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Thermal Behavior of Paper in Contact Fusing Technology

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Abstract. *In dry toner electrophotography, image fixing by roller fusing technology is affected by the process parameters, and by toner and paper properties. In this type of contact fusing, the fusing energy is applied in the form of pressure and conductive heat as a function of the dwell time determined by the process speed and fusing nip width. The present study was designed to provide a deeper understanding of the behavior of paper in a modified fusing nip with controlled speed and temperature. The effects of moisture content and coating color were examined as well, and some quality factors of toner images were correlated to the thermal behavior and bulk properties of the paper samples used in the experiment. In relation to electrophotography, the objective was to explore the role of paper in the fusing stage, and to show how different paper grades contribute to image quality at different fusing speeds and temperatures, which were the main fusing parameters controlled in the experimental setting. The results show that the thermal behavior of paper is strongly related to the paper mass expressed by grammage, and the thermal behavior is less sensitive to speed with increased paper density. Gloss and toner adhesion are affected by the thermal properties of paper. The experimental design, involving a wide range of fusing variables, confirmed the need to understand on the mechanism of toner fusing and the role of toner-paper thermal interactions more deeply. The thermally controlled fusing system used in this work was found to be useful in characterizing the influence of moisture content and coating color on the thermal behavior of paper and the quality of image fixing. © 2008 Society for Imaging Science and Technology.*
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INTRODUCTION

In dry toner electrophotography, the paper is involved in the last two steps of the printing process: toner transfer, where the electrical properties of paper are important for transfer and holding the toner image, and fusing, where the image is fixed permanently on the paper.[1–3] There are several fusing techniques capable of fixing the toner in electrophotography.[4] Thermally, they are all based on the principles of heat transfer: convection, radiation, and conduction. In the electrophotographic market, two types of fusing technology are available: noncontact and contact fusing.[5–7] In noncontact fusing, the effect of the paper grade on fixing quality is reduced because of the absence of pressure and noncontact heat transferred by radiation, whereas in contact fusing the paper and its thermal behavior play an essential role for both printability and runnability.[6,8] Noncontact fusing, such as radiant heat and near-infrared flashing, is usually used in high-speed digital presses.[6,7,9] In this technology, the paper reflects the wavelengths in the visible and near-infrared range, so the fusing energy is absorbed mostly by the toner image.[7,10,11] Therefore, noncontact fusing is possible in a wide range of applications, regardless of the paper grade or other media.

In any contact fusing technology, such as roller or belt fusing, the fusing energy is transferred to the toner and paper in the form of pressure and conductive heat. This occurs as a function of dwell time determined by the printing speed, nip width, and the geometry of the fusing unit. The interactions of these fusing process parameters with paper properties and their influence on image fixing quality have been examined through different sets of experimental designs at the Laboratory of Media Technology/Helsinki University of Technology.[1–3,10–15] In an early experiment, roller fusing was modified for adjustable pressure and dwell time to produce soft and hard nips,[15] and then examined the effect of these variables on the fixing quality of images printed on different paper grades.[2] The speed and roller temperatures were kept constant. In the experiment described in the present paper, the setting is based on another type of modified fusing unit described in the experimental section of this paper. The pressure and the nip width are constant, and speed and temperature are the main process variables to influence the interaction with paper.

In general, the thermal properties of paper determine the time and energy required for the paper to reach equilibrium with its environmental condition.[8] The following concepts and definitions can be used to describe the thermal behavior of paper in a contact fusing system.[16]

Heat is energy in transit from one system to another because of a temperature difference. The quantity of heat Q measured in joules (J) required to increase the temperature of a mass m (kg) of a material from T_1 to T_2 is found to be approximately proportional to the temperature change ($\Delta T = T_2 - T_1$) measured in (°C) or Kelvin (K). It is also proportional to the mass m of the substance, and depends on the nature and type of the material expressed by the specific heat capacity c measured in J/Kg °C. All these concepts are combined in the following equation:

$$Q = mc\Delta T. \tag{1}$$

In Eq. (1), Q and ΔT can be either positive, as the heat enters the body and its temperature increases, or negative,

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when the heat leaves the body and its temperature decreases.

Thermal conductivity k is the intensive property of a material that indicates its ability to conduct heat. It is defined as the quantity of heat dQ transmitted in a time interval dt (heat current dQ/dt) through a thickness L, in a direction normal to a surface of area A, due to a temperature difference ΔT, under steady state conditions and when the heat transfer is dependent only on the temperature gradient ($\Delta T/L$). Equation (2) gives expression to both; the thermal conductivity k measured in watts per meter-Kelvin ($W\ m^{-1}\ K^{-1}$), and the heat current dQ/dt measured in watts or (Js^{-1}):

$$k = \frac{Q}{t}\frac{L}{A\Delta T} \quad \text{or} \quad \frac{dQ}{dt} = \frac{kA}{L}T. \tag{2}$$

The reciprocal of thermal conductivity is thermal resistivity, measured in Kelvin-meters per watt ($K\ m\ W^{-1}$).

Thermal diffusivity α is the ratio of thermal conductivity to volumetric heat capacity, formulated as

$$\alpha = \frac{k}{\rho c_p}, \tag{3}$$

where ρc_p is the volumetric heat capacity which is defined as density ρ times specific heat capacity c_p, measured in joules per cubic meter-Kelvin ($J\ m^{-3}\ K^{-1}$), and the SI units for thermal diffusivity are square meters per second ($m^2\ s^{-1}$).

According to the above mechanism, heat is transferred from the roller surface to the paper and toner under the fusing nip. The arrangement is similar to temperature-gradient calendering of paper.[17] A major part of the energy is conducted to the paper, and a minor part transferred to the toner as determined by the mass and specific heat capacity of both paper and toner. Of course, a small part of the energy is lost to the atmosphere as heat radiation at a rate that is affected by the ambient conditions.

The main purpose of heating energy in electrophotographic applications is to fuse the toner image onto the paper. High-quality fusing is achieved only when the energy transferred to the toner image is enough to cause the toner to melt, sinter, spread, and penetrate into the paper. If there is more energy available, it will strengthen the fixing and improve the glossiness of the image.[2,6,7] These phases take place in a consecutive manner during the fusing process, and each of them requires a certain amount of the energy transferred to the toner, so if this part of energy is not enough, the fusing process will not be completed. This results in cold-set offset or poor image adhesion. The amount of heat calculated by Eq. (1) is valid only to predict the rise in toner temperature to pass through glass transition, reaching the softening range[7] prior to fusion. To accomplish fusing, additional thermal energy h (Jg^{-1}) for each of toner fusing phases is required. Depending on the physical and rheological properties of a toner, a different energy rate for desired fixing quality is required.[18] The heat required for complete toner fixing of high image quality can be expressed by the following conceptual equation:

$$Q_{toner\ fixing} = (mc\Delta T)_{toner\ softening} + (mh)_{toner\ fusing} + (mh)_{toner\ adhesion} + (mh)_{glossiness}, \tag{4}$$

where m is the mass of the toner.

