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Thermal Conductivity of Coated Paper

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Abstract In this article, a method for measuring the thermal conductivity of paper using a hot disk system is introduced. To the best of our knowledge, few publications are found discussing the thermal conductivity of a coated paper, although it is important to various forms of today's digital printing where heat is used for imaging, as well as for toner fusing. This motivated an investigation of the thermal conductivity of paper coating. This study demonstrates that the thermal conductivity is affected by the coating mass and the changes in the thermal conductivity affect toner gloss and density. As the coating mass increases, the thermal conductivity increases. Both the toner gloss and density decrease as the thermal conductivity increases. The toner gloss appears to be more sensitive to the changes in the thermal conductivity.

Keywords Coated paper · Heat transfer · Hot disk · Thermal conductivity

1 Introduction

Even though there has been considerable research carried out on the effects of surface coatings on the physical, optical, and mechanical properties of paper, very little information is found in the public domain on the effect of paper coating on thermal

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properties. The thermal conductivity of paper is very important when the paper is used for printing involving a thermal process to bind the toner. This includes thermal printing where the image is generated by heat patterns, and electrophotographic or laser printing. The toner image is formed with electrical charge and then fused to the substrate with intensive heat. A low thermal conductivity of the printing substrate is generally desired because it helps to retain the heat near or at the printing surface for toner fusing and image development.

Although the paper industry is facing many challenges including declining printing advertising and elevating energy costs, digital printing (thermal, ink jet, laser, Indigo, etc.) represents a value-added paper segment which is growing faster than the overall economy. Studies like this work, concentrating on the exploration of the fundamental aspect of the thermal conductivity of coated paper, are vital to the development of next generation paper with superior printing quality. This study contributes to the paper industry a new technique to evaluate the quality of coated paper and thus, enhances the paper industry's ability to make better digital printing paper products for various applications and allows it to be more competitive in the global market.

It is well-known that the coating composition as well as other parameters including coating mass and surface smoothness are crucially important in determining the printing performance. This article focuses on the coating mass effect on the thermal conductivity as well as the resultant impact on printing properties.

2 Background

Thermal conductivity plays a key role in heat transfer according to Fourier's first law of heat conduction equation [1]:

$$\frac{q}{A} = -k\nabla T \tag{1}$$

where q is the heat transfer rate, A is the area normal to the direction of heat flow, ∇T is the temperature gradient, and k is the thermal conductivity.

In the case of laser printing, A is determined by the hardware design, while k is affected mainly by the printing media. For example, in a laser printer, the amount of heat available for proper toner fusing is determined by a number of hardware properties including printing speed, heat roller's thermal capacity, temperature recovery capacity, etc. Printing substrate manufacturers will be interested in controlling the thermal conductivity. The lower the thermal conductivity, the lower the heat transfer rate needed to maintain the temperature gradient which is necessary for toner fusing and quality image development. Therefore, under equal conditions, a paper substrate with a lower thermal conductivity will have the advantage of being more robust to the printing equipment.

Based on our practical experience, the coating mass is a very important parameter that affects the ultimate printing quality [2]. Too thin of a coating will result in poor fiber coverage which is less desirable for good quality printing. On the other hand, too thick of a coating will lead to wasting coating materials and pushing manufacturing parameters beyond their normal operating conditions. Optimal coating mass for a laser printable grade needs to be well defined. Therefore, a method for determination of the thermal conductivity of the coating and its application to a study for correlating the coating mass and the thermal conductivity will be useful for printing quality improvement.

3 Experiments

3.1 Sample Preparation

The base paper used for the sample preparation was made by a paper machine using 75 % hardwood, 15 % softwood, and 10 % recycled fibers. The base paper was then coated with a rod coater with a coating mass at about 12 g $\cdot$ m^{-2}. The coating used contains clay and calcium carbonates as its pigments, and styrene–butadiene (SB) latex and starch as its binders. The clay-to-carbonate ratio is 50:50, and the binder-to-pigment ratio is at 18:82. The SB latex used is highly carboxylated. The coating is made at 60 % solids with a Brookfield viscosity of 850 mPa $\cdot$ s at 100 rpm. Samples with various coating masses, usually in a range from 0 to 19.2 g $\cdot$ m^{-2} (12 lb/3300 ft^2) were applied onto the base paper again using a cast coater. The coating mass was varied by changing the coating solids and the coating speeds. After coating, the samples were dried and conditioned under standard TAPPI conditions [3] at 24 °C(75 °F) and 50 % relative humidity for at least 24 h prior to any physical testing. The physical properties of the samples are listed in Table 1.

