Influence of the Thermal field on the Fusing step in Electrophotographic printing

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Abstract

Fusing consists in the last step of printing in dry toner electrophotography. Several fusing techniques are nowadays available, but the most widespread is hot-roll fusing. The paper carrying the toner is pressed between two rollers including a heated one. The temperature field in the nip is decisive for the future properties of the print. The evaluation of the thermal repartition depends on numerous parameters such as paper or toner properties, and nip geometry. This paper presents a new approach of the nip temperature evaluation based on an analytical model.

Introduction

The electrophotographic printing technology has been sharply widespread since the early 80's.
Chester Carlson invented the electrophotographic system in 1939. Ten years later, the Haloid Corporation (which became "Xerox") bought the patent. However, the first copier commercially available was putted on the market only in 1959.
To fit the improving quality of other non-impact techniques such as inkjet, electrophotography needs to be constantly improved. Customers ask for better quality, at higher speed and lower energy consumption. This requires improving the global efficiency of the electrophotographic printer, which mainly depends on the charge transfer and the fusing step. The main goal of this review is to describe (in the case of the classical hot roll fusing step) the thermal field in the nip in relation with the final print properties.
In the first part, a short description of electrophotography (black and white and 4 color) is presented. The process, the existing fusing techniques and the electrical consumption of printer elements are considered. The hot roll-fusing

step is detailed in relation with the final prints caracteristics in the second part. Keys elements of the thermal field are detailed in the third part. The last part is devoted to the thermal field modelization, which represents a central point of this paper.

1 The electrophotographic technology

(Duke, 2002), (Kipphan , 1998), (Damodar ,1993)
The different elements of an electrophotographic system are represented in Fig.1:

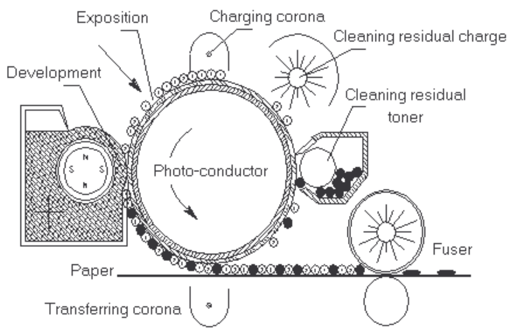

Fig.1: a typical black and white electrophotographic printing system (Duke, 2002).

The main element of the system is the central drum also called image carrier. It is built up on an aluminium body coated with a multi-layer photoconductive polymer. The five steps of the system take place around this drum:

- Imaging: charging and exposing
- Inking or development
- Toner transfer
- Fixing
- Cleaning

Typical resolutions go from 600 to1200 dots per inch (dpi). Nowadays resolutions are getting sharper. Digital printing can therefore directly compete with conventional printing processes.
There are two types of inks intensively used in electrophotographic printing: dry toner and liquid toner. Thanks to an electric potential difference the toner particles are transferred in a non-contact way onto the photoconductor. The small toner particles (around 8 µm in diameter) are charged in order to be fixed onto the photoconducting surface, thus building the image.
Fig.1 concerns a black and white printer with hot roller fusing. However, many other devices and techniques can be found in the market.

Four-color electrophotography can be achieved in two different ways: the multiple pass technique uses a single photoconductor drum: colors are transferred one after each other. Once the 4 print cycles are completed, the sheet is released and conveyed to the fusing station. In the single pass method there is one photoconductor for each color. The fusing step always occurs when the four colors have been transferred.
Globally speaking, the type of technology and process will affect the fusing step. It must be adapted to each kind of toners (colored or not), and to each kind of paper.
More than 50% of the total electric consumption of a copier is caused by the fixing/fuser rollers (Acquaviva, 1994) (for Takenouchi (1998) the electrical consumption exceeds 80%). A decrease in the electric consumption of the fusing step could be achieved by better understanding the phenomena taking places at this stage. Obviously the toner's rheological properties and its melting temperature are of main importance. It could also be interesting to improve the heating transfer characteristics of the materials playing a role in the system. Especially in order to reduce the time and energy consumed by the warming up of the machine.

The classical fusing method ensures a long-term fixation by pressing and heating the toner that has been electrostatically fixed onto the paper.
Others fusing techniques exist, namely cold pressure, radiant, flash, IR.

2 The fusing step and its consequences on optical properties

Most of the print quality characteristics are determined by the fusing step.
In a classical fusing system, the paper covered with the toner is pressed between two rollers (fig.2). The heater is a hollow aluminum roller coated with a fluoride resin; the pressure roller is coated with an elastomer (commonly silicon rubber). In the center of the heater roller, is a radiant heater.