The mechanisms of toner fusing have been studied by extensive experimental work at the Laboratory of Media Technology.[1–3,10,12–15]

Unfortunately, a major part of the fusing energy is conducted to the paper due to the high mass and contact surface area compared to the toner image. With full-coverage solid print, the toner weighs about 1 mg/cm^2 or less,[19] whereas normal 80 g/m^2 copy paper weighs 8 mg/cm^2 and receives the heat from both sides. The heating energy transferred to the paper is divided between the solids content (mostly fibers and fillers), the air occupying the porous structure of the paper, and the moisture content (m.c.%) in proportions and rates relevant to their mass, nature, phase (solid, gas, or liquid), and thermal properties. Since the minimum temperature of the experimental set-up of this study is always above boiling point (about 130°C), the energy transferred to the paper causes a partial phase change in some of the moisture, causing it to evaporate and raise the temperature of the solids content, which subsequently will promote toner fusing. The coating layer is an additional solid mass that increases the thermal capacity of paper.

According to the heat and thermal definitions given in Eqs. (1)–(3), the thermal properties of high-grammage papers are different from those of low-grammage papers because of the high mass, thickness, and/or density, in addition to the capacity for holding a high moisture content. Equation (1) can only estimate the heat required to rise the temperature of the paper to the boiling point of the moisture (about 100°C). After that level, Equation (1) continues to govern only the heat transfer to the solid content of the paper until the end of the fusing process. The heating energy h (Jg^{-1}) consumed in the phase transition of the moisture from liquid to steam at 100°C is the well-known value of 2256 $Jg^{-}1$. The amount of moisture that evaporates is determined by additional energy that is absorbed at this state. At a fast fusing speed, the short dwell time may not allow all the moisture to be evaporated, and in this case the image fixing process takes the advantage of this part of the energy. The total heating energy consumed by paper in fixing can be expressed as:[7]

$$Q_{paper} = (m_1 c\Delta T)_{paper} + (m_2 h)_{boiling\ \&\ evaporation}, \tag{5}$$

where m_1 is the mass of the solid and moisture contents of the paper, and m_2 is the mass of the moisture, only. The distribution of the energy among the sold and the moisture parts of paper is governed by the fusing process parameters and paper properties especially the grammage and the moisture content.

Accordingly, the heating energy transmitted to and consumed by a higher-grammage paper will be higher compared to lower-grammage paper. This means that the energy left for toner fusing may not be enough to complete all fusing phases for a satisfactory fusing result. Clearly, the total thermal energy necessary for image fixing is the sum of Eqs. (4) and (5). It was found to be about 1100 J per normal text printed page.[7] Less than 1% of the energy is consumed by the 0.05 g of toner on 75 g/m^2 paper of A4 size. More than 99% of the heat energy is consumed by the paper weight of about 4.7 g to rise the temperature to the toner softening range (~125°C). Experimentally, the moisture content of this type of paper is about 3% (0.14 g). This amount of moisture requires 45 J to bring about a temperature rise from room condition of 23°C to the boiling level (100°C). Typically, the moisture content dropped at least by about 1% after fusing, which requires about 110 J for the phase change of evaporation. Thus, 155 J/1100 J $\approx$ 14% of the heat is consumed by the moisture before reaching the level of toner softening, which for hot fusing toners is higher than the boiling point of water. The heat consumed by the moisture is even higher when condensation and re-evaporation of the moisture from both sides of paper is taken into consideration. The pressure is another form of energy supplied by the fusing nip for the same dwell time as the thermal energy. It will assist fixing by deformation and penetration of the toner into paper.[2,5]

The relationship between print quality and image fusing is determined by fusing parameters, and toner and paper properties.[1,3,7,18,20,21] Image fixing quality has been found to be a function of two dimensionless groups of parameters[2,22,23] (Pt^2/MD) and (T/T_a), where P is average nip pressure, t is dwell time, M is developed mass of toner per unit area on the substrate, D is the average diameter of toner particle, T is fusing temperature, and T_a is the ambient temperature. The relationship of fixing quality and the dimensionless numbers is however, somewhat weak, because paper properties is not included. Neither is the chemical composition of the toner or the materials of the fusing rollers taken into consideration. If the ignored properties can be kept constant in some experimental approach, then the weakness of the mentioned relationship will disappear and it will be valid for comparison between image qualities when changing any of the fusing parameters included in the dimensionless numbers such as temperature, pressure, dwell time, and consequently the nip width.

The present paper examines the thermal behavior of different paper grades and their influences on image fixing quality. The purpose is to find the limitations of fusing energy by controlling speed and temperature as the main variables of the roller fusing unit. Two types of toner but also of different colors (black and cyan) were used in the experiments.

EXPERIMENTAL

A modified fusing unit was the main device used in the experiments. Many experimental approaches related to the thermal properties of paper and fixing of toner images were examined with this device.[3,13,14,24] It was constructed from a roller fusing unit dismantled from a commercial color laser printer and installed together with a computer-controlled

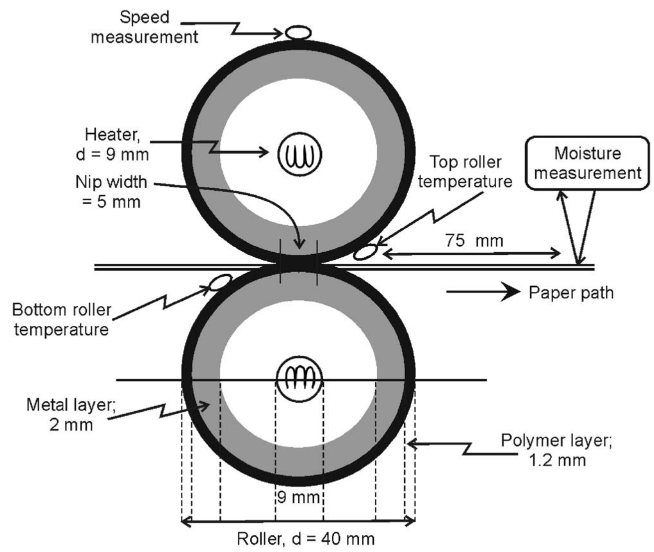

Figure 1. Fusing unit and the experimental arrangement.

system for adjusting and controlling fusing speed and temperature. The speed of the device can be adjusted between 30 and 720 mm/s. In terms of pages per minute, the speed range extends from 6 ppm to about 145 ppm. The fusing unit was designed to be heated by both top and bottom rollers, so that the temperature of both rollers can be set independently at any temperature from 20 to 230°C. For better image fixing quality, most of the commercial fusing units are constructed using a top (fixing) roller coated by softer and flexible polymer layer compared to a relatively hard and unyielding layer on the bottom (pressure) roller,[20,25] which is typically called a soft-on-hard roll pair.[25] In this experiment the top and bottom rollers were exactly the same in terms of material types and dimensions. The nip width is 5 mm for the pressure of 43.5 kPa. The speed and roller temperatures were monitored during operation at a frequency relevant to the scales of the variables. In addition, an online suitable moisture meter was installed to monitor the moisture content of the paper before and after the fusing nip. The fast, small, lightweight, and compacted infrared moisture meter (IRAM-7 model D®) is commercially available.[26] The sampling frequency and signal updating speed is 400 Hz. Figure 1 gives an idea about the experimental arrangement and the diagram of the fusing device.

