A new approach to model and characterize the heating up and spreading of toner particles trough the nip of an electrophotographic printer

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Abstract

The last step of electrophographic printing consists in fusing. The solid toner particles are pressed and heated up onto the paper surface. Hence the polymer creates mechanical and chemical bonds with the substrate in order to ensure long term fixation. Most of the future properties of the print are related to the fusing step, especially the gloss and the line width. In both cases the spreading capabilities of the toner particles play a heavy role. The spreading and agglomeration of toner particle structure is related to the temperature. The goal of this study is to investigate the thermal field in the nip related to toner agglomeration and spreading. An analytical method to describe the thermal field in the nip has been developed. Its validity was achieved by comparing the numerical simulation to the experimental data. Thus the paper characteristics can be taken into account: thermal properties, roughness and coating layer. The relative humidity of the air could also be integrated into the calculation. An experimental setup allows following in situ of the agglomeration and the spreading of toner particle structure that has been built. This equipment gives relevant information on the influence of high temperature on toner particles.

Keywords: Temperature field, electrophotography, nip, toner, spreading

1 Introduction

Electrophotography is a non impact printing method. Fusing is the last step in electrophotographic printing. The hot roll technique is the most widespread. It consists in heating and pressing the toner covering the paper between two rollers. A radiant lamp is situated in the center of the first roller. The roller is made of aluminium and coated with a fluoride resin. The roller above, called the pressure roller, is coated with silicon rubber. Hence, the paper and the toner are forced to pass through a nip. The aim is to ensure a long term fixation of the toner onto the paper structure. The effective combination of the heat transfer and the pressure melts the solid toner into a viscous liquid. Toner particles first agglomerates and then spread onto the paper surface, as illustrated in Fig.1. The toner fixation on the paper surface can be divided in three main steps: heating, spreading and solidification [1].

Most of the optical properties of the future print are related to this step [2,3,4,5] and especially the gloss and the line width. Besides, more than 50% of the global electrical consumption of a classic printer is caused by the radiant heat [6]. To achieve both good print quality with low electrical consumption, precise control and knowledge of the heat flux through the nip is needed.

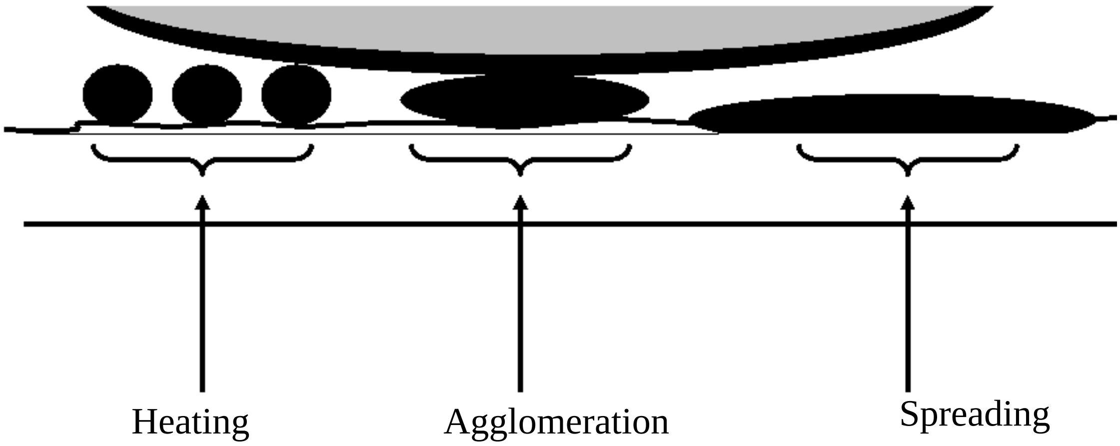

Figure 1: Fusing and fixing of the toner on the paper

The different elements of the nip are constituted of several layers. Thus, the relations between the physical properties and the temperature of each component in the nip are complex. Three types of family properties exist [7]:

- The toner properties: Besides its chemical properties (mainly, glass transition temperature, viscosity and thermal properties), the morphology of toner particles play a major role in the heat transfer. In the case of a full tone print, several layers of toner could cover a single surface area before fusing [8,9]. The reason for studying both the geometrical shape and the size distribution of the toner particles is to analyze the porosity of the global system including the paper. Indeed, air has a low heat conductivity. Therefore, a small amount of air could modify the temperature field. A typical value of porosity in a system composed by identical spherical particles is ε=0.36 in a random disposition.