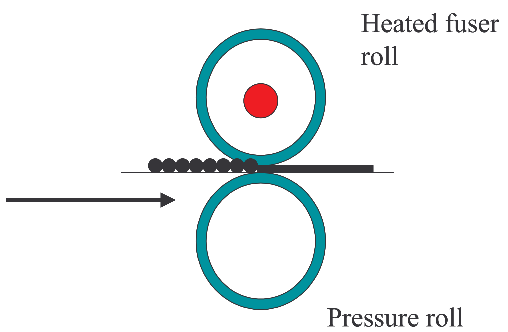

Fig.2: Schematic view of the fusing system

Heat transfer along with pressure melts the solid toner into a viscous liquid This liquid spreads onto the surface and creates bonding (mechanical and chemical) with the fibers. To prevent the toner from adhering onto the rollers some of the latter are coated with special oil (called a "released agent"). The area of contact between these rollers and the paper carrying toner forms a nip.

The optical properties of prints are linked to the fusing conditions, namely the gloss and the image quality (optical density, line width).
Gloss is a specular reflection of light. It is mainly affected by the refractive index of the material, the angle of incident light and the surface topography. It is known that calendering is a way to increase the gloss of a paper. This technique uses the same technology as the hot roller fusing system. By pressing and heating the paper and the toner the gloss is sharply increased. The surface of an electrophotographic print is smooth because the melted toner fills the apparent paper roughness. It is the reason why gloss is important. Recently, Chow (2005) has studied the gloss of fused images. He chose a theoritical approach and presented a model to describe the influence of materials on fusing.
One of the difficulties in controlling the gloss come from half-tone images. Indeed the degree of gloss change according to the different surface areas of a halftone image. Briggs (1999) investigated the effect of the fusing temperature on gloss. A toner fusing test system (QEA TFS-1000) has been used to perform the experimentations on two subtrats a coated paper and an uncoated paper. The experimental results met his expectation: the gloss increases sharply with the fusing temperature.
In fact, as long as the temperature rises the viscosity of the melted toner increases. Due to the roller pressure and the gravity, the toner film will be flat if its viscosity is low enough.
An other aspect that could be linked to the ability of the toner to spread is the tone value increase. Chow (2005) reported on experiments where he simply measured the width of line on the two same substrates (coated and non coated paper). The line width gain follow the the increasing fusing temperature. The coated paper is more affected by this temperature elevation. As the coated paper is less absorbing than the uncoaeted paper, the natural tendency of spreading is favoured.
The temperature field (and thus the print quality) depends on various characteristics. They can be classified into three groups of parameters (see table 1):

Toner properties	Paper properties	Process parameters
• Specific heat capacity • Thermal conductivity • Surface energy • Glass transition temperature • Viscosity • Particle size • Particle distribution	• Specific heat capacity • Thermal conductivity • Moisture content • Surface energy • Roughness • Porosity • Thickness	• Roller temperature • Ambient temperature • Pressure field in the nip • Dwell time • Nip width • Toner pile height

Table.1: parameters controling fusing quality (Rubaiey, 2004)

These factors and their relative influence in the thermal field will be detailed in paragraph 3.

3 Relation between physical properties and temperature of components in the fusing nip:

3.1-Heater temperature

The heater temperature could be regulated manually. But most of the time this temperature is defined for a certain type of machine. It depends mainly of the type of toner used, the speed of the printer and the paper thickness. Typical values are between 150 and 220°C.

3.2- Thermal properties of the nip components

The internal properties of the elements playing a role in the heat transfer in this area (aluminum core, coating layers, toner, air and paper) have to be known. The heat capacity, thermal conductivity and thickness are therefore of main importance. Thermal conductivity is the quantity of heat, *Q*, transmitted through a thickness *L*, in a direction normal to a surface of area *A*, due to a temperature gradient ΔT, under steady state conditions and when the heat transfer is dependent only on the temperature gradient . The specific heat capacity (symbol *c,* unit is $J \cdot kg^{-1} \cdot K^{-1}$) of a substance is defined as heat capacity per unit mass. It is the amount of energy required to raise the temperature of one kilogram of the substance by one kelvin. Several authors have proposed to evaluate the thermal properties of the materials (Mitsuya, 1992), (Samei, 1998, 1999), (Takenouchi 1999), (Menzel, 2001). As Takenouchi has intensively studied the heat transfer in the nip we will present the values he used in table 2.

Layer	Thickness [μm]	Thermal conductivity [W/(m.K)]	Heat capacity $[MJ/(m^3.K)]$
Heat roller core	1500	228.6	2.50
Coating layer	30	0.181	1.64
Toner	14	0.151	1.51
Paper	100	0.08	1.16
Elastic layer	100	0.281	2.01

Table 2: thermal properties and parameters of the fusing elements

3.3-Pressure between the two rollers

The pressure between the two rollers depends on various characteristics: the pressure applied by the roller, the deformation capacity of the polymeric elastomers coated on both rollers, and the diameters of the cylinders. For commercial devices, the pressure is fixed at the designing step. Mitsuya (1992) proposed a way to calculate the pressure field in the fusing nip. Local pressure is around 1.6×10^6 Pa.

