Solid State Science and Technology, Vol. 11, No.1 (2003) 51-58

MEASUREMENT OF THERMAL DIFFUSIVITY OF MALAYSIAN WOOD USING PHOTOFLASH AND PHOTOACOUSTIC TECHNIQUES

Chia Pei Fung, W. Mahmood Mat Yunus, Zaidan Abdul Wahab, and Paridah Mohd Tahir
Department of Physics, Faculty of Science and Environmental Studies
Universiti Putra Malaysia, 43400 UPM, Serdang, Malaysia.
43400 Serdang, Selangor Darul Ehsan, Malaysia.

ABSTRACT

Two experimental arrangements have been used to measure the thermal diffusivity at room temperature for ten species of Malaysian wood using photoflash and photoacoustic (PA) techniques. Both use circular disc samples with thickness 1 to 2 mm and 100 to 200 μm respectively. In the photoflash experiment, a flash pulse is irradiated onto the front surface of the sample. The time dependence of the temperature response at the back surface of the sample is measured using a K-type thermocouple. On the other hand, the PA experimental configuration uses a closed photoacoustic (PA) cell that serves as a pressure sensor as well as an acoustic chamber. It is based upon the measurement of the acoustic signal as a function of the modulation frequency in the region where the sample is thermally thick. Both experimental data are then used to calculate thermal diffusivity using appropriate analytical expressions. Scanning electron microscopy (SEM) observation has also been done on both radial and tangential surface of the samples. The results are in good agreement within experimental error, hence validating the experimental measurements.

INTRODUCTION

There have been a large majority of Malaysian woods submitted to complete studies of their physical properties. But, there is a notable lack of thermal characterization studies of these woods. This is mainly due to the lack of laboratory equipment and unfamiliarity with the appropriate techniques. Thermal diffusivity is an important thermophysical property. The value of thermal diffusivity, α, reflects the thermal propagating rate in transient process. Furthermore, by its relation to thermal conductivity, κ, one can derive κ coefficient from the data of α [1]. Because of the low thermal conductivity and moderate density and heat capacity of wood, the thermal diffusivity of wood is much lower than that of other structural materials, such as metal, brick, and stone and hence does not feel extremely hot or cold to the touch. Thermal diffusivity values are a very useful data for optimization of wood material used in many building and construction applications [2].

During the last three decades, the existing photoflash and photoacoustic (PA) techniques for nondestructive characterization of materials have been gradually applied to a wider range of science and technology branches. Unlike most traditional methods the photoflash and PA techniques require small sample, which can be as small as disks a few millimeters in diameter and a fraction of a millimeter thick.

The flash method, first proposed by Parker [3], is generally accepted as the standard method for measuring the thermal diffusivity of thin discs of solid materials. In this method, the thermal diffusivity is calculated from the measured temperature-time response curve at the back surface of a thin disc specimen after irradiating its front surface with an energy flash pulse. The photoflash method can be used for measuring the thermal diffusivity of solid in the range of ($1x10^{-3}$ to $1x10^{1}$) cm^2s^{-1}. The method was later modified by other authors such as Cape and Lehman (1963), and Clark and Taylor (1975). The modification was introduced by taking different considerations such as finite pulse-time, radiation loss, radiant energy penetration, non-uniform surface heating and specimen thickness effects.

The PA effect occurs when periodically interrupted radiation absorbed by a solid sample result in the variations in the temperature of the sample. The variation in the pressure of the air in contact with the surface of the sample when confined in a closed volume referred to as PA cell produces acoustic waves. In the optical case the PA signal is due to the periodic deposition of heat by light, the so-called "PT effect" which is caused by non-radiative de-excitation processes following the absorption of light by the sample. Monitoring the amplitude and phase of the acoustic signal by means of a sensitive microphone coupled to the cell provides information about various physical properties of the sample including its thermal diffusivity. This is due to the fact that the PA signals depend not only on the optical absorption coefficient of the sample and its light-to-heat conversion efficiency but also on the way the heat diffuses through the sample. The PA effect has been shown to provide the basis for a simple and reliable technique for measuring the thermal diffusivity of materials as diverse as glasses, semiconductors, polymers, plant leaves and foodstuffs [4].