- The paper properties: The paper surface properties are of main importance in the control of the heat transfer. The roughness of the paper induces the presence of air in the nip. Paper is known to be a strongly hydrophilic material. Its moisture content affects most of its properties, especially its thermal conductivity. For non-coated paper in the thickness direction, a variation of one percent of the moisture content (from 4% to 5%) decreases the thermal conductivity by 12.5% (from $7.10^{-2}$to 8.10^{-2} 8×10^{-2} (Wm^{-1}.K^{-1}) [10]. Air and toner properties will also be strongly affected by a variation of humidity.

- The process properties: According to the design of the machine, the heater temperature varies between 150 and 220°C. A typical value of dwell time is 60 ms for a nip width of 10 mm. The local pressure created by the two rollers is commonly around $1.6.10^{6}$Pa. The physical properties of the elements playing a role in the heat transfer (aluminum core, coating layers, toner, air and paper) have to be known. Table 1 presents the values of Takenouchi et al. [9] dedicated to heat transfer in the nip.

Table 1: Thickness and thermal properties of the fusing elements [9]

Layer	Thickness [µm]	Thermal conductivity [$W.m^{-1}.K^{-1}$)]	Heat capacity [$MJ.m^{-3}.K^{-1}$]
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

In the second part, a new analytical method to simulate the temperature field is given. Rheology and surface tension of the melt toner are strongly related to the temperature in the nip. That is why the last part of this paper will be devoted to analyzing the effect of the temperature on the agglomeration and the spreading of toner particles.

2 Analytical model of the temperature field in the nip:

2.1 Geometry of the nip

Several authors have modeled the heat transfer occurring in the nip [9,11,12,13]. Precise models were developed using numerical approaches. In order to solve the heat equation, the geometry of the problem has to be defined (Fig.2). The roller surface coating, the toner and the paper (and its coating layer) has to be taken into consideration. However, there is also the air interface existing in the toner pile and at the paper surface.

It is assumed that the thermal properties are isotropic.

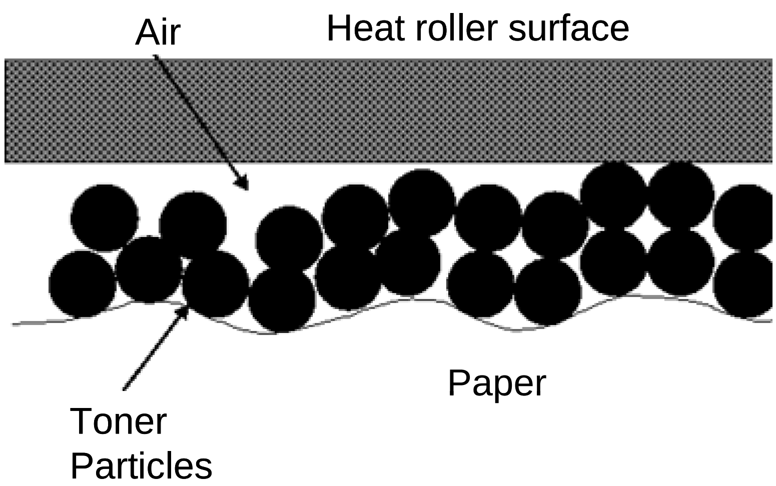

Figure 2: Schematic representation of interfaces in the nip region [9]

The heat transfer is considered using a 1D equation. The heat transfer is only considered here on the vertical axis (1), due to the velocity of the machine.

$$\rho.C\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}(\lambda\frac{\partial T}{\partial z}) \qquad (1)$$

Equation (1) was solved using an Alternating Direction Implicit method “ADI” [14].