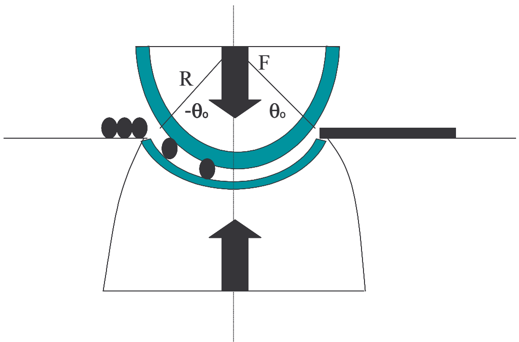

Fig.3: Schematic illustration of a nip

θ: Angle
F: Pressing force
R: heat roll radius
L: heat roll length
We suppose that the local nip pressure P(θ) proportional to local elasticity of the backroll. The deformation of the backroll is limited to the nip. Finally we assume that the Young modulus of the elastomer is uniform all over the nip .

Under those hypotheses, the local pressure in the nip could be written as follows (Mitsuya, 1992):

$$P(\theta) = \frac{F \times \cos\theta \times (\cos\theta - \cos\theta_0)}{2RL(\sin\theta_0 - \theta_0 \times \cos\theta_0)} \quad \text{Eq.1}$$

Using Eq.1 a value of local pressure of 1.6×10^6 Pa is obtained at the maximum (considering 35 $N.cm^{-1}$ for the linear pressure (Goldmann, 1999), and a diameter of 5 cm for the cylinders).
If the pressure increases, the thicknesses of all components decrease increasing the heat transfer.

3.4-Dwell time and width of the nip:

The heat transfer is time dependent. Consequently, it is obvious that the dwell time is a key parameter. This time depends on the speed of the machine and the deformation of the roller covering.
The width of the nip is determined by the diameters of the two rollers (the heater and the pressure roller), and by the elasticity of the elastomer. The diameters of the rollers are between 5 and 10 cm. Thus, the nip width can vary from 3 mm to 20 mm for high-speed printers.

3.5-Toner morphologies:

The particle size and particle size distribution of the toner play a major role in the heat transfer. This will be confirmed in modeling section. The average size of common toner particle is around 7 µm. However according to the type of toner (color or black) a large range of diameters exist: from 5 µm to 18 µm (Leroy, 2002). Decreasing of the particle size does not improve quality. Moreover the European legislation has fixed 5µm as the smallest limit to avoid inhalation risks. Besides, small particles (bellow 6 µm) cause runnability problems (Yamaguchi, 1996), as the toner will have a natural tendency to agglomerate (Mitsuya, 1997). To avoid defect in print quality, the toner's size distribution should be as narrow as possible. Takenouchi summarized the diameters of toners particles using the Coulter method. Studying 30.000 particles, he obtained a size of 7.6 µm with a standard deviation of 2.3µm. Nevertheless, most of the commercially available toners are barely spherical (Pëtterson, 2005). That is why an equivalent diameter can be used.

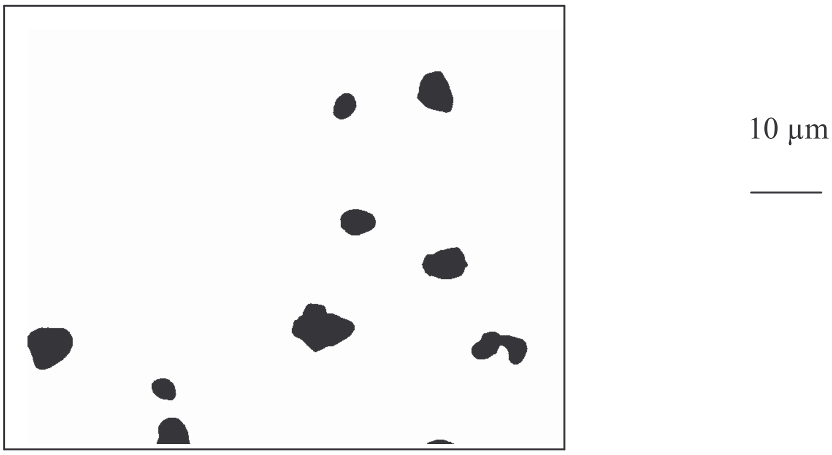

Fig.4: Binarized image of black toner particles (EFPG)

In the case of a full tone prints, several layers of tone could cover a single paper area before fusing (Mey, 1999), (Takenouchi, 1997). The reason for studying geometrical shape and size distribution of the toners particles is to analyze the porosity of the pile onto the paper. Air has low heat conductivity. Therefore, a small amount of air could modify the temperature field. A typical value of porosity in a system constituted by even and random spherical particles is ε=0.36. Under this hypothesis if we consider a pile of two toners of 7µm we obtain an equivalent air layer of 4µm.