In this paper we report the thermal diffusivity measurements, by means of the photoflash and photoacoustic (PA) techniques in a heat transmission configuration, of two different surfaces of ten kinds of Malaysian wood. The results of both measurements show a good agreement within the experimental error, hence validating air measurements.

MATERIALS AND METHODS

The samples used in photoflash technique were carefully cut by a saw and polished manually by hand in the shape of a circular plate with diameter of about 13 mm and 1 mm thickness. The samples used in PA technique were cut with a microtome into cross section slices of about 1 cm^2 and 0.200 mm thickness obtained from small blocks of about 1 x 1 x 2 cm^3. The blocks had been previously softened by keeping them immersed in boiling water for about 6 hours [5].

The experimental setup for the photoflash measurement is shown schematically in figure 1. The radial and tangential surface of wood was irradiated with the light pulse. The light pulse can easily penetrate porous materials such as wood. To avoid this problem, the specimens were thinly painted with carbon black. In simple terms four basic components are required in this photoflash method. There are sample holder made from perspex, light pulse source (Maxxum flash 5400HS), detection and amplification system, and recording and analysis assembly.

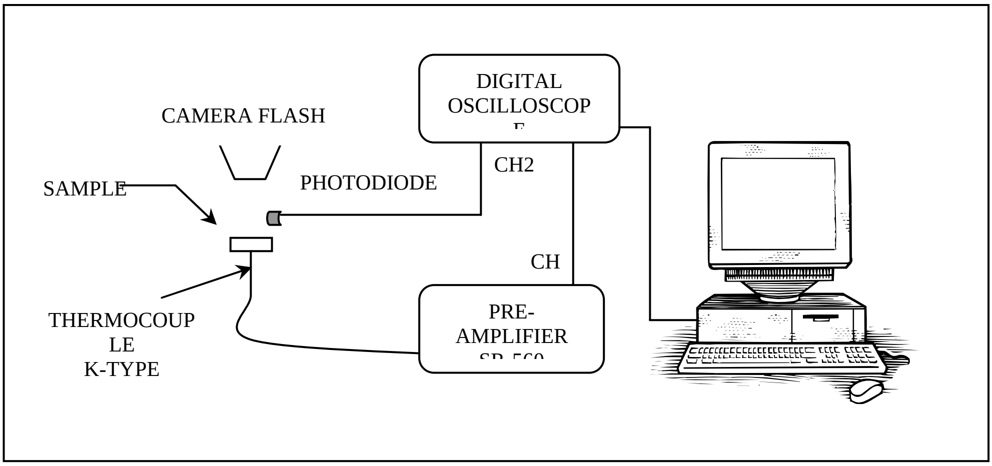

Figure 1 : Schematic diagram of experimental setup for photoflash technique.

In this experiment, the sample is mounted on the top of the sample holder. The front surface of the sample is irradiated with a single light pulse (~9ms). The back surface of the sample has a thin-wire K-type thermocouple attached. A photodiode was used to detect the light pulse from the photoflash and subsequently triggered the oscilloscope. The generated photoflash signal was amplified by the preamplifier and was transferred to the oscilloscope. Lastly, the signal was then analyzed for the thermal diffusivity calculation by the personal computer.

Schematic view of the experimental setup used for PA measurements of thermal diffusivity is shown in figure 2.

