

# DETECTION OF THERMAL DIFFUSIVITY FOR THIN SAMPLES AND POWDER WITH MICROPHONE-PHOTOACOUSTIC SPECTROSCOPY

Mengle QIAN<sup>1</sup>, Tatong WU<sup>1</sup>, Li HOU<sup>2</sup>, Peichun YANG<sup>2</sup>, and Lichang QI<sup>2</sup>

<sup>1</sup>*Institute of Acoustics, Tongji University, China*

<sup>2</sup>*Research Institute of Synthetic Crystals, Beijing, China*

Thermal diffusivity  $\alpha$  is a very important parameter in the study of some thermal processes and phenomena. But it is difficult to measure for some thin samples, e.g. thin films and coating layers, with traditional methods. Recently a new technique for detecting thermal diffusivity with PAS has been developed. This paper describes the theory and experimental results using this technique.

## 1. Theory

Assuming only the sample absorbs the light with absorption coefficient for excitation and located in region 1. The radial dimensions of three regions are considered as infinite because their lateral sizes are much larger than the light radius  $a$  and their thermal diffusivities length  $\mu=(2\alpha_j/w)^{1/2}$  and  $l_g \gg \mu_0$ ,  $l_2 \gg \mu_2$ . The temperature rise  $T(r, t)$  in each region satisfies the following equations

$$\Delta^2 T_j(r, t) - (1/\alpha_j)[\partial T(r, t)/\partial t] = 0, \quad (j = 0, 2) \quad (1a)$$

$$\begin{aligned} \Delta^2 T_1(r, t) - (1/\alpha_1)[\partial T_1(r, t)/\partial t] \\ = (-2P_0\beta/\pi^2 a_b^2 k_1) \\ \cdot \exp[-\beta z - (2r^2/a_b^2) + i\omega t] \end{aligned} \quad (1b)$$

and boundary conditions

$$\begin{aligned} T_0(r, 0, t) &= T_1(r, 0, t), \\ T_1(r, l, t) &= T_2(r, l, t), \end{aligned} \quad (2a)$$

$$\begin{aligned} k_0[\partial T_0/\partial z]_{z=0} &= k_1[\partial T_1/\partial z]_{z=0}, \\ k_1[\partial T_1/\partial z]_{z=l_1} &= k_2[\partial T_2/\partial z]_{z=l_1}. \end{aligned} \quad (2b)$$

The I-D solution  $T_j(Z)\exp(i\omega t)$  of region  $j$  ( $j=0, \text{ or } 2$ ) is given by

$$\begin{aligned} T_0(Z) &= [\beta P^0/\pi k_1(\beta^2 - \sigma_1^2)] \\ &\cdot [(r-1)(1+b)\exp(\sigma_1 l_1) \\ &\quad + (r+1)(1-b)\exp(-\sigma_1 l_1) \\ &\quad + 2(b-r)\exp(-\beta l_1)] \\ &\cdot [(1+g)(1+b)\exp(\sigma_1 l_1) \\ &\quad - (1-g)(1-b)\exp(-\sigma_1 l_1)]^{-1} \\ &\cdot \exp(\sigma_0 z) \end{aligned} \quad (3a)$$

$$\begin{aligned} T_2(z) &= [\beta P_0/\pi k_1(\beta^2 - \sigma_1^2)] \\ &\cdot \{[(r+1)(1+g)\exp(\sigma_1 l_1) \\ &\quad + (r-1)(1-g)\exp(-\sigma_1 l_1)] \\ &\quad \cdot \exp(-\beta l_1) - 2(g+r)\} \\ &\cdot [(1+g)(1+b)\exp(\sigma_1 l_1) \\ &\quad - (1-g)(1-b)\exp(-\sigma_1 l_1)]^{-1} \\ &\cdot \exp(-\sigma_2 z) \end{aligned} \quad (3b)$$