3.6-Toner fixation:

The fixation of the toner onto the paper could be described in for stages (Lee, 1973), (Prime, 1983), (Sipi, 2002):

1. The toner is heated over its glass transition temperature
2. The toner particles agglomerated
3. The melted toner wets the paper surface and spreads
4. Some penetration may occur, toner cools down and solidifies

The process of toner fixing during the fusing step is summarized in Fig.5

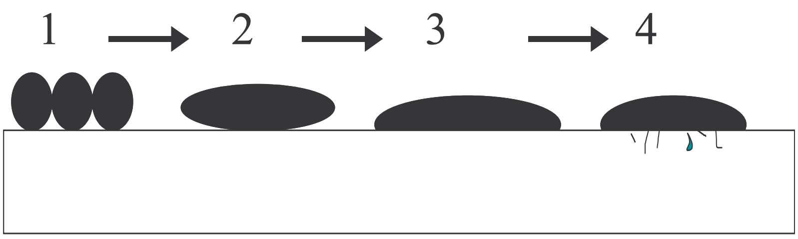

Fig.5: Fusing and fixing.

The toner adhesion onto the paper is both mechanical and chemical. Regarding the penetration of the melted toners into the paper, recent studies show that this effect is limited. Wang (2000) used a different approach from the classical Darcy's Law based on the Navier-Stockes equation. The calculated penetration is around 10^{-2} µm. This is confirmed by the image of a cross section of a black print (Fig.6a, Fig.6b and Fig.7)

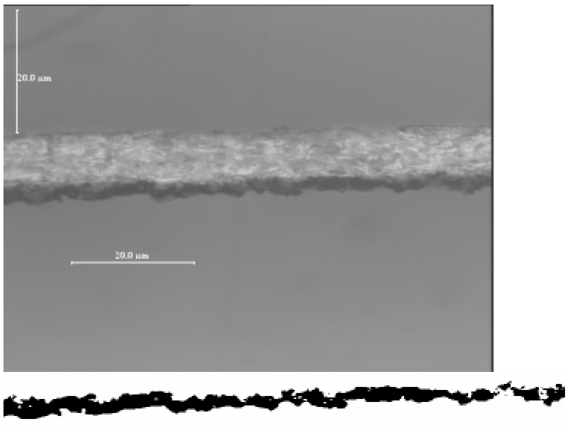

Fig.6a and 6b: Cross section (optical microscopy) of a black toner's layer after fusing on paper. Below (Fig.6.b) the binarization of this layer is presented. (EFPG)

Fig.7 shows that the toner images fill the voids at the top surface. There is no significant penetration into the paper structure.

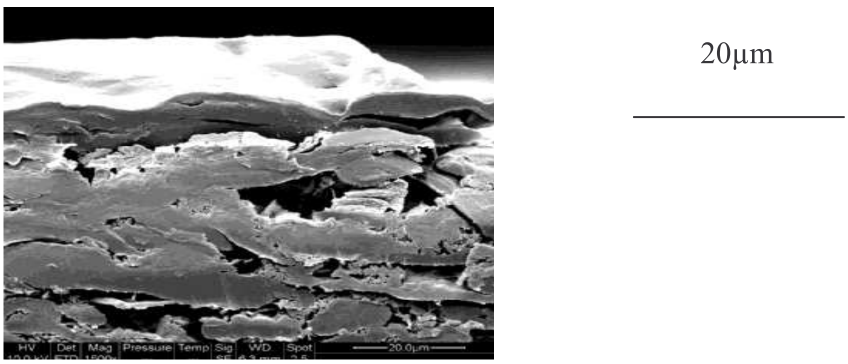

Fig.7 MEB cross section of a black melted toner onto paper (EFPG)

Studies on the toner properties at high temperature may be found in literature. The reference from Majava (1994) concerns an exhaustive study of commercial toners. The ability of those particles to spread on the paper will determine the final print quality. Key physical properties are the glass transition temperature, the surface energy of both the paper and the toner and the rheological behavior of the toner. The temperature modifies these properties.

Leroy (2002) intensively studied the rheological behavior of a representative series of commercial toners. Their viscosities were measured under a shear rate of $0.5s^{-1}$ on a Carri_Med CSL2500 rheometer. The results show a large scale of viscosity values depending on the toners. For example at 140°C, the viscosity values ranged from almost 0 Pa.s up to 12000 Pa.s.

The toner adhesion on paper is strongly related to the temperature in the nip. This adhesion is also linked to the surface chemistry of the substrate, the paper roughness and other parameters.

The technique used to measure the adhesion mainly depends on the author. Basically a solid black tone is submitted to a gumming (with oil (Forgo, 1993), tape (Britto, 1991), mechanically (Batten, 1996)). The fixing degree is defined as the ratio of the optical density before and after gumming. A European standard (ENV 12883) measuring fixing was developed.

According to Britto (1991), the degree of fixing increases from 40% to 90% if the roller temperature increases from 125°C to 160°C.