To set up an experiment, the top and bottom rollers were both heated to 175°C and kept at that temperature for about 8 min to stabilize the system. When the system was thermally ready, it was run at the desired speed and the heating switched off, allowing the temperature of both of the rollers to drop freely. The rate of change is the same because the rollers have exactly the same mechanical and thermal design and are in contact with one another while running at the same speed, forming a single thermal equilibrium system. Recording the temperature data could be started at any point to cover the desired range of data. The experiments were made in humidity and temperature controlled room under two different environmental conditions, allowing the

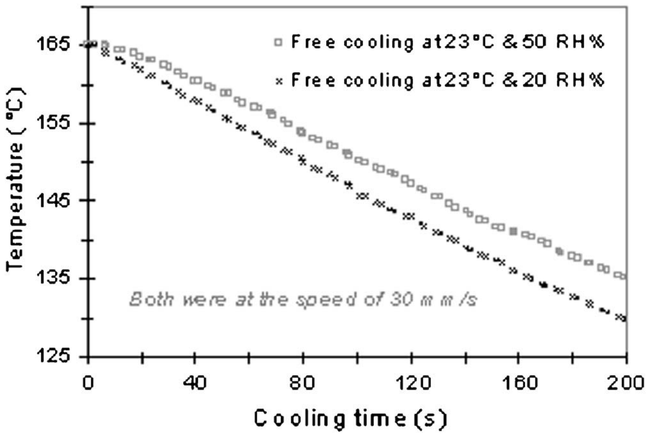

Figure 2. Effect of RH% on free cooling rate.

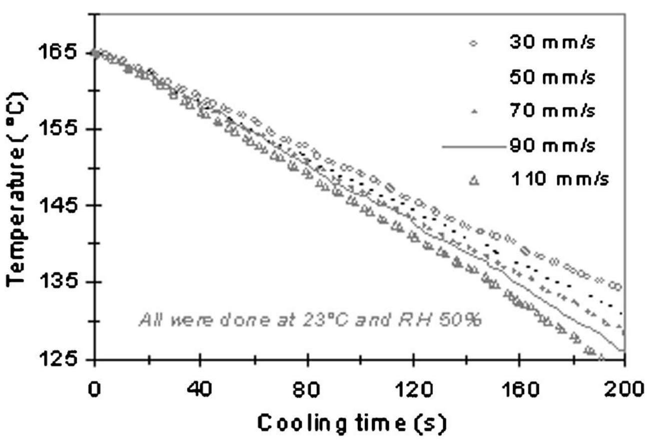

Figure 3. Effect of speed on free cooling rate.

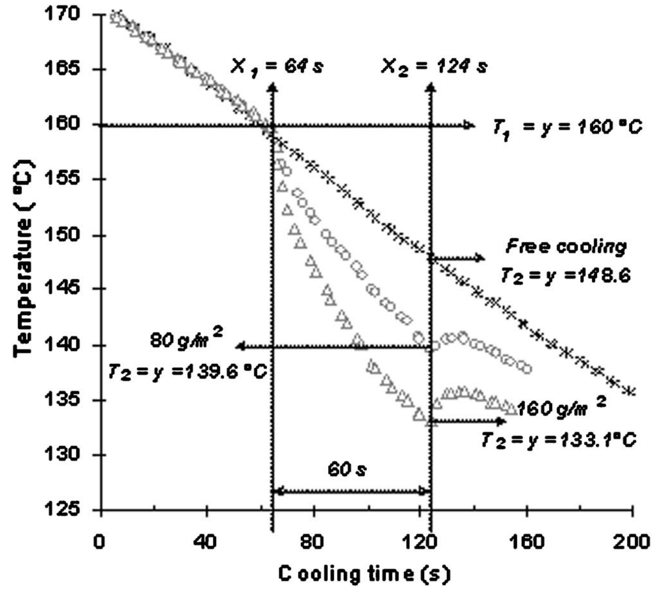

Figure 4. Two paper grades and free cooling.

Table I. Measured properties of paper samples.

Paper Sample	Grammage[a] (g/m²)	Thickness (μm)	Density (kg/m³)
A	160	168	959
B	85	102	812
C	80	103	766
D	70	65	1110

[a]Grammage given at ±0.2 g/m².

relationships between different running speeds and cooling rates to be examined.

Figure 2 illustrates the performance of the fusing system at a constant speed of 30 mm/s under two different humidity conditions. The average temperature of the rollers drops faster and the cooling rate is higher at the low relative humidity (RH) of about 20%. At the higher humidity of about 50%, the heat exchange rate between the unit and the humid atmosphere is lower. The rest of the experiments were run in constant conditions with an ambient temperature of 23°C and a relative humidity of 50%, in accordance with the TAPPI standard.

Figure 3 shows that the average temperature of the rollers drops faster as the speed of the fusing unit is increased. This is obvious, since both rolls transfers a certain amount of heat to the atmosphere during each revolution, and at higher speed there is a higher number of roller revolutions for the same cooling time. Figure 3 illustrates the free cooling rate at the five different speeds of 30, 50, 70, 90, and 110 mm/s used in the experiment.

Different paper grades were tested at each speed. At any selected speed, when the heating was stopped and the average temperature of the rollers started dropping, a paper web with a length of 1782 mm (length of six A4 sheets) and a width of 210 mm was fed into the fusing unit at the moment when the temperature of the rollers had dropped to 160°C. This temperature was always used as the starting point for feeding paper ($T_1 = 160\,°C$). The temperature recorded when a paper web has passed the nip is denoted by T_2. During the course of the temperature drop, paper is heated by absorbing energy two-sidedly from the rollers. This means that the cooling rate of the fusing system is affected by the paper grade. The performance of the modified fusing system was found to be very repeatable.

Figure 4 shows the cooling of the fusing system for two paper grades, compared to the reference of free cooling (where no paper was involved), at the same running speed of 30 mm/s. Clearly, Fig. 4 provides meaningful information for studying the thermal behavior of different paper grades as relates to structure and other basic properties such as grammage, density, thickness, etc.

A set of four uncoated copy papers, whose measured properties are listed in Table I, were used to evaluate thermal behavior in fusing. A toner image printed with either of two colors, black and cyan was fused. The test image was designed to enable measurements of density, gloss and fixing

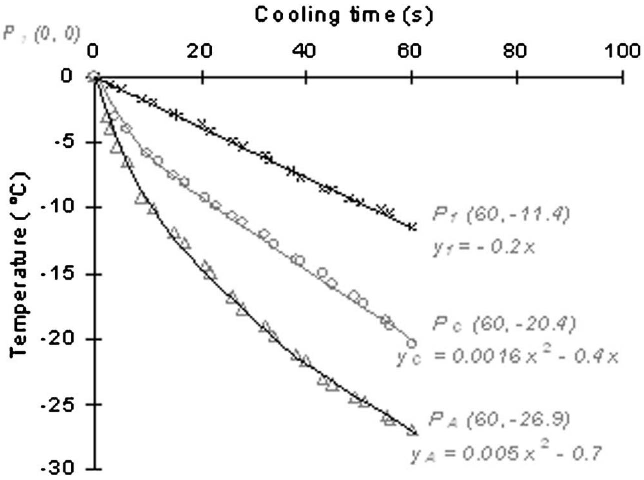

Figure 5. Two paper grades and free cooling [same as in Fig. 4, but in (0,0) coordinates].

rate percent (adhesion percent) as image quality attributes. Another set of papers, consisting of base paper coated by a single layer and by double layers, was tested to determine the effect of coating layers on the thermal behavior of paper.

