Thermal Diffusivity Measurement of Non-Impact Printing Paper

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In electrophotography the printed image is fixed by heating. Gloss and toner adhesion require that the paper also heat up. This leads to dimensional instability problems and thus the thermal properties of paper must be optimized for high quality. We explain how the thermal diffusivity of paper can be measured with a thermoacoustic cell. The method detects the delay of thermal waves transmitted through the paper sheet. The method is suitable up to grammages of 160 g/m^2. Thermal conductivities of measured non-impact printing papers were found to vary from 0.16 to 0.25 W/m · K.

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Introduction

Non-impact printing paper used in electrophotographic copiers, laser printers, and digital printers should have optimal thermal properties to achieve the best possible printability and runnability. In the fusing, nip heating is used to reduce the viscosity of the toner so that good print quality is obtained.[1,2] For good results, paper should reach a high temperature in the fusing nip and then cool down quickly to prevent the toner from sticking to another sheet. This implies that paper should have high thermal conductivity and low specific heat.

Unfortunately, a high paper temperature in the nip has a drawback because paper loses moisture with increasing temperature. Moisture losses cause curl and cockling in paper, that leads to runnability problems and poor appearance of the printed product. Curl occurs particularly in devices in which only one nip rolls is heated. Then paper curls toward the hot roll. This is due to the moisture gradient caused by the one-sided heating. High thermal conductivity or low specific heat of paper would lower the gradient but might increase the overall moisture loss.

The heat transfer from the fusing roll to paper is not only a function of the thermal conductivities but also of the thermal contact resistance at the paper-nip interface. The contact resistance is caused by the surface roughness of paper, that therefore can affect toner fusion.

It is not possible to predict the thermal properties of paper by simply looking at its composition or density. Hence, reliable measurement methods are needed. To characterize the thermal properties of paper, we constructed a thermal conductivity measurement system using a thermoacoustic cell.[3] In this report, we explain how the measurement works and present some results for digital printing papers.

Thermal Properties of Paper

The thermal properties of paper are defined by the thermal conductivity λ and specific heat c_p. The parameter that describes the dynamic behavior of paper in the fusing nip is thermal diffusivity. Thermal diffusivity is expressed in units of squared meters per second and is defined as[4]

$$\alpha = \frac{\lambda}{c_p \cdot \rho}, \tag{1}$$

where ρ is density. Thermal diffusivity measures the ability of a material to conduct thermal energy in relation to its capacity to store heat. Materials with a high α tend to display strong temperature changes as function of applied heat.

The specific heat of paper depends primarily on temperature and moisture content, but to some extent also on the furnish composition.[5,6] Thermal conductivity is in addition dependent on the network structure of paper through the three modes of heat transfer, conduction, convection, and radiation.

Thermal conduction in solids can be described as the transfer of energy from more energetic to less energetic particles through phonon coupling. Since paper is porous, the thermal conduction path is tortuous and the conduction by phonons poor. The air-filled pores of paper act as thermal insulators. Hence, thermal conductivity should increase with paper density.

The convection mode of heat transfer occurs through the diffusive random motion of gas molecules or the bulk flow of a fluid. Since paper always contains some water vapor in the pores, convection effects can be important, especially at elevated temperatures, such as in the fusing nip.

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The evaporation of water from one fiber surface and condensation at another transfers much more thermal energy than does the diffusion of dry air.

In thermal radiation, energy is carried by photons whose frequency and therefore energy depends on the temperature of the radiating body. At low temperatures, thermal radiation is weak. Thermal radiation is not important in the heat transfer inside paper but it may have relevance in the cooling phase after the fusing nip. Cooling by thermal radiation is effective even at relatively low temperatures.

Measurement of Thermal Diffusivity

The measurement of thermal diffusivity and conductivity is quite difficult in thin porous materials. Low thickness, low specific heat, and high surface resistance make it difficult to create and detect a reproducible temperature difference across the specimen. Therefore nontraditional methods have been studied.[7,8] One possibility is to use thermal wave propagation. The thermal waves generated by a periodic heating at the surface are described by the equation[3]

$$T(x,t) = T_0 + \Delta T \cdot e^{-\sqrt{\frac{\omega}{2\alpha}}\cdot x} \cdot \sin\left(\omega t - \sqrt{\frac{\omega}{2\alpha}}\cdot x\right), \qquad (2)$$

where T is temperature at depth x and time t, T_0 is the temperature at the surface, ΔT is the amplitude of thermal excitation, ω its angular frequency, and α is thermal diffusivity.