3.7-Moisture content:

Paper is known to be a strongly hydrophilic material. Its moisture content and affects most of its properties, especially its thermal conductivity. For a non-coated paper in the thickness direction, a variation of one percent of the moisture content (from 4% to 5%) decreases of the thermal conductivity by 12.5% (from 7×10^{-2} to 8×10^{-2} (W/m.K) (Serra-Tosio, 2004). Air and toner properties will also be affected by a variation of the degree of humidity.

3.8-Paper properties:

The effect of paper properties on print quality is obvious. Sanders (1995) studied the paper characteristics related to the fusing fix. Recent studies were focused on paper topography for electrophotographic printing**.** Their aim is to establish a link between the roughness and the heat transfer. The surface will induce a barrier for the heat flux. Takenouchi (1999) measured the roughness profile of laser papers. The maximum height profile Ry was 12.5µm (an average between machine and cross directions) and the mean spacing of profile Sm was 115.7µm.

Toner particles with a diameter of 7 µm could be small compare to the roughness profile. Hence toners could avoid being in contact with the rollers if they happened to be in a paper pore (Sipi, 2002). This effect will influence the gloss of the final print (see Fig.8)

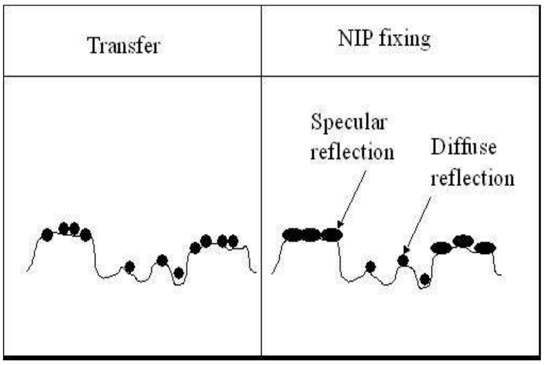

Fig.8: Toner on paper surface before and after the fusing nip.

The thermal properties of paper were thought to be of main importance in the control of the thermal field. Recent articles proposed various methods to measure the paper diffusivity of a non-impact printing paper. (Simula, 1998), (Hashimoto, 1998)
The paper should reach a high temperature in the nip, and cool down as fast as possible. Requirements are therefore high thermal conductivity and low heat capacity.
The useful parameter to describe the dynamic variation of temperature in a medium is its diffusivity α .

For a homogeneous material α is defined as: $\alpha = \dfrac{\lambda}{\rho C}$ Eq.2

Where ρ is the mass density and C the specific heat.
The difficulties in measuring the paper's diffusivity are its porosity and the thinness of the samples.

3.9-Synthesis:

The issues tackled previously show the complexity of the phenomenon involved in the nip during the fusing step. A good control of those parameters is needed to achieve a good print quality. Acceptable print is achieved in a "fusing window" illustrated by Tse (see Fig 9).

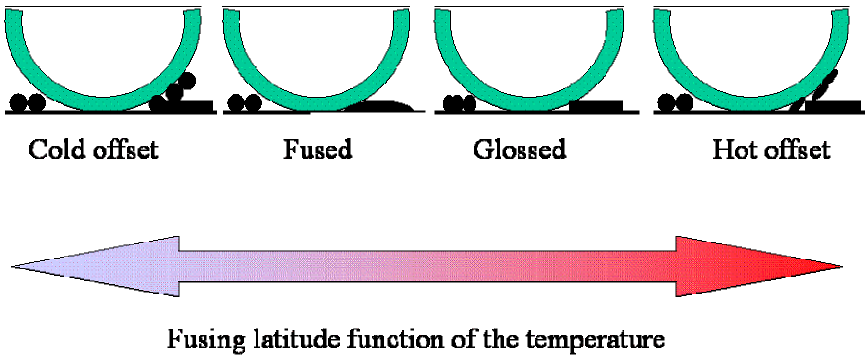

Fig.9: Fusing latitude in hot roll fusing (Tse, 1998)

- Cold offset: when the nip temperature is too low, some parts of the toner leave the nip unfused and are transferred onto the hot roller.
- Hot offset: the toner's adhesion to the hot roller is greater than the adhesion to the sheet (Menzel, 2001).

A key factor related to the fusing is obviously the quality of the toner fixing. It depends on numerous parameters such as surface chemistry, roughness of the paper surface. However, the fusing temperature is playing a key role in this process.
A too high temperature in the nip could also damage the paper. The paper moisture decreases as long that the temperature increases. This could cause curling and cockling (Simula, 1998).

4 A new approach to Modelize the temperature field in the nip:

To reach the best compromise between the dwell time and the heating of the roller, it is necessary to simulate the temperature field in the nip.