where  $\sigma=(i\omega/\alpha_j)$ ,  $g=K_0\sigma_0/k_1\sigma_1$ ,  $b=k_2\sigma_2/k_1\sigma_1$ ,  $r=\beta/\sigma_1$ ,  $w$ =modulating frequency,  $k$ =thermal

conductivity,  $\alpha=k/\rho C$  thermal diffusivity,  $\rho$ = density, and  $C$ =the specific heat, and  $P_0$ =the light power. If the medium in region 0 or 2 is gas, the PA signal  $p(t)$  is given by

$$p(t) = (-\gamma P/Tl_j) \int_{l_j} T_j(z) \exp(i\omega t) dz$$

$$= [-\gamma P\mu_j \exp(-i\pi/4)/\sqrt{2} Tl_j] T(z_j) \cdot \exp(i\omega t) \quad (4)$$

where  $j=0$  or  $2$ ,  $z_j=0$  or  $l_1$ ,  $\gamma$ =the ratio of the specific heats of gas,  $P$  and  $T$ =the ambient pressure and temperature, respectively. When both media in regions 0 and 2 are gas and the sample is a strong light absorber, the phase responses of the PA signal in region 0 and 2 are obtained from Eqs. (3) and (4) with  $g, b \ll 1$  and  $r \gg 1$  is:

$$\varphi_0(f) = (-\pi/2) - \tan^{-1}[\sin(2x)/\text{sh}(2x)] \quad (5a)$$

$$\varphi_2(f) = (-\pi/2) - \tan^{-1}[\tan(2x)/\tanh(2x)] \quad (5b)$$

where  $x=(\pi f/f_c)^{1/2}$ , and  $f_c=\alpha_1/l_1^2$ =the character frequency of the sample. If the thickness  $l_1$  of the sample is known and its phase response  $\varphi_j(f)$  is determined, its thermal diffusivity  $\alpha$  is obtained from Eq. (5) easily.

## 2. Determination of phase response for detection system

The PA detection system is shown in Fig. 2. The

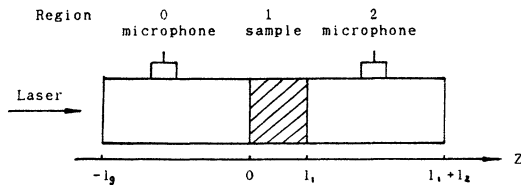


Fig. 1. PA cell and three-layer theoretical model.

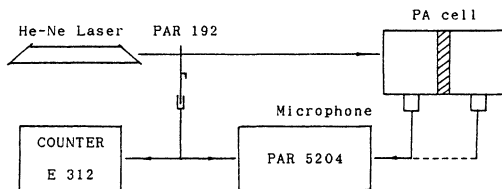


Fig. 2. PA detection system.

measured phase response  $\varphi(f)$  consists of the sample and detection system phase response

$$\varphi(f) = \varphi_j(f) + \varphi_s(f). \quad (6)$$

The theoretical sample phase response  $\varphi_j(f)$  calculated from Eq. (3a) is shown in Fig. 3. Obviously,  $\varphi_j(f)=0$  and  $\varphi(f)$  when  $f < 2.5f_c$ . Selecting a sample whose  $f_c$  is lower than  $0.4f_L$  ( $f_L$  is the lowest interested frequency), the system response  $\varphi_s(f)$  can be measured with a ceramic sample whose  $f_c=0.44$  KHz and  $l_1=1.503$  mm (Fig. 4). Therefore the  $\varphi_j(f)$  can be obtained by deducting the  $\varphi_s(f)$  from  $\varphi(f)$  in 5–1000 Hz. When the sample is a thin strong material, we put it into the PA cell and determine the phase responses  $\varphi_F(f)$  and  $\varphi_R(f)$ . Reducing the  $\varphi_s(f)$  from  $\varphi(f)$ , the phase responses  $\varphi_{0F}(f)$  and  $\varphi_{2R}(f)$  are obtained. Fitting the  $\varphi_{0F}(f)$  and  $\varphi_{2R}(f)$  to that given by Eq. 5a and 5b by a microcomputer, the thermal diffusivity  $\alpha_1$  of the sample and fitting error  $Q$  can be obtained immediately. If the sample is diamond powder, we place the powder in just one layer of thickness  $l_1$ , equal to the average diameter of the powder on a transparent paper as a sample. Then