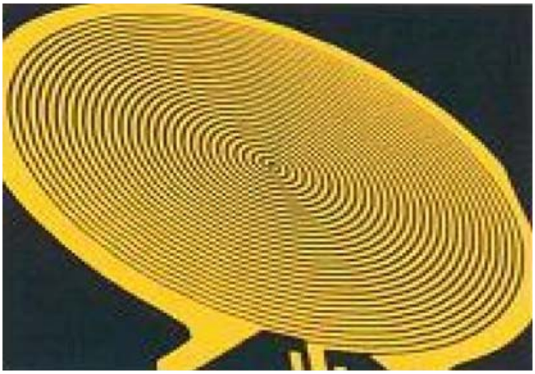
3.2 Hot-Disk Thermal-Conductivity Measurement System

The thermal conductivity of the coated and uncoated paper was measured by a hot-disk system. The hot disk is a transient plane source technique and was invented by Gustavsson et al. [4]. During the measurement, a thin film probe is sandwiched between two pieces of paper sheet and two high-conducting stainless-steel background blocks. The probe serves as a heat source and as a temperature sensor. The probe as shown in Fig. 1 [5] is made of a double spiral of nickel wire which is sandwiched between two thin sheets of Kapton® material for electrical insulation and mechanical support. An output of power in the double spiral is generated when a single current pulse is applied. In all the paper thermal conductivity experiments, we used an output power of 1.5 W and a 40 s pulse duration. These parameters are chosen based on the sample thickness,

Table 1 Physical properties of the lab coated paper samples at various coating masses

Coating mass (g $\cdot$ m^{-2})	0	10.4	13.3	16.3	19.2	22.2
Gloss of unprinted sheet (%)	27.4	85.1	85.8	86.0	86.6	86.7
Hagerty porosity (s)	1730	5600	6410	8470	9210	9840
Ash content (%)	16.6	18.1	19.6	20.4	23.7	23.5
Surface resistivity (Ω/□)	2.30×10^{11}	2.10×10^{12}	1.10×10^{12}	1.30×10^{12}	1.60×10^{12}	1.10×10^{12}
Volume resistivity (Ω $\cdot$ cm)	4.10×10^{11}	2.60×10^{12}	1.10×10^{12}	1.70×10^{12}	2.30×10^{12}	1.50×10^{12}
PPS smoothness (mm)	4.1	0.36	0.35	0.32	0.29	0.29

Fig. 1 Hot disk sensor probe [5]



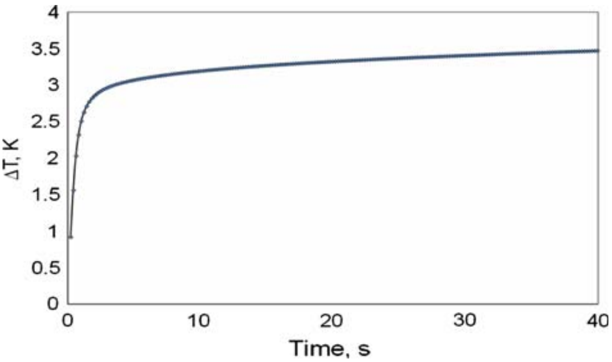


Fig. 2 Average increase of sensor temperature (T) as a function of time during a typical hot-disk measurement. The measurement was taken on the base paper under 1.5 W and 40 s

type of sample material, and sensor diameter. During the transient, the voltage drop across the probe is monitored. This voltage is directly proportional to the temperature increase (ΔT) of the sensor because the resistance of the probe can be expressed as

$$R = R_0[1 + \alpha \Delta T(t)] \tag{2}$$

where R_0 is the initial probe resistance, α is the thermal coefficient of resistivity, and t is the time.