4.1-Geometry of the fusing zone:

One of the difficulties is to represent the sheet of paper carrying the toner in contact with the two rollers in the nip. This transfer is conductive . Thanks to the radiative flux, the aluminum core is heated. Then it transmits the flux by contact. The simplest model is to consider a toner layer on a paper sheet between the rollers, as illustrated in Fig.10 (Leroy, 2002):

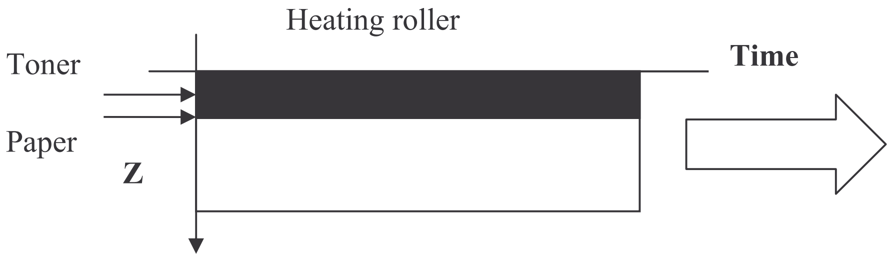

Fig.10: Simple model geometry for the heat transfer in the nip (Leroy, 2002).

Numerical approaches of this heat transfer were performed by solving the heat equation:

$$\rho C \times \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda \frac{\partial T}{\partial z}) \qquad \text{Eq.3}$$

Depending on the assumption, Eq.3 may be simplified into a one or two-dimensional problem.
Mitsuya (1992) and Leroy (2002) chose the model geometry presented in Fig.12 to simplify Eq.3 considering a one-dimension problem in the thickness direction (z direction).

$$\rho C \times \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(\lambda \frac{\partial T}{\partial z}) \qquad \text{Eq.4}$$

Then they solve Eq.4 using the finite element method.
Samei (1999) showed that the reality is far more complicated: models have to take into account the quantity of air between each interface, the thermal characteristic of the paper surface in the case of sizing, as well as the roughness and micro capillarity of the paper. The state change of the toner itself is also worth being considered.
Therefore the air layers between the toner and the roller, in the toner's pile and eventually due to the paper roughness have to be considered.

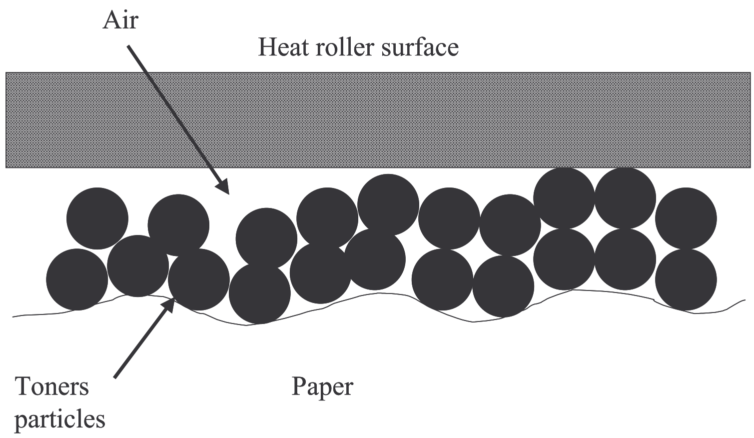

Fig.11: Interfaces existing in the nip region

A numerical method is used to solve Eq.1 in the case of a multilayer system. The model has to take into account: the roller, the coating layer, a first air region, parts of the toner, a second air region, the second part of the toner and finally the paper sheet.
Eq.5 is simplified into a two dimensional problem:

$$\rho C \times \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda \frac{\partial T}{\partial z}) \qquad \text{Eq.5}$$

Eq.5 was solved using an alternating direction implicit method (ADI) (Samei, 1999).
Thanks to an infrared camera, Takenouchi measured the temperature field at the outlet of a fusing nip. The comparison between the experimental and calculated results was good and enabled to the model.

4.2-Analytical model:

It is also possible to simulate the heat transfer by an analytical method. We borrowed the main ideas of the model to the theory of heat transfer through walls (Antonopoulos, 1997). We also consider the system as a one-dimension problem. Thus,Eq.7 has to be solved for every layer included in the studied geometry. The layer number only depends on the choice of the representation. If, for example, the air contained in the toner structure is taken into account.
To solve this equation, we used a classical methodology:
We first applied the heat equation to each layer

$$C_i \times \frac{\partial T_i}{\partial t} = k_i \times \frac{\partial^2 T_i(x,t)}{\partial x^2},\qquad \text{Eq.6}$$

With $x_i \le x \le x_{i+1}$, $t > 0$, i=1,2,3,….,m

Where i refers to the number layers considered.