RESULTS AND DISCUSSION

Thermal Behavior of Paper

The first test involved two uncoated paper grades, A and C, with the properties listed in Table I. The fusing system and the thermal setting were as described in the experimental section. Speed was 30 mm/s. In Fig. 4, the recorded temperature drop data are plotted together with the free cooling data at the same speed. In free cooling, the temperature dropped from $T_1=160\,°\mathrm{C}$ to $T_{2f}=148.6\,°\mathrm{C}$, causing a temperature change $\Delta T_f = T_{2f} - T_1 = -11.4\,°\mathrm{C}$. The minus in ΔT_f stands for cooling of the system rather than heating. Paper sample C of 80 g/m^2 caused the average temperature of the rollers to drop from $T_1=160\,°\mathrm{C}$ to $T_{2C}=139.6\,°\mathrm{C}$, resulting in $\Delta T_C=-20.4\,°\mathrm{C}$. Also shown in Fig. 4, paper A of 160 g/m^2 caused the temperature to drop from $T_1=160\,°\mathrm{C}$ to $T_{2A}=133.1\,°\mathrm{C}$with $\Delta T_A=-26.9\,°\mathrm{C}$. The three cases of temperature changes occurred over a time period of about 60 s that it took for the 1782-mm-long web to pass the nip. It is important to note that the temperature data recorded include the energy transferred to the atmosphere in free cooling, and the energy used to heat the paper. When the paper web has exited the nip, the temperature of the rollers started to rise again. This means the paper has conducted the heat from the polymer layer faster than the polymer conducted it from the metal layer (this is due to the lower thermal conductivity of the polymer layer compared to the metal core). This difference can cause a nonlinear temperature gradient between the layers.

To ease the mathematical treatment, $P_1(x_1, y_1)$ was extracted from its real value P_1 (64 s, 160°C) in Fig. 4 to the x, y (0, 0) coordinates in Figure 5, and the rest of the points were moved from Fig. 4 to Fig. 5 accordingly. In both Figs. 4 and 5, x-axis is the time scale denoted by (t) and y-axis is the temperature scale denoted by (T).

The area limited by the data points and the x-axis is a measure of heat transmitted from the rollers. The best fit equation for the data points of free cooling is a straight line. The curves for cooling in the presence of paper are in the form of ($y=ax^2+bx$). It is assumed that the heat transfer is governed by heat current dQ/dt given by Equation (2) ($dQ/dt=kA\Delta T/L$), and that the heat current is mostly affected by temperature change ΔT. This approximate assumption was suggested[16] and supported[25] for the similar experimental conditions; therefore, the following values are obtained.

The heat at free cooling Q_f, expressed by the temperature change over a period of 60 s, is

$$Q_{\mathrm{free}} = \int_0^{60} (-0.2t)dt \approx -360. \tag{6}$$

The heat due to paper sample C is

$$Q_{\mathrm{C}} = \int_0^{60} (0.0016t^2 - 0.4t)dt \approx -600. \tag{7}$$

The heat due to paper sample A is

$$Q_{\mathrm{A}} = \int_0^{60} (0.005t^2 - 0.7t)dt \approx -900. \tag{8}$$

As was mentioned, the negative values of the heat amounts refer to heat released by cooling of the fusing rollers, from which the average temperature is recorded. The heat is assumed to be conducted to paper, and from that standpoint the values are positive. The unit area in this calculation is temperature (°C) per time (s), which was assumed to be proportional to the temperature gradient over time or heat current represented by Eq. (2). The heat current is equal to the heat amount per time (dQ/dt), and the three cases of temperature changes have occurred at the similar time of 60 s. This may allow considering the integration results as the heat amount, which is in this case a function of temperature change. The heat due to paper C is $600-360=240$ unit area, and the heat due to paper A is $900-360=540$ unit area. It turns out that the ratio of heat calculated for samples A and C is nearly equal to or close to the ratio of temperature changes of the same cases:

$$\frac{900}{600} = 1.5 \cong \frac{26.9}{20.4} = 1.32.$$

This ratio remains approximately the same if it is correlated to the net temperature changes caused by papers:

$$\frac{900}{600} = 1.5 \cong \frac{(26.9 - 11.4)}{(20.4 - 11.4)} = 1.7.$$

This suggests that temperature change alone can be used as a measure for the thermal behavior of paper. This applies for instance to the influence of speed. Speed as a variable in the experiments provides a way to test the dynamic thermal behavior of paper.

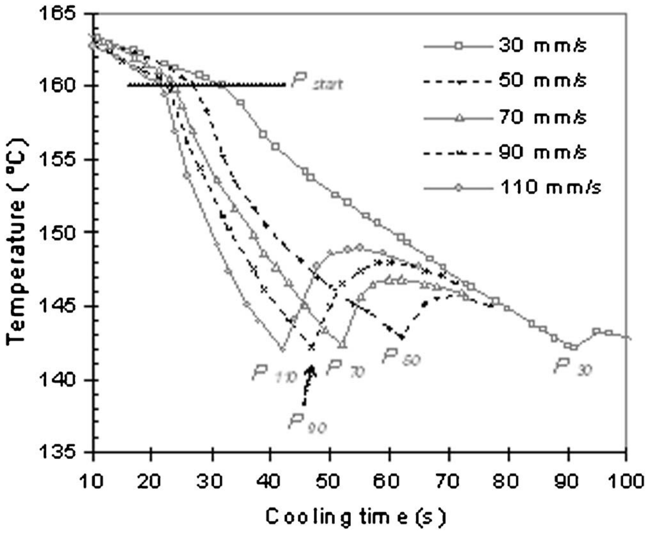

Figure 6. Sample C fed to the fusing system run at five speeds.

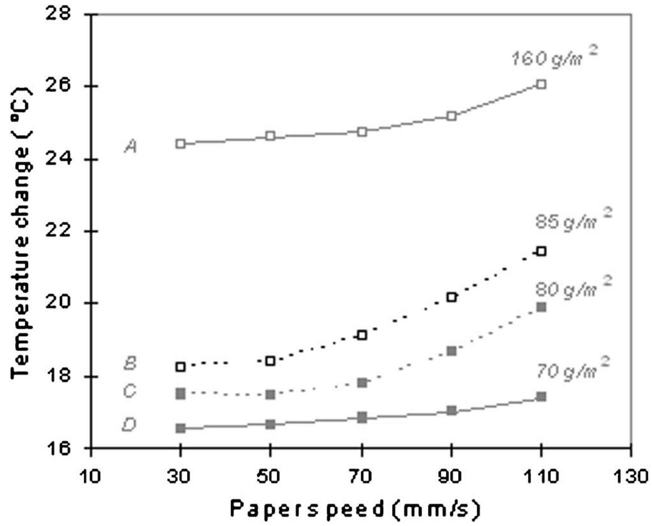

Figure 7. Temperature changes of the roller surfaces due to paper samples at five speeds.