The validation of the numerical resolution of the system was achieved when [9] measured the temperature field at the outlet of a fusing nip. The comparison between the experimental and calculated results validated the model.

Nevertheless it is also possible to simulate the heat transfer by an analytical method. The main ideas came from the theory of heat transfer through walls [15]. The system has also been simplified into a one-dimensional problem. Thus, (1) has to be solved for every layer included in the studied geometry. The heat equation was transformed in a differential equation using the Laplace equation and then solved for each layer considered in the system. Then an inversion is carried out to come back in the temporal space. This method is detailed in [15].

2.2 Graphical representation of the temperature

Figure 3 shows the evolution of temperature of the three interfaces, in a system in which are considered the roller, a first air layer, the toner pile, a second air resistance and the paper. Numerical data of the three physical parameters taken into account for the calculation are given in table 2. The heater temperature is fixed at 180°C. The values given by the analytical model to Takenouchi's results [9] for the paper surface temperature have also been included. The result fits both numerical and experimental data from Takenouchi.

Table.2: Thickness and thermal properties of the considered layers [9]

Layer number	Thickness (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

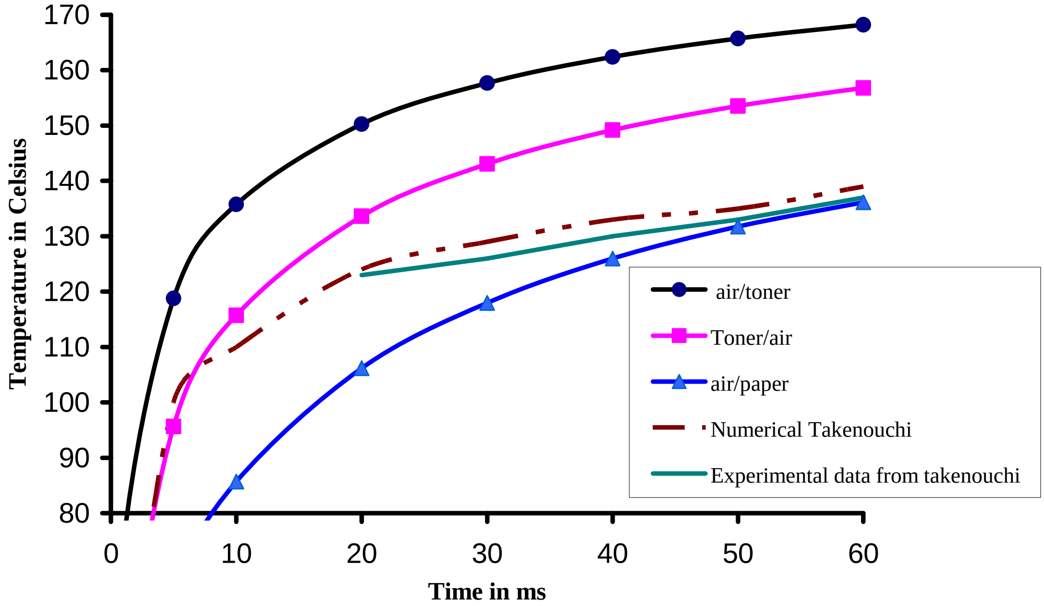

Figure3: Interface temperature evolution and comparison to the literature results

This model offers different possibilities. For example, it is possible to plot the surface temperature interface as a function of the paper surface porosity. As a matter of fact the quantity of air present at the paper surface is proportional to the paper roughness. 180°C was chosen for the hot roll temperature and a dwell time of 40 ms (as illustrated on Figure 4).

