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Thermal Diffusivity Measurement of the Commercial Papers Using Photoacoustic Technique

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ABSTRAK

Pengukuran photoakustik ke atas sampel kertas telah dilakukan. Ianya berdasarkan kepada pengukuran isyarat fotoakustik sebagai satu fungsi kepada frekuensi modulasi dalam satu kawasan yang ketebalan sampel, l_s, adalah sama dengan panjang serapan terma, μ_s. Nilai peresapan terma untuk kertas yang dikaji didapati mencukupi untuk kegunaan pengguna. Ini terbukti bahawa teknik fotoakustik merupakan satu kaedah yang boleh digunakan untuk membandingkan dan mengawal sifat-sifat terma kertas dan untuk penilaian kesan semasa pemprosesan di industri dan juga makmal penyelidikan.

ABSTRACT

We have carried out photoacoustic measurements of thermal diffusivity on samples of commercial papers. It is based upon the measurement of the photoacoustic signal as a function of the modulation frequency in the region where the sample thickness, l_s, was equal to the thermal diffusion length, μ_s. The value of the thermal diffusivities for the commercial papers was found to be adequate to their end users. It is also proven that the photoacoustic technique can be a valuable tool for comparing and controlling the properties of papers and for evaluating the effects of processing parameters upon these properties industrially or on the laboratory scale.

Keywords: Photoacoustic technique, commercial papers, thermal diffusivity, wood industries

INTRODUCTION

During the past two decades, the use of photoacoustic (PA) measurements has gradually diffused into a wide range of branches of science, from agricultural and medical sciences to environmental sciences in general (Lima *et al.* 2000). This encouraging process can be connected to the sensitivity of the PA signal to changes in the sample's physical characteristics due to modifications in processing conditions. The PA effect can be detected by enclosing a sample in an airtight cell and exposing it to a chopped light beam. As a result of the periodic heating of the sample, following the absorption of light, the pressure

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in the air chamber oscillates at the chopping frequency. A sensitive microphone coupled to the cell wall detects the resulting pressure fluctuation in the gas. The PA signal so produced depends not only on the amount of heat generated in the sample (i.e. on the optical absorption coefficient of the sample and its light-into-heat conversion efficiency), but also on how this heat diffuses through the sample and its exchange with the surrounding gas in the cell (Rosencwaig *et al.* 1976). The quantity that measures the rate of diffusion of heat in the sample is the thermal diffusivity α, given by:

$$\alpha = \frac{k}{\rho C_p} \tag{1}$$

where k is the thermal conductivity, ρ is the mass density and C_p is the specific heat at constant pressure of the sample.

The PA technique has proven to be a simple and reliable technique for measuring the thermal properties of almost any material. It has been used for measuring thermal diffusivity of materials as diverse as superconductor, semiconductors, glasses and polymers (Fanny *et al.* 1999; W. Mahmood Mat Yunus *et al.* 1999). The technique has also been used for direct assessment of change in material properties induced by processing, e.g. in composite preparation and food processing (Lima *et al.* 2000; Perondi *et al.* 1987). In this paper, we report on the photoacoustic measurement of the thermal diffusivity of several commercially available papers. These included white paper (for office printing), press paper (partially bleached), fax paper (for thermal printing), filtering paper, canson paper (for painting and drawing) and wrapping paper (tear resistant).

THEORY

The theory of the photoacoustic effect in solid sample was first described in 1976 (Rosencwaig and Gersho 1976). According to the proposed model, the heat generated in the sample will diffuse from the sample to the gas in immediate contact with the sample. An important parameter involved is the thermal diffusion length of the sample μ_s, which can be defined in terms of the thermal diffusivity by

$$\mu_s = \sqrt{\alpha / (\pi f)} \tag{2}$$

where f is the modulation frequency of the incident light. From Equation (2), it is obvious that μ_s decreases with the increasing modulation frequency. The chopping frequency is termed as characteristic frequency, f_c ($f = f_c$) when the thermal diffusion length, μs becomes equal to sample thickness, l_s (i.e. $\mu_s = l_s$). Thus, there are two possible regimes to be distinguished: first for $f > f_c$ which