Then we defined the initial and the boundary conditions. The boundary conditions are the continuity of the temperature (or Dirichlet condition Eq.8) and the continuity of the heat flux (or Neuman condition Eq.9) trough the system :

$$T_1(x,t) = T_0,\ \text{x}=x_1 \qquad \text{Eq.7}$$

$$T_i(x,t) = T_{i+1}(x,t),\ \text{x}=x_{i+1},\ \text{i=1,2,3,….,m-1} \qquad \text{Eq.8}$$

$$k_i \times \frac{\partial T_i(x,t)}{\partial x} = k_{i+1} \times \frac{\partial T_{i+1}(x,t)}{\partial x},\ \text{x}=x_{i+1},\ \text{i=1,2,3,….,m-1} \qquad \text{Eq.9}$$

First we set the initial temperature of the system at 0°C because we will deal with temperature difference. Equation 7 is transformed in a differential equation using the Laplace transformation. Then we solved this system of m layers in a non-temporal space. An inversion is carried out to come back to the temporal space. At this step we need to solve n homomorphous equations. We obtain a system defined as follow:

$$\int_{t=0}^{t_0} [k_{m-1} \times T_{m-1}(t_0) \times (\frac{\partial V_{m-1}}{\partial x})_{x_{m-1}} + k_m \times T_m(t_0) \times (\frac{\partial V_m}{\partial x})_{x_m} - k_{m-1} \times T_m(t_0) \times (\frac{\partial V_{m-1}}{\partial x})_{x_m} - k_m \times f_{i+1}(t) \times (\frac{\partial V_m}{\partial x})_{x_{m+1}}]dt = 0 \qquad \text{Eq.12}$$

The Vi functions are defined in the Annex.

There is a unique solution to this system. As we have (m-1) unknown interface temperatures and (m-1) independent equations.

4.3-Results and discussions

We have chosen a 4 layer-system (Cylinder/air/toner/air/paper), with the following parameters data:

Layer number	Thickness in µm	Heat Conductivity (W/m.°C)	Heat capacity (MJ/m^3.°C)
1-Air	5	0.03	0.0012
2-Toner	10	0.151	1.51
3-Intermediate air layer	4	0.03	0.0012
4-Paper	100	0.08	1.16

Table.3: Thermal properties

We considered that the heated roller had a uniform and constant temperature of 180°C.
In Fig.13 the three interfacial temperatures and their time evolution are plotted.

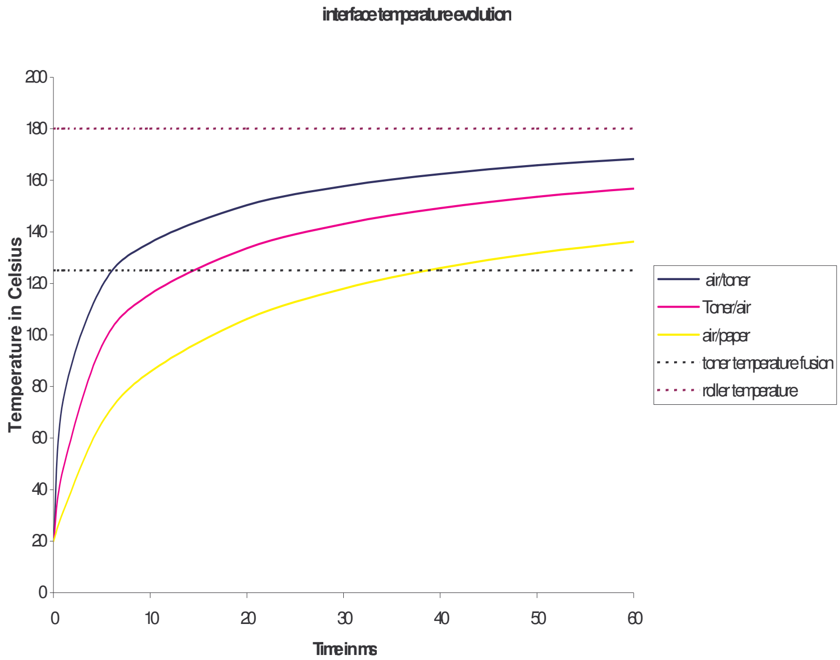

Fig.13: interfacial temperature calculated with the analytical method

The estimation of the temperature at the interfaces is realistic. Hence, according to this model, a resident time of 40 ms is needed to ensure a total melting of toners.
In order to test the simulation and to compare it to other authors (Takenouchi, Leroy and Simula), we have plotted in Fig.14 results of the different modelizations. A value of 155°C was chosen for the roller surface.