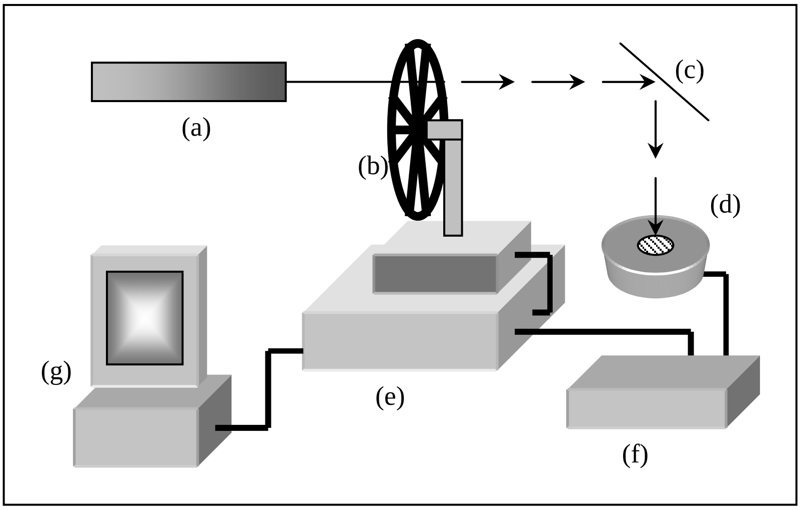

Figure 2 : Schematic view of the experimental setup used for PA measurements of thermal diffusivity: (a) He-Ne laser, (b) mechanical chopper, (c) mirror, (d) close photoacoustic cell, (e) lock-in amplifier, (f) pre-amplifier, (g) computer.

The He-Ne laser (Melles Griot, Model 05LHR991) was used as a light source and its monochromatic light beam intensity was modulated at a frequency *f* by a variable speed mechanical chopper SR540 (Stanford Research Systems). The microphone (Bruel & Kjaer) is mounted at the second plate and the sample is placed on the sample. The sample is illuminated with chopped laser light and the heat is transferred to the surface of the sample where it heats the gas in the cell. The periodic heating generates a pressure variation in the surrounding gas medium, which can be detected by the microphone. The PA signal voltage obtained is then amplified by the preamplifier SR560 and further analyzed by using the lock-in amplifier SR530 interfaced to a personal computer, which permits recording of the data (amplitude and phase of the signal) as a function of the modulation frequency.

RESULTS AND DISCUSSION

The generated signal from photoflash was transferred to the personal computer. The *Origin Software* was used to analyze the graph (Amplitude versus time) as shown in figure 3. The half rise time was determined and then thermal diffusivity of the samples was calculated by using equation 1 and 2.

The half rise time $t_{1/2}$ can be determined from the time taken to reach half of the maximum temperature rise. The thermal diffusivity of the sample can be computed using equation 2. In this experiment, the heat loss correction was calculated using Clark and Taylor rise–curve [6]. The ratio $t_{0.75}/t_{0.25}$ is determined from the experimental data where $t_{0.75}$ and $t_{0.25}$ are the time to reach 75% and 25% of the maximum respectively. Then the correction factor, K_R can be calculated from the equation 1:

$$K_R = -0.3461467 + 0.361578\left(\frac{t_{0.75}}{t_{0.25}}\right) - 0.06520543\left(\frac{t_{0.75}}{t_{0.25}}\right)^2 \quad (1)$$

The corrected value of thermal diffusivity at the half–time will be

$$\alpha_{\text{corrected}} = \frac{\alpha_{0.5} K_R}{0.13885} \quad (2)$$

Another situation, which should be considered in this experiment, is the finite pulse–effect. The pulse duration, τ for the photoflash (Maxxum flash) is 9ms. According to Cape and Lehman, when the width of the heat pulse $\tau << t_c$, where $t_c = \pi^2 L^2/\alpha$, finite pulse–time effects are negligible [7]. In the present experiment, the calculated ratio τ/t_c for all samples are much smaller than 1 ($\tau/t_c <<1$), therefore the finite pulse time in this case is negligible.