The total temperature increase (ΔT) changes with time and consists of two parts, the temperature drop over the probe insulating layer $[\Delta T_{\mathrm{i}}(t)]$ and the temperature increase of the tested paper surface facing the probe insulating layers $(\Delta T_{\mathrm{p}}(t))$. The probe insulator is made very thin so that $\Delta T_{\mathrm{i}}(t)$ becomes constant after 10 ms. At the beginning of the transient, the temperature drop across the insulating layer is a function of time. If we neglect this time period, the thermal conductivity of the paper sheet can be derived from a plot of the total temperature increase versus time. A typical temperature versus time plot is shown in Fig. 2.

Measuring the thermal conductivity of a paper coating is very challenging due to its extremely low thermal conductivity. To have a better comparison between samples and eliminate the measurement equipment factor on the thermal-conductivity value, all the tested samples were run within one day after the stabilization of the hot-disk equipment.

3.3 Printing Performance Testing

An HP Color LaserJet 4600 printer was used to print on the paper samples for printing quality assessment under both the "Plain Paper Setting" and "Heavy Glossy Paper Setting." These two printing settings were selected to represent the extreme printing conditions with the printer. The plain paper setting usually has faster printing speed than the heavy glossy paper setting. The toner gloss and density on the printed images were measured using a MacBeth Densitometer. Our testing pattern consists of four solid ink blocks: black, blue, red, and yellow. Gloss evaluates the capacity of a surface to reflect directed light [3]. There is a TAPPI Standard Test Method for the gloss measurement (T480-om-90 for 75° and T 653 pm-90 for 20°). In the paper industry, evaluating toner gloss involves the measurement of reflectance using a scale on which a clean plaque of polished black glass with a refractive index of 1.540 measures 100 units. It measures the specular reflectance of paper at 75° (15° from the plane of paper). The specular gloss used in this work is defined as the ratio of flux reflected in a specular direction to incident flux for specified source and receptor apertures.

Toner density gives an evaluation on the visual impression of darkness. It is approximately proportional to the layer thickness or coverage of the ink or toner. Toner density is measured using the Macbeth reflection densitometer RD-921 at Smart Papers, a manufacturer of coated and uncoated printing papers, located in Hamilton, Ohio. The toner density is defined as the negative logarithm of the reflectance of the sample by $\{-\log(\text{reflectance})\}$.

4 Results and Discussion

4.1 Effect of the Thermal Conductivity on the Toner Gloss

As shown in Fig. 3, the higher the coating mass, the greater is the thermal conductivity. This is easily explained by the higher thermal conductivity of the coating material compared to the base cellulose paper materials. It is evident that the toner gloss decreased significantly with an increase of the thermal conductivity for both "Heavy Glossy Paper setting" (Fig. 4) and "Plain Paper setting" (Fig. 5). The paper with higher thermal conductivity was losing more heat to the substrate underneath the coating layer, which leads to a smaller amount of heat available for fusing the toners. Less fused toner results in lower printed gloss. The thermal conductivity of each sample was measured 3 times, and an average value is taken. The deviation from the average is within $0.0005\,\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$.

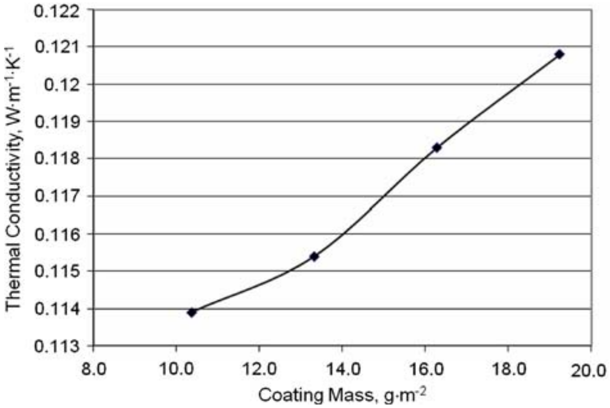


Fig. 3 Effect of coating mass on thermal conductivity

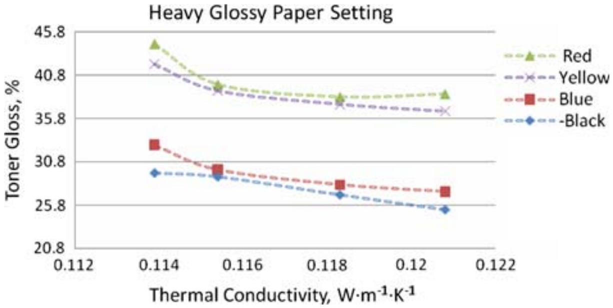


Fig. 4 Thermal conductivity effect on toner gloss under heavy glossy paper setting