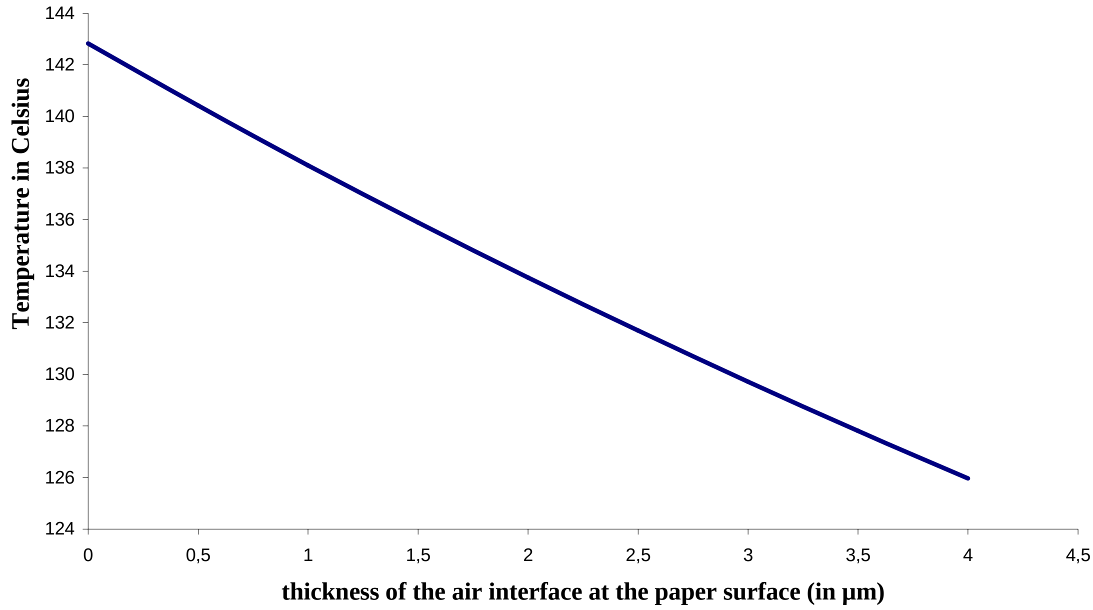

Figure 4: Paper surface temperature vs. the paper surface porosity (expressed as a thickness in µm)

This result demonstrates the sensitivity of the model to the air layer thicknesses. For example, if both simulated air layers thicknesses are doubled, the paper surface temperature drops from 120°C to 92°C (for 40 ms of dwell time). Now if the air layers are divided by two, the paper surface temperature raises to 142°C.

It is also possible to provide paper surface temperature depending on paper thermal conductivity and paper heat capacity (Figure 5).