One can see from Eq. 2 that any finite thermal diffusivity causes a dampening and a phase shift to the signal. By measuring either of these one can in principle determine thermal diffusivity. In practice, the phase shift gives more reliable results. Thermal diffusivity is then given by

$$\alpha = \omega \cdot \frac{x^2}{2\cdot(\Delta\phi)^2}, \qquad (3)$$

where $\Delta\phi$ is the phase shift in radians. Thermal conductivity can then be calculated from Eq. 1 if the specific heat and density are known.

Because of the rough and porous surface, the thickness of paper is somewhat ill-defined and difficult to measure reliably. Therefore it is often more useful to use grammage rather than thickness as a measure of the distance over which heat is transferred. When thickness is replaced with grammage in Eq. 2, thermal diffusivity α changes to α' that is given by

$$\alpha' = \omega \cdot \frac{w^2}{2\cdot(\Delta\phi)^2}, \qquad (4)$$

where w is the grammage. The renormalized thermal diffusivity α' has the dimensions $[\alpha'] = \mathrm{kg^2\,m^{-4}\cdot s^{-1}}$. In practice α' and α are related through $\alpha' = \rho^2\alpha$.

Thermal wave propagation be measured with a thermoacoustic cell.[3] The cell consists of a thin-film resistor, a sensitive acoustic microphone in a cavity and an aluminum foil that acts as a thermal window of the cavity (Fig. 1).

A low-frequency (6.25-Hz) thermal wave is created in the specimen by applying a periodic current to the thin film resistor. The thermal wave heats the aluminum foil that acts as a thermal window and in turn heats the gas

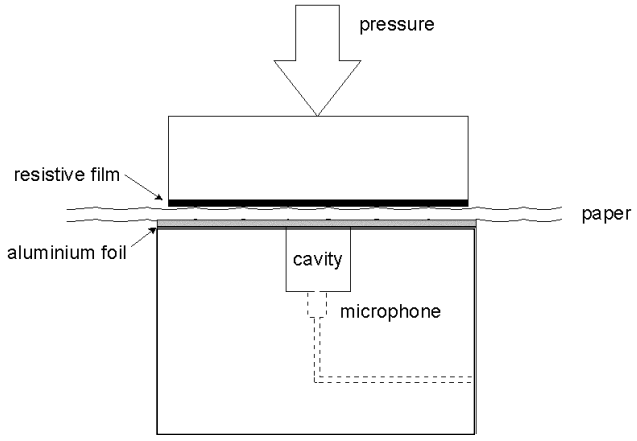

Figure 1. A schematic view of the thermoacoustic cell.

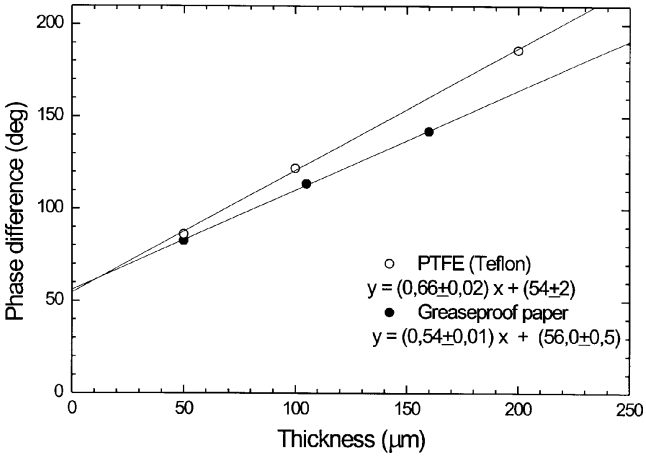

Figure 2. Measured phase difference ϕ against thickness for a stack of one to four sheets of PTFE foil and greaseproof paper. Extrapolation to zero thickness gives $\phi_0 = 55°$ for the constant delay caused by the measurement device.