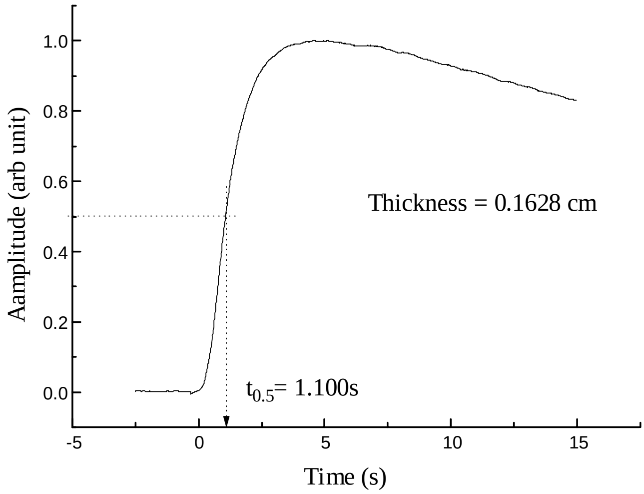

Figure 3 : Amplitude (arb unit) versus time (s) for Bakau (*Rhizophora mucronata*)

In the photoacoustic cell measurement, a straightforward application of the one-dimensional thermal diffusion model of Rosenwaig and Gersho (1976) to an optically opaque sample of thickness L and thermal diffusivity α for the case that the sample is thermally thick, where *f* is the chopper frequency, predicts that the PA amplitude, S_{model}, varies as

$$S_{model} = (A/f)\exp\left(-\alpha\sqrt{f}\right) \tag{3}$$

It can be shown that the thermal diffusivity, α, can be experimentally determined from the measurements of the PA signal amplitude, S, as a function of the modulation frequency, by fitting the corresponding PA signal data to the expression above. Here, A is a constant and

$$a = \sqrt{\pi L^2/\alpha} \tag{4}$$

with L being the sample thickness. From the fitted value of a, the thermal diffusivity α is readily obtained. In figure 4, we show a typical result for the PA signal amplitude data taken, at room temperature, as a function of the modulation frequency. The solid line in Figure 4 corresponds to the data best fitting to the theoretical expression for the PA signal amplitude given by equation 3. The result we got from this data fitting for the value of α was 1.766 x 10^{-3} cm^2/s. The same procedure was applied to all samples investigated, and the corresponding results for the thermal diffusivity are summarized in Table 1.

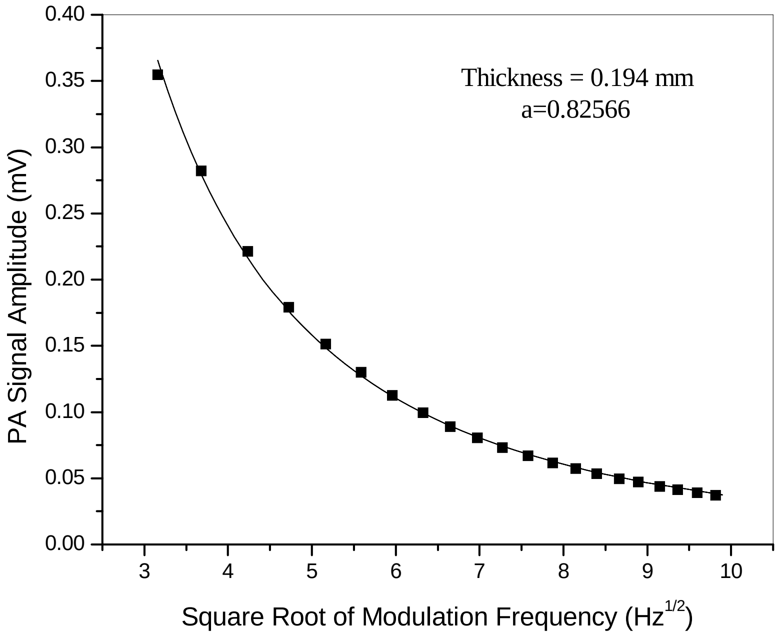

Figure 4 : PA signal amplitude as a function of the square root of the modulation frequency for Nyatoh (*Palaqium burakii*) radial surface.