$\mu_s < l_s$, in this case the sample is thermally thin. Then the amplitude of the photoacoustic (PA) signal decreases as f^{-1} one decreases the modulation frequency. At high modulation frequency, $f > f_c$ which $\mu_s < l_s$, the sample is thermally thick then the amplitude of PA signal varies as $f^{-1.5}$. Hence, by knowing f_c, l_s, and applying the Equation (2), which corresponds to the situation $l_s = \mu_s$, the thermal diffusivity can then be obtained as

$$\alpha_s = \pi f_c l_s^2 \tag{3}$$

EXPERIMENTAL METHOD

The experimental set-up used for the present study is shown in *Fig. 1.* A 75 mW helium-neon laser, cw beam, is mechanically chopped by an optical chopper (SR540). The modulated beam then illuminated onto a sample kept inside a non-resonant PA cell. The cell was fitted with an electret microphone (Cirkit product, UK) and covered with a silica glass window. The absorption of the modulated beam on the sample produce in periodic heating. The generation of heat is transferred to the gas in contact. Consequently, the pressure in the air chamber oscillates at the chopping frequency. This phenomenon is known as a photoacoustic effect which can be detected by a sensitive microphone. The generated photoacoustic signal was then amplified by a preamplifier (SR 560) and further analyzed by using a lock-in amplifier (SR 530). The amplitude of photoacoustic signal is recorded as a function of the modulation frequency.

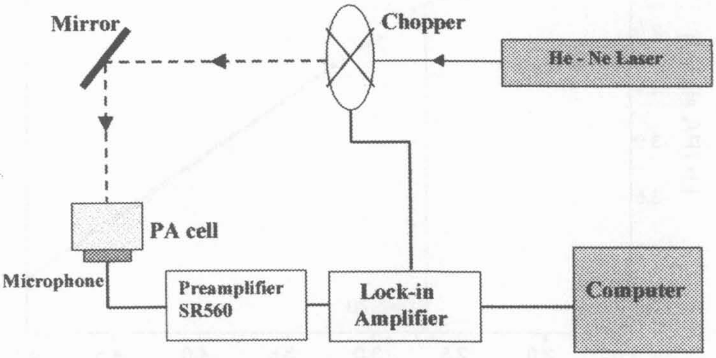

Fig. 1: Schematic diagram of the exprimental set-up

RESULTS AND DISCUSSION

The PA Signal of white paper (thickness 0.072 mm) varies exponentially with the frequency as shown in *Fig.2.* By using the analysis method proposed by Da Costa and Siqueira (1996), the ln (PA Signal) was plotted against ln (*f*) as shown in *Fig.3.* The characteristic frequency, f_c was obtained by measuring the frequency at which the sample changes its behavior from thermally thin to

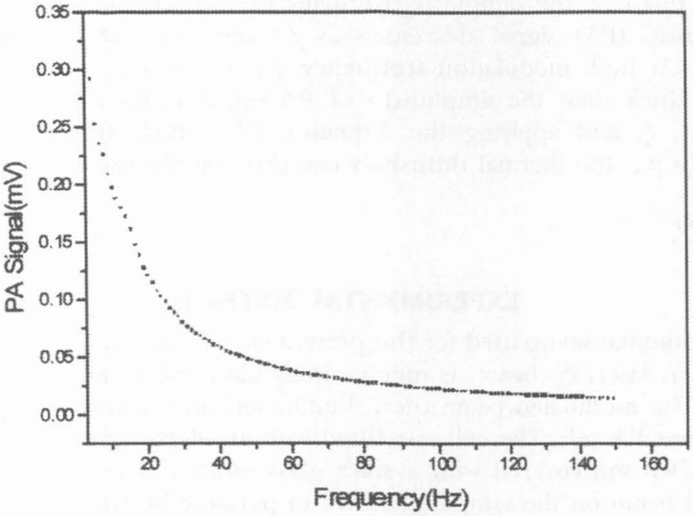

Fig. 2. Photocoustic signal amplitude as a function of the modulation frequency for white paper