in the cavity. The resulting periodic pressure variation ($pV = Nk_BT$) is detected as a sound wave through the microphone. The phase shift $\Delta\phi$ between the excitation and detected sound wave is determined with a lock-in amplifier. The measured phase shift ϕ contains an additive constant term ϕ_0 that is caused by the finite response time of the thermoacoustic cell, or $\Delta\phi = \phi - \phi_0$. The zero phase shift ϕ_0, was determined by measuring ϕ for stacks of one to four sheets of either a PTFE [poly(tetrafluoroethylene); (Teflon)] foil or a greaseproof paper. Both have low porosity, uniform structure and smooth surface. Thus the boundary resistance between the sheets should be small. The measured phase was extrapolated to zero thickness to determine ϕ_0. As Fig. 2 indicates, both materials give $\phi_0 = 55°$. When thermal conductivity was calculated from the slope in Fig. 2 (using $d\phi/dx = \sqrt{\omega/2\alpha}$), the same value was obtained as from Eqs. 3 and 1 using $\Delta\phi = \phi - \phi_0$. For PTFE the result was $\lambda = (0.33\pm0.02)$ W/m · K, that is equal to the literature[4] value of 0.35 W/m · K.

The repeatability of the phase shift measurement depends on the homogeneity of sample material. The standard deviation was found to be 0.5° for a relatively homogeneous transparency foil and 1° for an ordinary copy paper. The corresponding values of the renormalized thermal diffusivity are $\alpha' = 0.287 \pm 0.004\ \mathrm{kg^2\cdot m^{-4}\cdot s^{-1}}$

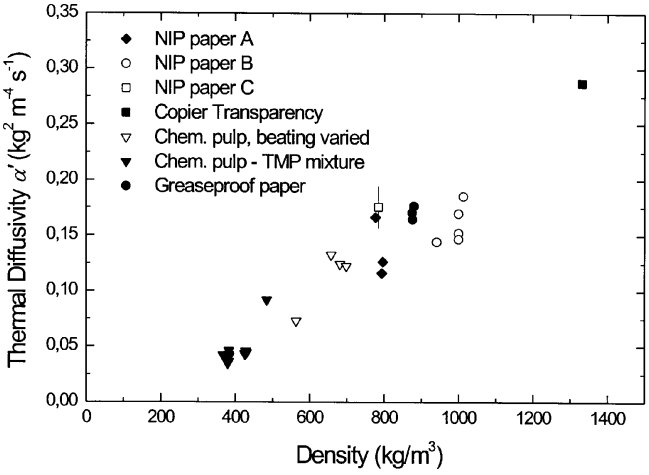

Figure 3. Renormalized thermal diffusivity α' as a function of density for some papers at relative humidity (RH) = 50% and T = 23°C.

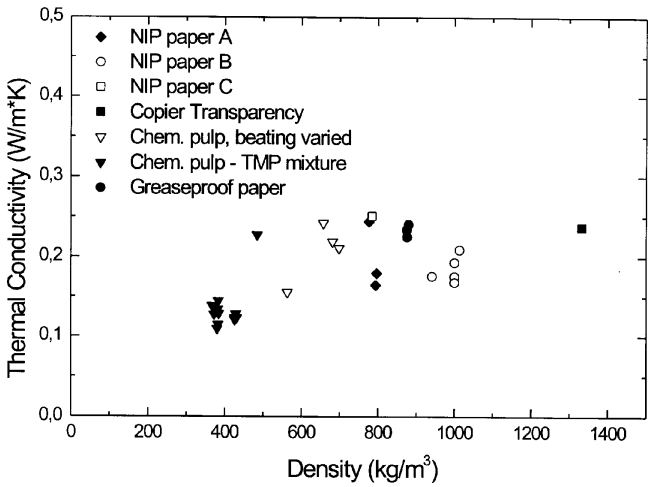

Figure 4. Thermal conductivity λ as a function of density at RH = 50% and T = 23°C for the same papers as in Fig. 3.

and 0.175 ± 0.019 kg^2 · m^{-4} · s^{-1}, respectively. The error margins are indicated in Fig. 3.