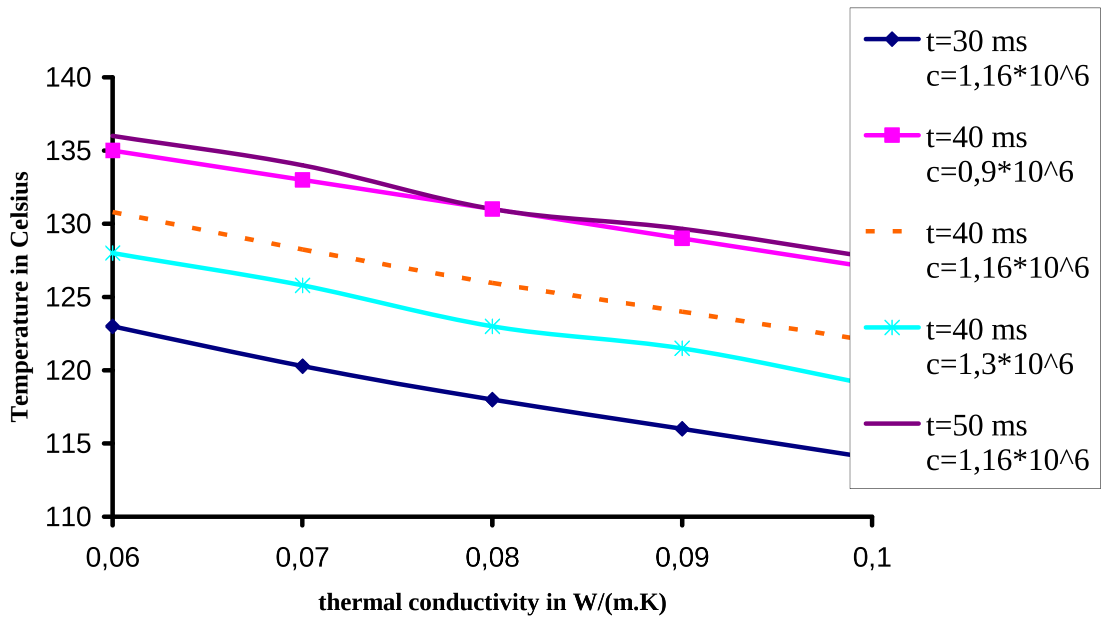

Figure 5: Surface paper temperature Versus paper thermal conductivity, for different heat capacities and dwell times.

An important parameter is the phase change of the toner, which is due to the glass transition. Hence, there are different ways to reach the glass transition temperature of the toner. For example, a paper surface temperature of 123°C could be obtained as follow:

- A low thermal conductivity (0.06 W. ($m^{-1}.K^{-1}$)) with an intermediate heat capacity ($1.16.10^6$ $MJ.m^{-3}.°C^{-1}$) and a short dwell time (30 ms).
- A high thermal conductivity (0.9 $W.m^{-1}.K^{-1}$)) with an intermediate heat capacity ($1.16.10^6$ $MJ.m^{-3}.°C^{-1}$) and an intermediate dwell time (40 ms).
- An intermediate heat conductivity (0.08 W. ($m^{-1}.K^{-1}$)) with a high thermal capacity ($1.3.10^6$ $MJ.m^{-3}.°C^{-1}$) and an intermediate dwell time (40 ms).

It has been claimed [16], that requirements for the paper thermal properties are high thermal conductivity and low heat capacity. Under these hypotheses, the paper could reach a high temperature, and cool down rapidly. However, as there is no penetration of the toner [17], there is no need to heat up the paper. Consequently, the main factor consists in the paper/toner interface. The temperature at this interface decreases dramatically when the paper conductivity drops, as shown in Figure 5.

The temperature field in the nip has been fully described and allows to adjust the paper and toner properties to reach the most suitable temperature in the nip. However, the temperature is also of main importance for the control of the toner spreading. Solid toner particles melt when they reach a sufficient temperature and begin to spread as the viscosity of the toner polymer decreases. The next section aims to describe the toner spreading and the toner agglomeration dependency to the temperature.

3 Consequences of the heating of toner particles on agglomeration and spreading:

3.1 Material and method

Most of the commercial toner particles have a characteristic size of 10 µm. They are composed of binder resins, colorants and additives. The agglomeration and the coalescence of the toner particles in the nip are due to temperature and pressure.

Literature on toner behaviour at high temperatures is quite rare. There are few references on the kinetics and the thermodynamics of this process [1,18].

The study of spreading of individual toner has been recently performed [19]. A method has been developed to study in situ, the spreading behaviour of individual toner particle during heating. The aim was to simulate the fusing process occurring in electrophotographic printing of paper (for both Infra-Reds fusing and hot roll fusing).

The key parameter to follow the spreading is called the spreading factor, SP, and is defined by:

$$SP=\frac{A}{A_0}-1 \tag{2}$$

where A is the projected area of the particle and the index $_0$ refer to the initial state.

Petterson and Fodgen [19] demonstrated that the spreading factor of four different toners at high temperature is related to the surface tension of the substrate. This spreading factor can take values from 1.5 to 8 depending on the toner and on the substrate. Moreover the rate of heating does not play a crucial role in the final state.

The goal is to study the spreading and the behaviour of toner particles structures in realistic condition. Therefore, a new way to characterize toner agglomeration will be introduced, following the evolution of the circularity.