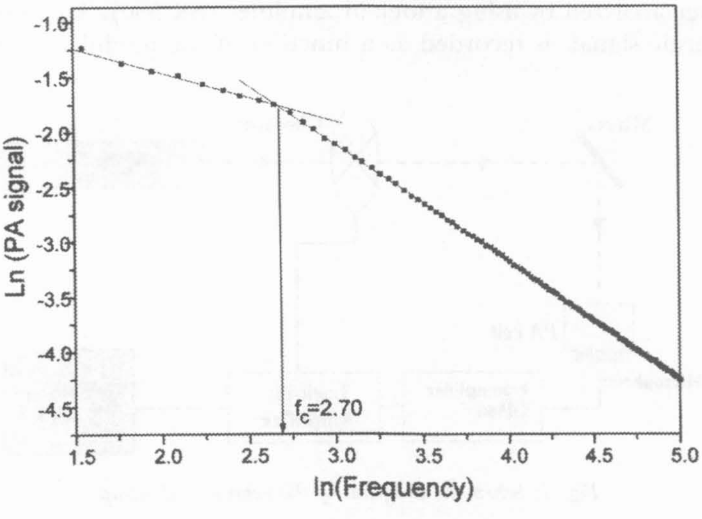

Fig. 3. ln (PA signal) versus ln (frequency) for white paper

thermally thick and it was found to be 14.89 Hz. By using the Equation (3), the thermal diffusivity of this sample was calculated as 2.42 x 10^{-3} cm^2s^{-1}. The same procedure was used for the other commercial paper samples and the measured thermal diffusivity values of all our samples are tabulated in Table 1.

TABLE 1
Thermal diffusivity of commercial paper samples obtained by a closed photoacoustic cell technique

Paper Samples	Thermal diffusivity (cm^2s^{-1})
Canson Paper	11.58×10^{-3}
Wrapping paper	2.85×10^{-3}
White Paper	2.42×10^{-3}
Filtering Paper	2.16×10^{-3}
Press Paper	1.22×10^{-3}
Fax Paper	0.53×10^{-3}

The measurements of thermal diffusivity for various commercial papers are summarized in the histogram of *Fig. 4.* The differences among the tested samples in this experiment indicate that different processing conditions were applied during manufacturing in order to satisfy the end user. These results are in agreement with those reported by Lima *et al.* (2000) using the open cell technique. It is known that canson paper has a considerably looser packing of the processed pulp, so that a large fraction of air filled space is present within the samples. Additionally, air has a rather high thermal diffusivity which is about 0.21 cm^2s^{-1}. These two factors are combined to explain why canson paper has a comparatively high thermal diffusivity.

In contrast, fax paper, apart from having specific chemical additives incorporated into it during the manufacturing process, is also a rather more compacted type of paper. Its thermal diffusivity measured with the printing side

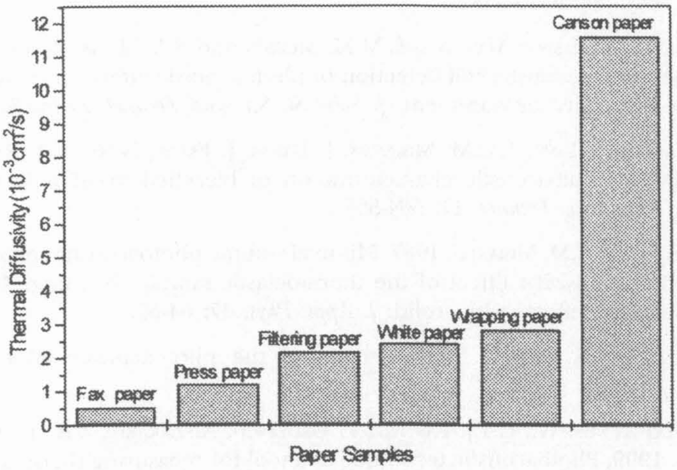

Fig. 4. Thermal diffusivity of commercial papers measured by closed photoacoustic cell technique

facing the incoming light (α=0.53×10^{-3}cm^{2}s^{-1}) was the smallest among the tested papers. This finding is in due agreement with the expected end use of the material. Indeed, the formatted heat delivery to the printing surface is required to remain as localized as possible, both for good contrast and for high resolution in thermal printing. This requirement is satisfied better by a paper having a small thermal diffusivity, in agreement with our findings. In between these two extremes lie, in ascending order, the results for press paper and for wrapping paper (α=1.22×10^{-3}cm^{2}s^{-1} and 2.85×10^{-3}cm^{2}s^{-1}, respectively).

CONCLUSION

In this paper, the usefulness of the PA technique for measuring the thermal properties of several commercially available papers is demonstrated. The largest and the smallest thermal diffusivity of the tested papers are found to be canson paper and fax paper, respectively. Finally, PA measurements can be a valuable tool for researchers and in industrial plants for comparing, controlling and evaluating the effects of processing parameters particularly in wood-based industries.

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