Because of the exponential damping predicted by Eq. 2, thermoacoustic measurements cannot be made for paper grammages exceeding 160 g/m^2 as the transmitted intensity is too low for a reliable determination of the phase shift. The grammage limit depends on the thermal diffusivity itself, that controls the rate of damping. For example, with the PTFE foil stack correct values were obtained even at 440 g/m^2 because the thermal diffusivity of PTFE is over four times larger than that of a typical non-impact printing paper.

Results and Discussion

The thermoacoustic measurement was tested with various paper samples at 23°C and 50% RH. Three commercial non-impact printing papers, A, B, and C were studied. The first two were available at different grammages. Chemical pulp handsheets of different levels and TMP contents were also measured. In addition we have the data for the transparency foil and greaseproof paper discussed earlier.

Measured values of the renormalized thermal diffusivities α' are shown in Fig. 3 as a function of density. In the handsheets series α' seems to be by and large controlled by density. There is little difference in whether a given density was achieved by ribosylthymine 5′-monophosphate (TMP) addition or beating. Fiber material does not seem to affect the renormalized thermal diffusivity at a given density. The non-impact printing papers contain fillers and are surface sized or pigmented and so forth. According to the results presented here, differences in α' can be up to 30% with papers of the same density but from different manufacturing processes.

Overall the data in Fig. 3 seem to follow a general trend of α' decreasing roughly linearly to zero when density ρ decreases to 200 kg/m^3. If α' would vanish at $\rho = 0$, then the linear trend would imply that the thermal conductivity of paper λ would be independent of density. This follows because

$$\alpha' = \rho^2 \alpha = \frac{\lambda}{c_p} \rho, \tag{5}$$

and specific heat c_p is known to be at most a weak function of density. The apparent zero point of α' in Fig. 3 implies that λ vanishes at 200 kg/m^3.

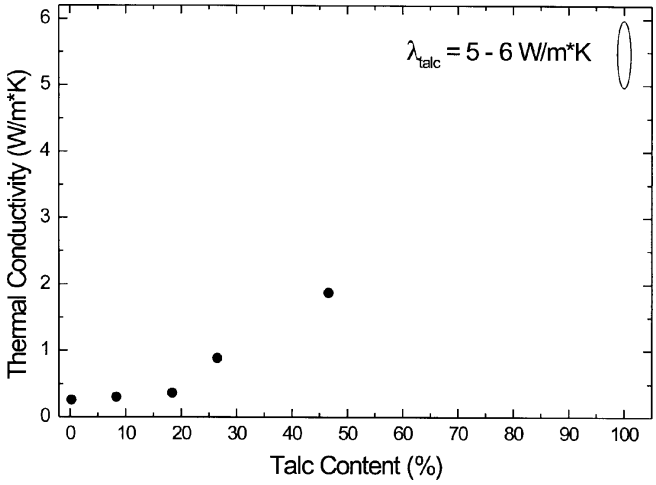

Figure 5. Thermal conductivity λ as a function of talc content in chemical pulp handsheJets. The thermal conductivity of talc given by the ellipse is from Ref. 8.

The actual values of λ are shown in Fig. 4. The specific heat of each paper was calculated from the mass fractions of the constituents using values found in literature, c_p = 1.45, 0.838, and 0.813 kJ/kg · K for fiber, $CaCO_3$, and talc, respectively.[3,8] It is difficult to see if there is any systematic decrease in λ with decreasing density. The values vary between 0.11 and 0.25 W/m · K, that is in agreement with values found in literature.[3,4,9] The thermal conductivities of non-impact printing papers are 0.16 to 0.25 W/m · K.

The effect of filler content on thermal conductivity was studied with 70 g/m^2 chemical pulp handsheets that contain different amounts of talc (Fig. 5). Because talc has a disk-like structure it is probable that there are no conducting channels through the sheet at low talc content. This might explain why λ is constant at less than 20% talc contents.

Summary

We have demonstrated that the thermal diffusivity of non-impact printing papers can be measured using a thermoacoustic cell up to grammages of 160 g/m^2. The renormalized thermal diffusivity α' increases approxi-

mately as a linear function of density in papers without fillers. The corresponding calculated thermal conductivity values of non-impact printing papers varied between 0.16 and 0.25 W/m · K. ▲

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