The evolution of toner network was monitored in situ (see Fig.6). The toner samples were dispersed on a clean cover glass. The quantity of toner varies according to the network to be studied. Samples were put on the heating cell (Linkam THMS 600). For the experiment, a rate of 20°C, per minute was chosen. Nevertheless, the temperature on the glass is only proportional to the frame temperature. Moreover, there exists a delay before reaching equilibrium. A microscope equipped with a 20x-lens was used to see the spreading from above. On top of the microscope was a CCD (Nikon 2400) colour camera linked to an acquisition software (Optimas 6.5). The image analysis itself has been performed with the software imageJ. Images were binarised using an appropriate threshold.

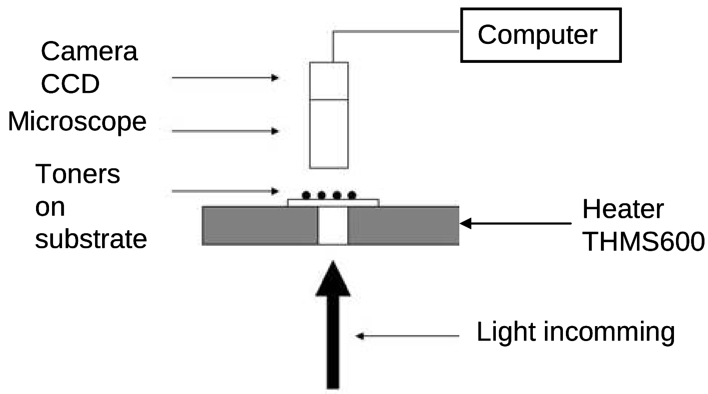

Figure 6: Experimental setup

Four different types of toners have been chosen: Cyan, Magenta, Yellow and Black, from a Xerox docucolor printer.

In order to characterize the particles, the size distribution was measured considering them as discs.

The mean diameters are 8.1µm (the standard deviation is 1.9µm) for yellow particles and 6.8µm (the standard deviation is 2.3µm), respectively for black particles.

3.2 Result analysis

The spreading of yellow toner particles has been studied according to the experimental method described above. A light initial density was chosen, around 4% (where the density is defined as the ratio of the surface of toner particles divided by the total surface). Moreover attention was focused on various areas. First the whole structure has been considered (Figure 7). Then a single particle (Figure 8) and a small network of three particles (Figure 10) were studied. Results are shown in Figure 9.

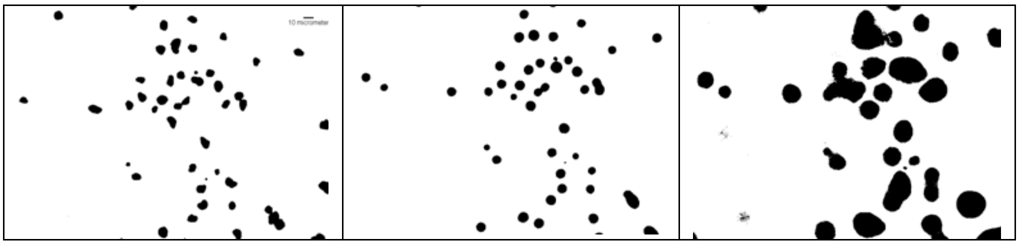

Figure 7: Projected area of light yellow toners network at three temperature (20, 170 and 220° C)