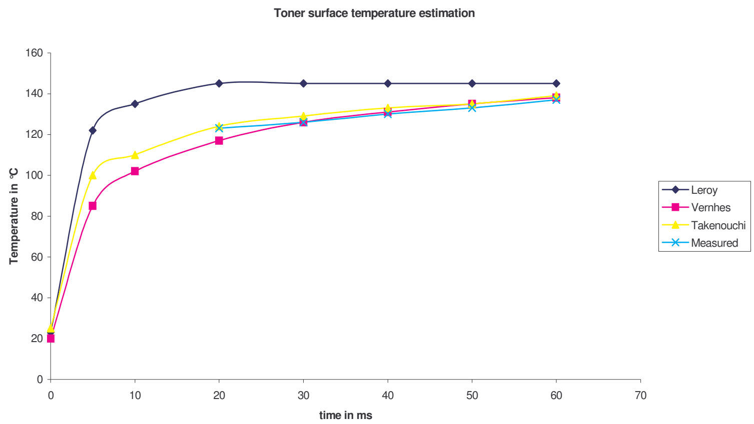

Fig.14: Toner surface estimation according to different models

Takenouchi (1999) showed that air layers are of main importance. This is why Leroy's model is not consistent with the experimental data. The analytical method presented in this paper fits both experimental data and the numerical model given by Takenouchi.
Fig.15 shows the paper temperature surface for 3 different times (20, 30 and 40 ms) and their dependence to the paper heat conductivity.

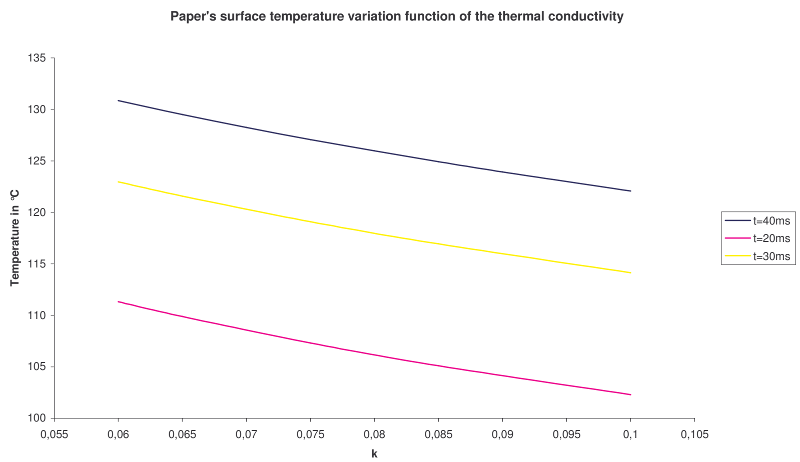

Fig.15:Variations of the paper surface temperature as a function of the thermal conductivity of the paper.

For the longer dwell time (40 ms), the paper conductivity must be considered. The paper temperature falls from 131°C to 122°C as the conductivity is increasing from 0.06 to 0.1 W/(m.K).

Because it does not take into account the phase transformation of the toner, this model is of course not complete. However, the toner heat of fusion is rather small (40.3 KJ/Kg in the case of a toner made of styrene-acrylic (Takenouchi, 1998). We assume that the error is relatively small.
A global drawback of all those models (numerical and analytical) developed in the past is to consider the thickness of the layers constant during the dwelling time in the nip. In fact, due to the pressure the rubber and the paper are deformed. Furthermore, the toner is also spread leading to a decrease of its thickness.

Summary and Conclusion

The fusing step in electrophotography was detailed. The main physical properties of materials playing a role in the nip were studied in relation with their thermal characteristics.
Two methods for estimating the thermal field in the nip of an electrophotographic system device were compared. Our new approach based on an analytical method to solve the heat equation provides reasonable results in comparison to the existing numerical solutions and experimental data.

Annex:

$$(\frac{\partial V_{i-1}}{\partial x})_{x_{i-1}} = \frac{1}{x_i - x_{i-1}} + \frac{2}{x_i - x_{i-1}} * \sum_{n=1}^{\infty} (-1)^n * \exp[-\frac{k_{i-1} * \pi^2 * n^2 * (t_0 - t)}{C_{i-1} * (x_i - x_{i-1})^2}]$$

Eq.11

$$(\frac{\partial V_i}{\partial x})_{x_i} = -\frac{1}{x_{i+1} - x_i} - \frac{2}{x_{i+1} - x_i} * \sum_{n=1}^{\infty} \exp[-\frac{k_i * \pi^2 * n^2 * (t_0 - t)}{C_i * (x_{i+1} - x_i)^2}]$$

Eq.12

$$(\frac{\partial V_{i-1}}{\partial x})_{x_i} = \frac{1}{x_i - x_{i-1}} + \frac{2}{x_i - x_{i-1}} * \sum_{n=1}^{\infty} \exp[-\frac{k_{i-1} * \pi^2 * n^2 * (t_0 - t)}{C_{i-1} * (x_i - x_{i-1})^2}]$$

Eq.13

$$(\frac{\partial V_i}{\partial x})_{x_{i+1}} = -\frac{1}{x_{i+1}-x_i} - \frac{2}{x_{i+1}-x_i} * \sum_{n=1}^{\infty}(-1)^n * \exp[-\frac{k_i * \pi^2 * n^2 * (t_0 - t)}{C_i * (x_{i+1}-x_i)^2}]$$

Eq.14

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