Figure 6 shows paper C fed into the fusing system at five different speeds. Free cooling data for each speed is available for calculation of conducted heat current in dynamic conditions, but the temperature differences may be enough to be counted and plotted against the speeds. The techniques used in producing Fig. 6 were repeated for all the samples. The relationships between speeds and temperature changes are illustrated in Figure 7.

Based on Fig. 7, the temperature change increases as the process speed is increased for all the samples. This is made understandable by the fact that at the lowest speed of 30 mm/s the system conducts heat into the atmosphere for about 60 s, while the paper web is running and absorbs the major part of the energy from the system. At the highest speed of 110 mm/s, the paper web takes about 16 s to pass the fusing nip. In this shorter time, less heat is radiated from the system to the surrounding atmosphere, and instead the paper absorbs more energy, as indicated by a greater temperature change. This is also an indication that the heat is conducted to the paper at a higher rate than the heat transferred to the atmosphere—at least under these experimental conditions. Also, according to Fig. 7, the temperature change as an indicator of the effective thermal conductivity of paper is strongly correlated with the paper grammage of all the samples. There are also some interrelated effects of density, thickness, moisture content, and paper structure,[8] but grammage, as a direct function of paper mass, is the property governing the thermal behavior of paper. It is known that thermal conductivity is a weak function of paper density, but it also has a noticeable effect on the thermal diffusivity of paper, which is to some extent related to the filler content.[24] Therefore, based on the relatively small effect of paper density evident in Fig. 7 for different speeds and samples, density clearly acts by reducing the slope of the curves so that a temperature change in a dense paper (such as samples A and D with the densities of 959 and 1110 kg/m^3, respectively), is less affected by the running speed. This more stable thermal behavior is beneficial in real applications allowing the paper to be used in a variety of electrophotographic machines running at different speeds.

Effect of Moisture Content

The results show that the higher the grammage, the more the temperature will change, irrespective of the speed. As the speed is increased, more heat is conducted into the paper instead of being transferred into the atmosphere. These results and explanations may give the impression that the moisture loss from the paper in the fusing process is higher when the temperature change is higher at higher speed. This would be obvious, if the moisture (liquid-water) were similar in nature to paper (solid—mostly fibers and fillers), but it is not. Experiments with more than 100 paper samples run at five speeds (not reported in detail here) showed that the moisture loss from paper due to a higher temperature change at higher speed is less than the moisture loss due to a lower temperature change at lower speed. With all the samples, the trends of temperature changes and moisture changes were similar to the trends shown in Figure 8. Thermodynamic physics can provide explanations of the interactions between heat fusing and moisture inside the paper. The change in temperature is not necessarily proportional to the change in moisture content. As paper and moisture are different substances, the flow rate of the heat in the solids content of the paper is different from the heat flow rate into the moisture. In addition, the moisture needs a certain amount of energy and time to reach the boiling point and to be evaporated by phase change, and further for recondensation.[8,27,28] This is ultimately recognized and recorded by the moisture meter, as moisture not vapor, at higher temperature change caused in reducing the temperature of the system. Therefore, the flow of heat energy and the phase change in the moisture requires more time than the time required for conducting the heat through the solids content of the paper. Thus, the difference between the thermal behavior of the solid content of paper and its moisture content is in the heat flow rate.[28]

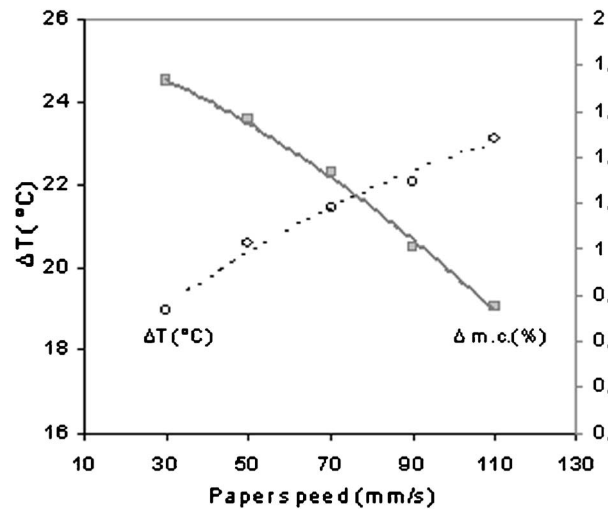

Figure 8. Changes in moisture (m.c.%) and temperature [*T* (°C)] of paper at five speeds.

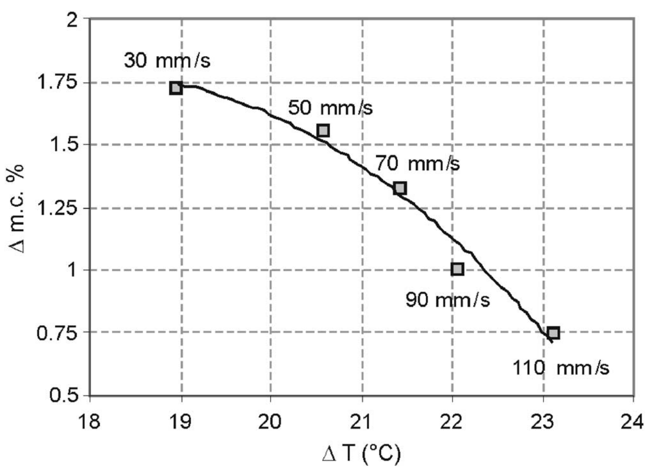

Figure 9. Change in moisture content (m.c.%) as a function of temperature change at five speeds.

If the moisture content of paper is about 5% or less, all the moisture can be described as bound water, referring to the bonds between the moisture and the fibers, which is different from free water. It is known that dry fibers conduct heat faster than bound water, and that bound water conducts heat faster than free water, governed by the thermal conductivity and diffusivity of fibers, bound water, and free water.[27–29] In addition, when applying heat at high speed, the pressure in a semiclosed system under the nip is increased fast, and there is not enough time for the water to be evaporated from the paper, thus causing recondensation to moisture.[29] The moisture evaporation and recondensation in a dynamic of thermal system is an extremely complicated issue, which is simultaneously governed by several mechanisms.

Figures 8–10 refer to the same data for the same paper sample. The moisture content of this paper was about 3.7% after conditioning at 23°C and 50% RH and before feeding into the fusing system. After fusing at a lower speed

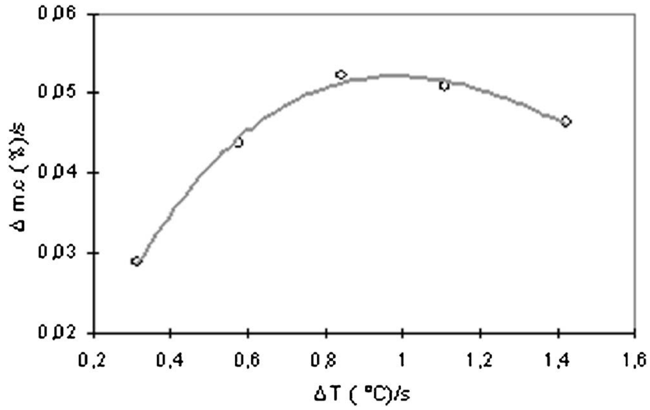

Figure 10. The rates of the changes in both moisture content (m.c.%) and temperature at five speeds.

of 30 mm/s, the average moisture level was 1.97%, (Δm.c.% = 3.7% − 1.97% = 1.73%), and the temperature dropped from 160°C to about 141°C, ($\Delta T = -19°C$) within 60 s. At the highest speed of 110 mm/s, the average moisture level was found to be 2.95% (Δm.c.% = 3.7% − 2.95% = 0.75%), and the temperature change about ($\Delta T = -23°C$), within 16 s. Comparing these two cases, clearly the moisture change requires more time, and instead of consuming this energy, the solids content of the paper has to conduct it from the rollers of the system and cool it for a temperature change of 23°C. Although the paper has different temperature along the paper web, the temperature is still above the boiling point of the moisture. This explains the fact that the average moisture level was found to be fairly constant along the paper web. The temperature range used in this experiment extends from 160°C at the beginning of the paper web to a minimum of 137°C at the end of the web for the highest speed. If the temperature range of the experiments shifted down for instance to the range of 110°C to 80°C, then the situation with moisture along the web would certainly be different.