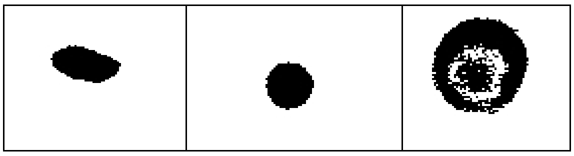

Figure 8: Spreading of individual toner yellow particle

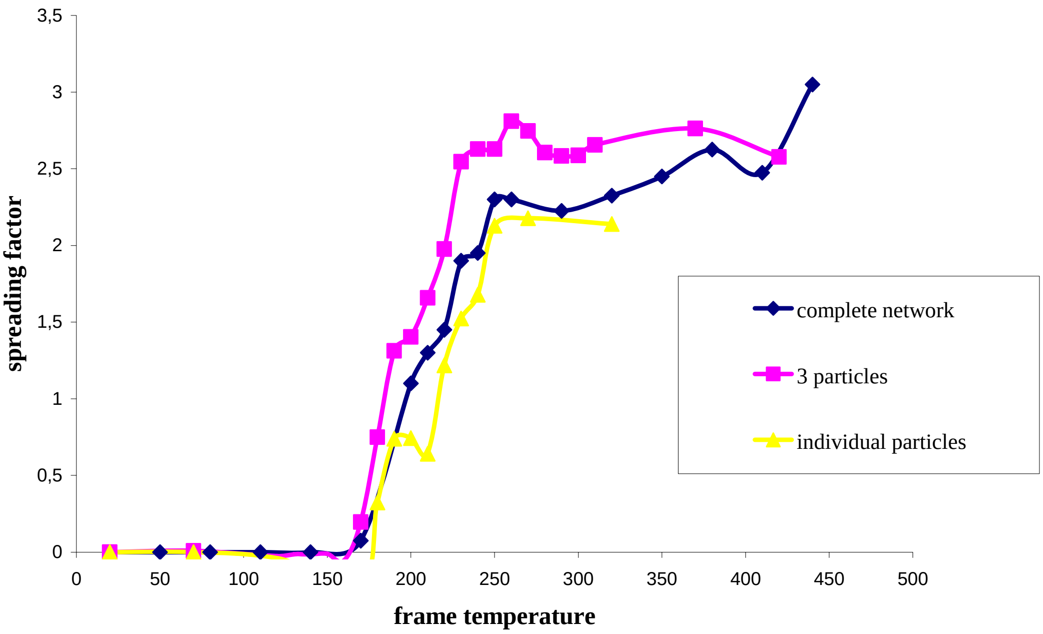

Figure 9: Spreading of various toner structures vs. the temperature of the metallic frame

As a matter of fact, there is a sharp increase for each curve between 200 and 250° C. A narrow range of temperatures induces a huge variation of spreading in this zone. That justifies and underlines the need for a control of the temperature field.

The study of the agglomeration of toner particles is tricky. From the Figures 7 and 8, there are obviously different steps occurring during toner melting. First the particles which have random shapes appear to be turning spherical without spreading. Then, thanks to the temperature increase, they begin to spread. In the case of high density of particles (close network), the growing of the independent toner particles can be obstructed by their neighbours. This agglomeration is followed by a rearrangement of the agglomerates. Eventually the system reaches equilibrium. This phenomenon is exhibited in Figure 10, considering only three particles:

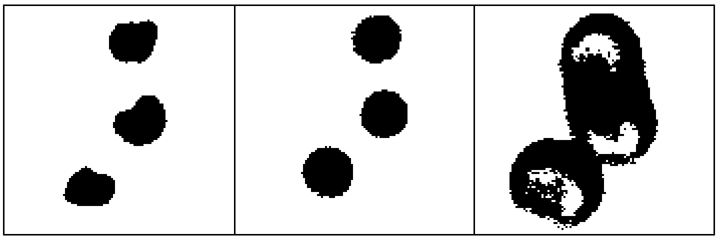

Figure 10: Binarised pictures of the agglomeration of toner particles (the temperature of the metallic frame are respectively, 20°, 170° and 220° degrees Celsius)

The experiments were done on glass which has a surface energy of 47 mJ/m^2 [20]. The cellulose which is the main constituent of the paper has a surface energy of 50 mJ/m^2 [21]. Depending on its surface treatment the paper surface energy varies from 25 to 60 mJ/m^2 [22] The surface energy of the substrate greatly influences the spreading of the toner [19]. Basically the higher this surface tension, the higher is spreading.

First, the evolution of the area of the projected surface of the toners has been studied (either individually or in network). However, it does not give any information on the rearrangement of the system. Therefore, variation of the average circularity of the particles constituting the system was introduced. The circularity c, is defined in Eq.8:

$$c = \frac{4a\pi}{p^2} \quad (3)$$

Where a and p represent the projected area of the object and the projected perimeter of the object, respectively. Under this definition a perfect circle has a circularity of 1, and a straight line is 0.