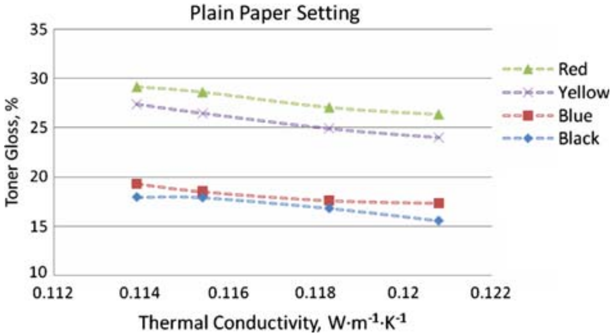


Fig. 5 Thermal conductivity effect on toner gloss under plain paper setting

4.2 Effect of the Thermal Conductivity on the Toner Density

The paper substrates with various coating masses were printed using a laser printer, and the toner densities were then measured on the printed color blocks. The toner density was not influenced by the thermal conductivity significantly for the "Heavy glossy

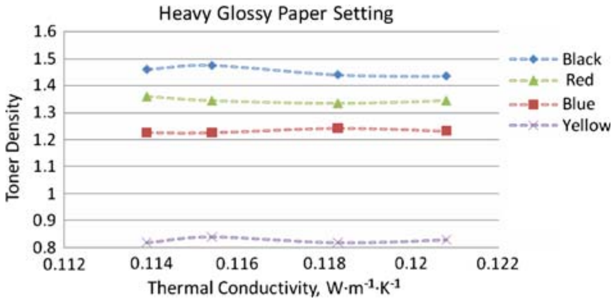


Fig. 6 Thermal conductivity effect on toner density under heavy glossy paper setting

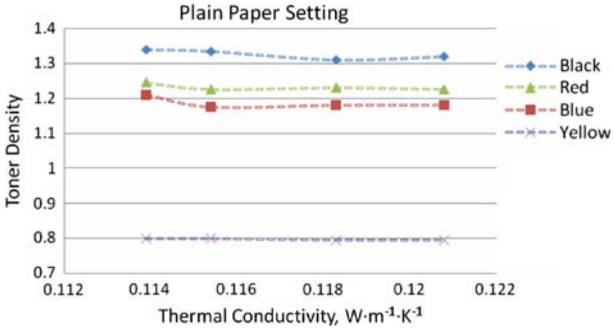


Fig. 7 Thermal conductivity effect on toner density under plain paper setting

paper setting" (Fig. 6) and the "Plain paper setting" (Fig. 7). Only a slight decrease of toner density was observed with an increase of the thermal conductivity. Toner density seems to be much less sensitive to thermal conductivity when compared to toner gloss. This is because toner density is mainly governed by the amount of toners on the paper. For each sample, the same amount of toner is applied. Toner gloss is determined by the toner fusing which is directly affected by thermal conductivity. The slight decrease in the toner density was attributed to the difference of image toner gloss: the higher the toner gloss, the higher the density readings even though the amount of ink toners could be the same.

5 Conclusions

The hot-disk system was successfully applied for evaluating the thermal conductivity of coated paper substrates. It was demonstrated that the thermal conductivity of paper increased with increasing coating mass. Toner gloss is much more sensitive to the thermal conductivity change than toner density. The paper substrate with higher thermal conductivity showed lower printed gloss. The toner density did not show a significant dependence on the thermal conductivity. The correlation between thermal conductivity and printing performance indicates that the higher thermal conductivity of a paper substrate represents poor printing efficiency when heat is employed. However, the poor fiber coverage might become an issue if one tries to optimize thermal conductivity for printing by applying lower coat mass. Therefore, it is necessary for the paper industry to optimize the coating formulation or the coating process to develop a superior substrate with minimum thermal conductivity for printing applications.

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