Effect of Coating

The coating color is another factor that influences the thermal behavior of paper. Figure 11 demonstrates the temperature changes of a base paper coated with a single low weight coating color, and a base paper with double coating layers and a silk surface finish.

The first coating color has caused a drop in the slope of the temperature change curve; i.e., the slope is less than that of the base paper. This means that the paper behaves thermally in a more stable manner at different fusing speeds. The same result is evident in Fig. 7 when the paper density increased. According to Fig. 11, the second coating layer reproduced the results shown in Fig. 7 when the levels of temperature change were increased at all the speeds due to the higher effective thermal conductivity gained by the mass of coating layers. Regardless of the type of coating color, coating is meant to improve the printability of paper by improving its grammage, thickness, density and surface smoothness.[30] The pressure of the experimental fusing unit

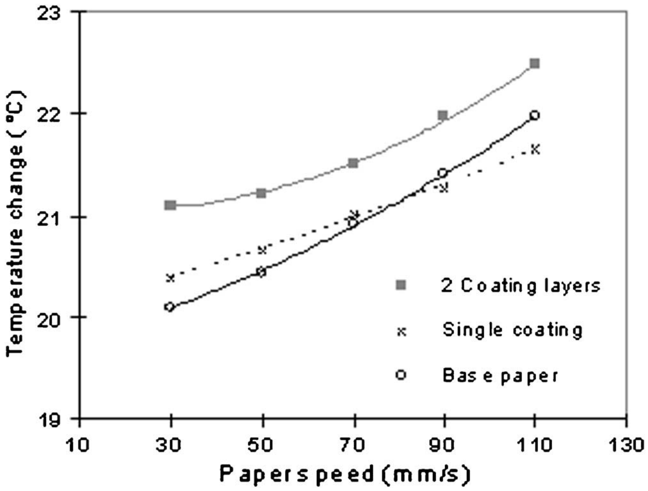

Figure 11. Effect of coating on thermal behavior of paper.

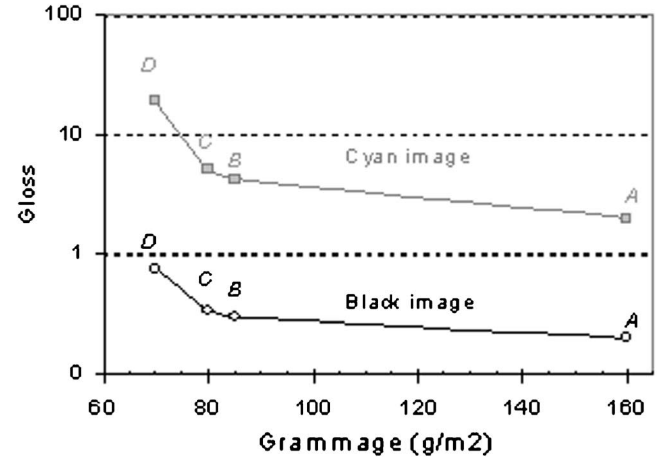

Figure 12. Gloss of the images obtained on the paper samples.

Table II. Measured image quality factors.

Paper Sample	GSM (g/m^2)	Gloss black	Gloss cyan	Adhesion % black	Adhesion % cyan
A	160	0.20	2.00	16.50	28.50
B	85	0.30	4.25	87.00	93.50
C	80	0.35	5.00	90.00	96.50
D	70	0.75	19.50	97.50	98.50

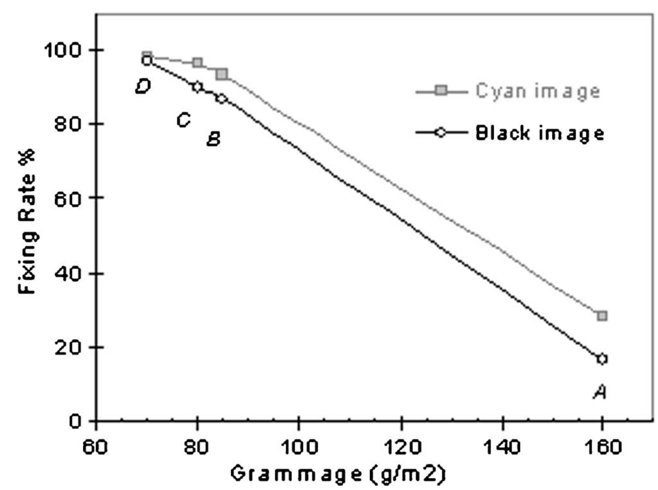

Figure 13. Image fixing rate as a function of paper grammage.

was kept constant, but the compressibility of the paper was increased by the additional thickness of the coating layers. Because of the smooth surface obtained by coating and silk finishing, the effective contact area between the smooth paper surface and hot rolls is larger than with rougher paper,[30,31] and good contact usually increases the thermal conductivity.[32] The coating method was also found to have an influence on the thermal properties of paper.[4,31,33] It is difficult to establish a relationship between fusing quality of image and physical paper properties, because some correlation could be due to different surface energies produced by different paper chemistry, surface additives and coating color formulation.[21] In this experiment, coated paper was merely tested to get a general idea of the effect of coating.

Image Quality

Table II provides some information about toner images printed on the four paper samples identified in Table I, using black and cyan. A sheet carrying the unfused toner image was fed as the second sheet in the sequence of six A4 sheets forming the paper web. The fusing unit was run at the speed of 70 mm/s (equaling about 14 ppm). The experiment was repeated for each of the samples A, B, C, and D. Basic image quality factors such as density, gloss, and adhesion strength were measured from both black and cyan regions and shown in Table II.