The same network of yellow particles has been analysed in order to get the evolution of the average circularity of the toners (Figure 11). The initial toner's density was 4% and it increases up to 16%.

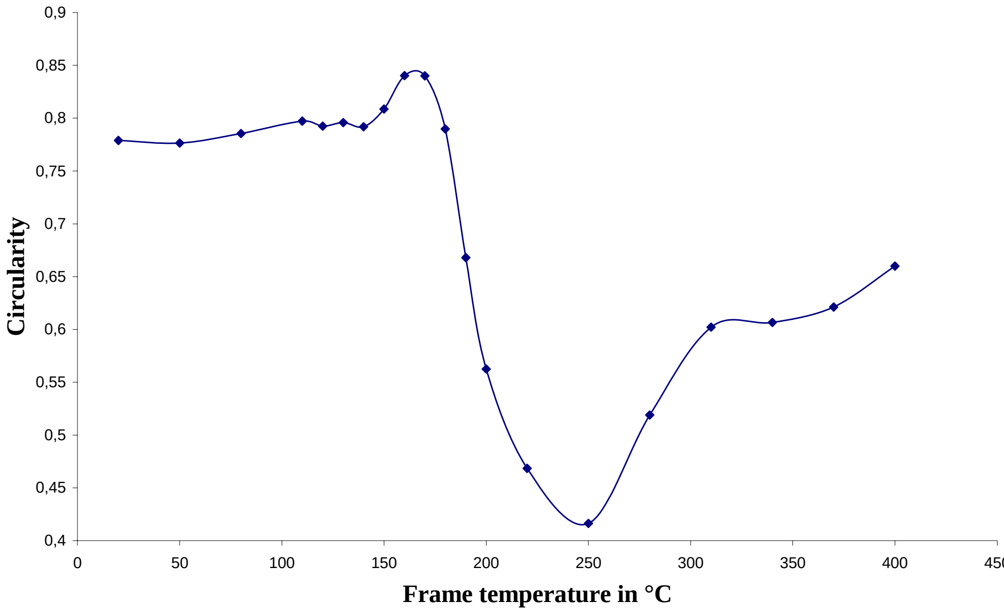

Figure 11: Average particle circularity evolution function of temperature of the metallic frame

From Figure 11 the three steps (rearrangement of the single toner, agglomeration, and rearrangement of the agglomerate) are clearly observed. Under 150°C, the particles are isolated from the others and their shape becomes more circular. Between 150° and 250°C, there is a dramatic decrease of the average circularity, due to the agglomeration of the toner particles. Finally the agglomerates spread and are barely transformed into spheres.

This experiment could be linked to the toner viscosity analysis at high temperature. Under 150°C, the particles are still solid and their viscosity tends to infinity. Then, they begin to spread, meaning a flow of melt polymer. At this point, the circularity evolution is expected to be related to the temperature dependency of the melted toner viscosity. Theoretical expressions of such a dependency can be found in the literature (namely the Eyring law or the WLF theory).
The roughness of the substrate has also to be taken into account to understand the toner agglomeration. Experiments were done on flat glass, but cellulosic substrate could own an important roughness. In fact the paper surface is composed of valleys and peaks. Hence the roughness may reduce the toner agglomeration by isolating particles.

4 Conclusion

Most of the optical and adhesive properties are related to this stage. The interaction of the toner and the paper depends on many parameters. Two methods for estimating the thermal field in the nip of an electrophotographic system device were compared. A 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. However, this method introduces complementary modeling possibilities. Hence, it was possible to relate the temperature reached in the nip at the different interfaces, considering the paper properties (heat conductivity and capacity, roughness and thickness).

This temperature was correlated to the coalescence and agglomeration of toner particles in the nip, by following their spreading. It confirmed that a good control of the temperature of the toner is needed. Indeed, the spreading of the toner structure is achieved for a narrow range of temperatures (between 200 and 250° Celsius).

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