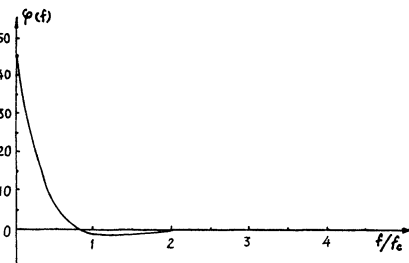


Fig. 3. Theoretical sample phase response.

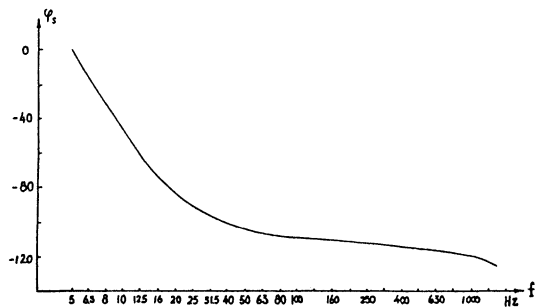


Fig. 4. Detection system phase response.

Table 1. Experimental results of thermal diffusivity (cm/s)

Sample	PAS technique					Thermoconductor $\alpha$ (cm <sup>2</sup> /s)
	$l_1$ (mm)	Front exc. $\varphi_{0F}(f)$		Rear exc. $\varphi_{2R}(f)$		
		$\alpha$ (cm <sup>2</sup> /s)	$Q$ (%)	$\alpha$ (cm <sup>2</sup> /s)	$Q$ (%)	
<b>Cn</b>						
Armoc Fe	0.635	0.17	1.70	0.18	1.56	0.18–0.20
Cu	2.200	0.95	3.90	0.96	0.23	1.01
Alloy Al	0.611	0.583	1.30			0.542
Ge	2.152	0.352	0.56			0.35*
<b>Diamond ceramic</b>						
H <sub>8</sub>	2.250	1.59	1.03	1.56	3.50	1.64
H <sub>16</sub>	2.200	2.00	2.10	2.03	2.40	2.10
H <sub>40</sub>	2.478	0.44	0.63	0.48	1.28	0.48
<b>Paper</b>						
2-3	0.249	$2.9 \cdot 10^{-3}$	4.33	$3.1 \cdot 10^{-3}$	8.63	
2-1-2	0.261	$3.4 \cdot 10^{-3}$	2.10	$3.5 \cdot 10^{-3}$	6.91	
Blue	0.120	$6.9 \cdot 10^{-4}$	4.74	$7.2 \cdot 10^{-3}$	4.83	
White	0.143	$1.1 \cdot 10^{-3}$	1.61	$1.1 \cdot 10^{-3}$	8.71	
<b>Diamond powder</b>						
JR <sub>1</sub> <sup>6</sup>	0.280	2.70	2.16			
JR <sub>1</sub> <sup>2</sup>	0.323	2.99	2.82			
JR <sub>2</sub> <sup>6</sup>	0.309	3.45	3.67			2.88–4.12**
JR <sub>2</sub> <sup>2</sup>	0.284	2.73	2.48			

\*This value and \*\*this value are given by Ref. 2) and 3) respectively.

the  $\varphi_{0F}(f)$  and the thermal diffusivity can be obtained by the same method.

### 3. Experimental results

The thermal diffusivities of some samples are measured by Microphone-PAS. The results are shown in Table 1. The results determined by Laser Thermoconductor are also given in Table 1. They are in good agreement.

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