It is interesting to correlate the measured image quality attributes to the thermal behavior and basic properties of the paper samples. Figure 12 shows that the gloss values of both the black and cyan parts of the image decreased as the paper grammage increased. According to Fig. 7, the temperature change and effective thermal conductivity of paper A are grater than those of papers B, C, and D. Thus, the part of the energy conducted to the toner was less with paper A than with the other samples, and it was not enough to complete the fusing to the desired quality. This conclusion is supported by the percent adhesion, illustrated in Figure 13 as percentage image fixing rate, measured as the ratio between image densities before and after a tape test. The fixing ratio indicates that also the temperature change was higher in paper A, though it did not reach the toner to be fused and penetrate into the paper, as in the case of paper C of 80 g/m^2. Figure 14 shows the interrelationship between image gloss and adhesion as both were functions of paper grammage in Figs. 12 and 13. The results of this figure explain that the extra thermal energy absorbed by the toner will contribute to the glossiness of the image after satisfactory image fixing quality. Even though toner properties were not examined in this experiment, the results show that the cyan toner has a higher thermal conductivity than the black

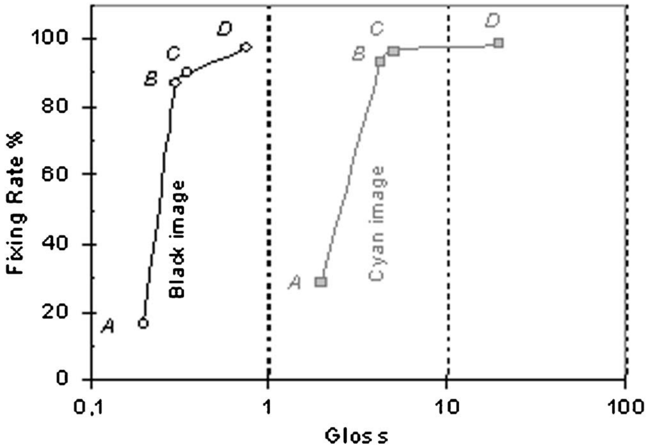

Figure 14. The relationship between image gloss and fixing rate.

toner. In all the samples, the heat transferred to the toner was picked up mostly by the cyan. This is one reason that the cyan image produced better gloss and adhesion strength compared to the black toner. In sample D, the temperature change with 70 g/m^2 paper left a lot of energy to produce a high-gloss cyan image. In this case, the fusing energy was sufficient to achieve thermal equilibrium between toner and paper through the toner-paper contact surface. Of course, the toner manufacturer prefers the black toner image to be less glossy since it is meant for text, whereas the other toner colors are designed for fine glossy images. The readability of black text should not be affected by the illumination and detection angles, which are sensitive to gloss.

Fusing Model

The results of this study suggest that a simple phenomenological model can be drawn to depict the interactions between paper and toner in fusing nip. The data quoted originates from literature sources and previous studies done at Helsinki University of Technology. Figure 15 shows a time-temperature plane sketch of the model.

Before the fusing nip, the toner and paper (solid and moisture) are all in the room temperature of 23°C. They enter the fusing nip at the same time to be treated by the same pressure and temperature for the duration of the nip dwell time. The heat required for the moisture content of paper to reach the boiling point is about 323 Jg^{-1}, which is calculated from Eq. (1) ($Q=mc\Delta T$), where $c=4.2\ J/g°C$ and $\Delta T=(100°C-23°C)$. The amount of moisture depends on the paper grade and relative humidity. At this point, the toner has passed through the glass transition (T_g) region of about[7] 60°C and sintering[34] of toner particles has started prior to coalesce.[35] The moisture needs about 2256 Jg^{-1} of heat to reach the evaporation point at 100°C, and by that time the toner is already softened and starts to melt in the so-called blocking region. After the evaporation point, the steam continues to consume about 2 $J/g°C$ of heat as the temperature continues to rise to reach the flow region of the toner around[7] 125°C with relatively high viscosity. It was found that the toner consumed about 20% of its fixing energy to reach the melting range where the viscosity is at its

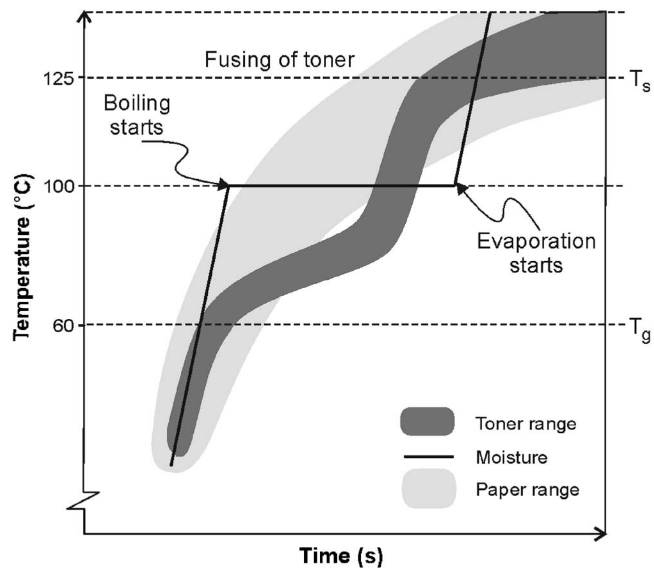

Figure 15. Phenomenological model of fusing.

highest of about 130 Pa s,[36] and the rest 80% to cause the viscosity to drop from 130 to less than 5 Pa s within a temperature change from softening point T_s (around 125°C) to fixing temperature of about 185°C, and at this range (from softening to fixing), the toner melting energy (Jg^{-1}) is an exponential function of temperature. However, in the flow region of toner, the viscosity, starts to drop rapidly causing the wetting and spreading of the toner on paper surface which has already reached the same level of temperature. At low viscosity, the melted toner flows to fill in the irregularities[35] of the paper surface and by the help of nip pressure, the toner then penetrates into the porous structure[35] and the fibers[34] of the paper. The upper right corner of Fig. 14 illustrates that at high fusing temperature, a wide range of toners are compatible with a wider range of papers for acceptable image fixing quality. Therefore, the designed roll fusing temperature in real applications is always over the highest possible toner flow point (125–130°C) by at least 40 to 50°C. Even such high temperatures do not cause heat-set offset when the other parameters (pressure, speed, and nip width) are optimized.[37]

Figure 15 illustrates that the heat consumption rates of toner, moisture and the solid content of paper are different at each phase of fusing. The range of thermal paper properties marked by the light gray region indicates the wide selection of paper grades which can be used in one given printer, compared to the dark gray region of the narrow thermal properties of toner. This is obvious, since the toner is the choice of the printer manufacturer, whereas the paper is the choice of the end-user. The choice is made from a wide recommended range of papers. The toner is designed according to the printer specifications and it is considered as an integral part of the printing process. The mass production nature of papermaking and the uncontrollable properties of the paper so produced influenced the moisture content of the paper in different humidity conditions beyond precise customization to correspond to a certain set of printing process parameters.[38] Ultimately the print application and desired quality are the main factors that influence the type of printing technology selected, and limit the flexibility in paper choice.

CONCLUSIONS

A complex set of phenomena interact in hot nip fusing. According to the results of this study, the higher the grammage of paper, and the greater the heat energy conducted to the paper, the less energy is left for toner fusing. Therefore, lower-grammage papers produce better strength and optical fusing quality, as indicated by adhesion percentage and gloss values. Higher density of paper was found to stabilize the thermal behavior, regardless of printing speed.

In striving to gain a better understanding of the toner fusing mechanism, the present experiments have provided additional information for examining the relationship between fusing energy, toner amount and print uniformity. If a sufficient amount of toner is present and the gloss has reached saturation level, extra thermal energy will contribute to image uniformity. However, the energy should be limited to avoid reaching the heat-set offset level.

