calculated values in amplitude ratio values is found when the thermal effusivity values of the two samples are widely different leading to a difference in sign for R_E and R_R , as in copper-nylon combination tabulated in table 1. This point is discussed in greater detail in the next section. The thermal effusivity values of a few samples determined from PA amplitude ratio and phase difference measurements are tabulated in table 2. The corresponding values calculated from available data are also tabulated for comparison.

6. Discussion and conclusion

In this work we have demonstrated a rather simple and direct method for determining the thermal effusivity by a photoacoustic scanning technique. Since measurements are made relative to a reference sample, the technique is free of PA cell calibration and other experimental conditions. The only requirement is that the thermal parameters of the reference sample should be known accurately. Experimentally it is found that providing a uniform coating over the surfaces of the two samples is not difficult. Of course, one must ensure that the samples have flat top surfaces and must be in the same level. But in a routine experiment, one can have a standard reference sample and the experimental sample can be inserted into an appropriate cavity made in the reference sample.

As is evident in some of the plots shown in figures, the boundary between the two samples gives rise to abrupt increase or decrease in amplitude and phase. But the regions corresponding to reference and experimental samples are quite clear and explicit.

Analysis of the results presented in table 1 shows that we have a good agreement between measured and calculated values of amplitude ratios when the thermal wave reflection coefficient R at the absorber-backing sample boundaries are both positive or negative. Negative value for R corresponds to the situation when the thermal effusivity of the backing is more than that of the absorber layer. In this situation, more of the thermal waves generated in the absorber sample by photothermal conversion which propagate and strike the boundary, are transmitted into the backing medium. The extent to which these waves are transmitted into the backing medium is reflected in the corresponding PA signal amplitude. When R_R and R_E are both negative, (8) holds good and we have good agreement between calculated and experimental values. When R is positive, that is when

the thermal effusivity of the backing is smaller than that of the absorber layer, more of the thermal waves get reflected back into the absorber layer reducing the PA amplitude. When R_R and R_E are both positive the reflected thermal waves from the two backings are in phase and in this case equation (9) holds good and we have good agreement between calculated and experimental values. When R_R is positive and R_E is negative or vice versa, an extra phase factor between the transmitted and reflected thermal waves at the two boundaries will appear which is not accounted for in (10). So there is large difference between calculated and experimental amplitude ratio values in this case. This aspect is under further investigation. However, with a suitable choice of the reference sample this limitation can easily be got over.

In any case, phase difference measurement do not suffer from any such limitation. Taking into account the approximations used to get equation (7), it must be said that the agreement is very good irrespective of the sign of R_E or R_R . In this regard, one must also take into account the errors in the values used to calculate the numbers quoted in table 1 and experimental uncertainties. Since phase difference measurement is enough to determine the effusivity of any sample, the method works for all samples irrespective of their effusivity values.

Since these measurements do not involve any variations in frequency, sample thickness or backing material as in other experiments, the technique is quite straightforward and fast. This method could be developed into a standard experiment set up with which thermal analysis of unknown samples can be done in a routine way.

Acknowledgements

This work was supported by the Department of Science and Technology.

References

- [1] A Rosencwaig, *Photoacoustics and photoacoustic spectroscopy* (Wiley, New York, 1980)
- [2] C K N Patel and A C Tam, *Rev. Mod. Phys.* **53**, 517 (1981)
- [3] A C Tam, *Rev. Mod. Phys.* **58**, 381 (1986)
- [4] P Korpiun and R Tilgner, *J. Appl. Phys.* **51**, 6115 (1980)
- [5] J Ospal and A Rosencwaig, *J. Appl. Phys.* **53**, 4240 (1982)
- [6] J Baumann and R Tilgner, *J. Appl. Phys.* **58**, 1982 (1985)
- [7] U Seidel, K Haupt, H G Walther, J Burt and B K Bein, *J. Appl. Phys.* **75**, 4396 (1994)
- [8] P Charpentier, F Lepoutre and L Bertrand, *J. Appl. Phys.* **53**, 608 (1982)
- [9] A Lachaine and P Poulet, *Appl. Phys. Lett.* **45**, 953 (1984)
- [10] K N Madhusoodanan, M R Thomas and J Philip, *J. Appl. Phys.* **62**, 1162 (1987)
- [11] M J Adams and G F Kirkbright, *Analyst* **102**, 281 (1977)
- [12] A Rosencwaig and A Gersho, *J. Appl. Phys.* **47**, 64 (1976)
- [13] C L Cesar, H Vargas, J Mendes Filho and L C M Miranda, *Appl. Phys. Lett.* **43**, 555 (1983)
- [14] A Lachaine, *J. Appl. Phys.* **57**, 5075 (1985)
- [15] B Bonne, J L Laporte and Y Rousset, *J. Appl. Phys.* **67**, 2253 (1990)
- [16] U Zammit, M Marinelli, R Pizzo Ferrato, F Scudieri and S Martellucci, *J. Phys.* **E21**, 935 (1988)
- [17] Z Yasa and N Amer, in *Topical meeting on acoustic spectroscopy* (Ames, Iowa, 1979) WA5-1
- [18] O Pessoa Jr, C L Cesar, N A Patel, H Vargas, C C Ghizoni and L C M Miranda, *J. Appl. Phys.* **59**, 1316 (1986)
- [19] S Thomas, J Isaac and J Philip, *Rev. Sci. Instrum.* **66**, 3907 (1995)