Table 1 : Thermal diffusivities of the ten Malaysian woods measured with the photoflash and photoacoustic techniques described in this paper.

Commercial name	Botanical name	Thermal Diffusivity (x10^{-3} cm^2/s)			
		Radial surface		Tangential	
		Photoflash	PA	Photoflash	PA
Bakau	*Rhizophora mucronata*	1.468	1.475	1.390	1.396
Cengal	*Neobalacarpus heimii*	1.634	1.662	1.442	1.478
Nyatoh	*Palaqium burakii*	1.716	1.766	1.332	1.349
Ramin	*Gonystylus bancanus*	1.542	1.578	1.294	1.301
Sentang	*Azadirachta exelsa*	1.722	1.748	1.428	1.451
Sepetir	*Sindora palustris*	1.367	1.377	1.233	1.248

Acacia a	*Acacia auriculiformis*	1.430	1.435	1.116	1.128
Acacia m	*Acacia mangium*	1.417	1.438	1.372	1.391
Sesendok	*Endospermum malaceusse*	1.783	1.802	1.442	1.464
Terap	*Artocarpus elasticus*	1.800	1.848	1.650	1.680

The difference values in percentage of the measured thermal difusivities of the ten kind of Malaysian wood using photoflash and PA techniques have been found to be in ± 3% correlation. Thus, validating the measured thermal diffusivity results. We note that the thermal diffusivity value measured using both photoflash and photoacoustic techniques are nearly the same for tangentially and radially. The slightly higher radial diffusivities are possibly due to radially oriented ray cells and the arrangement of fibers in radial files as shown by scanning electron microscope (SEM) study.

The radial diffusivities is larger than that of tangential values by 3.2% to 36%. The difference in the thermal diffusivity is probably due to the orientation of the fibrous cells. Therefore, this results show that its fiber orientation plays an important factor in the flow of heat through wood samples.

CONCLUSION

Two independent experimental set-ups have been used to measure the thermal diffusivities of ten kinds of Malaysian wood. The measured values in both experiments have been found to be in good agreement for both the radial and tangential surfaces. Care has been taken to guard against the sources of errors identified through the analyses, and hence good experimental results have been obtained. This study was an initiative to determine the thermal diffusivity of the known species of wood in Malaysia. It might not be intensive but should serve as a guide towards collective effort of providing more information on the subject. However to the best for our knowledge, the thermal diffusivity of these specific species used in this study had not been reported in the literature.

ACKNOWLEDGEMENT

The authors are grateful to Universiti Putra Malaysia and The Malaysian Government for their financial supports through PASCA (Chia Pei Fung).

REFERENCES

[1] G. T. Tsoumis, 1991. *Science and Technology of Wood: structures, properties and utilization:* New York.

[2] H. Kubler, 1980. *Wood as Building and Hobby Material:* John Wiley & Sons.

[3] W.J.Parker, R.J.Jenkins, C.P.Butler and G.L.Abbott, 1961. *Journal of Applied physics* **32**(9).

[4] J. J. Alvarado, 1994. *J. Appl Phys*. **76**(11) 7217.

[5] G. Leon, J. Cruz-de-Leon, L. Villasenor, 2000. *Meas Sci Technol* **58**(2000) 241

[6] L.M. Clark, R.E. Taylor, 1975. *J.Appl. Phys.* **46** (2): 714.
[7] J.A. Cape, G.W.Lehman, 1963. *J. Appl. Phys*. **34** (7) 1909.
[8] Forest Products Laboratory, 1989. *Handbook of Wood and Wood-Based Materials for Engineers, Architects, and Builders:* US Department of Agricultural.
[9] K.D.Maglic and R.E Taylor, 1992. Compendium of thermophysical property measurement methods 2, Plenum Press, New York, London.
[10] Rosenwaig and A. Gersho, 1976. *J. Appl. Phys*. **47**(1): 64.