To summarize, the experimental approach used in the present study is considered to be a practical tool for studying the impact of coating and other surface treatments on the development of digital paper, with the aim to achieve optimal electrophotographic image quality.

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REFERENCES

[1] P. Oittinen, H. AL-Rubaiey, K. Sipi, and K. Vikman, "Research on paper-ink-process interactions in electrophotographic and ink jet printing", *Proc. DPP2001* (IS&T, Springfield, VA, 2001), pp. 327–330.

[2] H. AL-Rubaiey and P. Oittinen, "Controlling fusing parameters by optical image quality in electrophotographic printing", Graphic Arts in Finland-GAiF **33**(1), 1 (2004).

[3] K. Sipi, "Toner layer structure and toner adhesion on coated paper", *Proc. IS7T's NIP17* (IS&T, Springfield, VA, 2001), pp. 145–150.

[4] K. D. Brooms, "Design of the fusing system for an electrophotographic laser printer", IBM J. Res. Dev. **22**, 26–33 (1978).

[5] H. Kipphan, *Handbook of Print Media* (Springer, Berlin, 2001), pp. 677–756.

[6] L. B. Schein, *Electrophotography and Development Physics*, 2nd ed. (Springer-Verlag, Berlin, 1992), pp. 38–48.

[7] J. L. Johnson, *The Handbook of Non Impact Printing Technology* (Palatino Press, Irvine CA, 1998), Chap. 13, pp. 1–14.

[8] K. Niskanen, *Papermaking Science and Technology, Book 16: Paper Physics* (TAPPI Press, Fapet, Finland, 2000), Chap. 9, pp. 284–317.

[9] M. Katsukawa, "High-speed printing technology in electrophotography", *Proc. ICIS'02* (SPSTJ, Tokyo, 2002), pp. 600–601.

[10] H. AL-Rubaiey, T. Hartus, and P. Oittinen, "The influence of flash fusing variable on image fixing quality", *Proc. ICIS'02* (SPSTJ, Tokyo, 2002), pp. 600–601.

[11] T. Kishimoto, A. Iwaishi, and T. Akuta, "Flash fixing apparatus and printer using the same", US Patent 6,721 (2004), p. 531.

[12] K. Sipi, M. Lamberg, and P. Oittinen, "Print Quality in Contact and Non-Contact Fixing", *Proc. IS&T's NIP15* (IS&T, Springfield, VA, 1999), pp. 426–429.

[13] K. Sipi and P. Oittinen, "Print quality with hot roller and IR-radiation fixing methods", J. Imaging Sci. Technol. **44**, 442 (2002).

[14] J. Heilmann, I. Heikkilä, M. Majava, and P. Oittinen, "Print quality in hot air fusing of toners", in *Recent Progress in Toner Technology* (IS&T, Springfield, VA, 1997), pp. 420–424.

[15] B. Kavoosi, "Long-nip low-pressure roll fusing", Laboratory of Media Technology, Helsinki University of Technology internal experiment report (2001).

[16] Hugh D. Young and Roger A. Feedman, *University Physics*, 9th ed. (Addison-Wesley, Reading, MA, 1996), Chap. 15, pp. 460–498.

[17] R. H. Crotogino, "Temperature-gradient calendaring", Tappi J. **65**(11), 97–101 (1982).

[18] M. Nakamura, "The effect of toner rheological properties on fusing performance", in *Recent Progress in Toner Technology* (IS&T, Springfield, VA, 1997), pp. 404–407.

[19] H. AL-Rubaiey and P. Oittinen, "Transfer current and efficiency in toner transfer to paper", *Proc. IS&T's NIP17* (IS&T, Springfield, VA, 2001), pp. 648–652.

[20] A. W. Henry, J. C. Azar, and J. Sagal, Jr., "Fusing member for electrostatographic copiers", US Patent 4,373 (1983), p. 239.

[21] D. J. Sanders, D. F. Rutland, and W. K. Istone, "Effect of paper properties on fusing fix", J. Imaging Sci. Technol. **40**(2), 175 (1996).

[22] C.-H. Chen and T.-B. Yang, "Dimensional analysis on toner fusing process", in *Recent Progress in Toner Technology* (IS&T, Springfield, VA, 1997), pp. 401–403.

[23] R. B. Prime, "Relationship between toner properties, fuser parameters, and fixing of electrophotographic images", Photograph. Sci. Eng. **27**(1), 19 (1983).

[24] S. Simula, A. Ketoja, and K. Niskanen, "Heat transfer to paper in a hot nip", Nord. Pulp Pap. Res. J. **14**(4), 265 (1999).

[25] D. M. Bott, S. M. Russel, and D. P. Van Bortel, "Closed loop control of nip width in a fuser system", US Patent 6,819 (2004), p. 890.

[26] VISILAB Oy website, www.visilab.fi, (manufacturer of the moisture meter, model IRMA-7-D), accessed February 2008.

[27] S. Simula, K. Niskanen, and O. Karjalainen, "Thermal diffusivity measurement of non-impact printing paper", J. Imaging Sci. Technol. **42**, 550 (1998).

[28] M. Karlsson, *Papermaking Science and Technology, Book 9: Papermaking, Part 2: Drying* (TAPPI Press, Fapet, Finland, 2000), Chap. 2, pp. 54–83.

[29] A. Kovonov, Personal discussions on his experience with semi-dry air-forming in papermaking, Laboratory of Paper Technology, Helsinki University of Technology (March 2007).

[30] H. AL-Rubaiey, N. Khanyeza, and P. Oittinen, "The effect of coating color on toner transfer in digital printing", *Proc. PulPaper 04 Conferences*, (Finnish Paper Engineers Assoc., Helsinki, 2004) pp. 35–40.

[31] L. Kerr, R. Dinwiddie, H. Wang, Y. Pan, R. C. Peterson, and R. Zhang, "Thermal conductivity of coated paper", unpublished results presented at the 2006 Annual Meeting of the AIChE, San Francisco, CA, 2000.

[32] R. J. Kerekes, "A simple method for determining the thermal conductivity and contact resistance of paper", TAPPI J. **63**(9), 137–140 (1980).

[33] S. Simula, "Electrical and thermal properties of papers", Doctoral Thesis, Helsinki University of Technology, Helsinki, Finland (1999), pp. 24–32.

[34] L.-H. Lee, *Thermal Fixing of Electrophotographic Images, Adhesion Science and Technology* (Plenum Press, New York, 1975), pp. 831–852.

[35] E. Hakola, "Toner dynamics in fixing", Licentiate's Thesis, Laboratory of Media Technology, Helsinki University of Technology, Helsinki, Finland (2007), pp. 52–55.

[36] T. Hartus, "Adhesion of electrophotographic toner on paper", Graphic Arts in Finland-GAiF **30**(1), 14 (2001).

[37] H. AL-Rubaiey, P. Räsänen, and P. Oittinen, "Detail rendering in digital dry toner electrophotography", in *Advances in Printing Science and Technology* (Acta Graphica Publications, Zagreb, Croatia, 2006), Vol. 31, pp. 13–25.

[38] H. AL-Rubaiey, "Electrostatic Toner Transfer and Efficiency in Electrophotography", M.Sc. Thesis, Helsinki University of Technology, Helsinki, Finland (2001), pp. 129–131.