Offset During Duplex Printing in Electrophotographic Systems

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Two-sided imaging in laser printers or electrophotographic copiers present design problems at the fusing stage. A typical fuser consists of a pair of counter-rotating rollers forming a nip, a heated roller on the side of the sheet having its image fused, and a pressure roller on the un-imaged or previously-imaged side of the sheet. Through a combination of heat and pressure in the nip, toner particles become viscous. The particles then meld with each other and adhere to the surface of the sheet. As this is happening, it is essential that a previously fused image on the opposite side of the sheet not lose its adherence to the sheet and "offset" to the pressure roller. This article describes the use of an approximate finite-difference numerical model that can be used to predict temperatures in the nip and, consequently, allow the designer to assess the possibility of damage to the opposite-side image. Parameters investigated include toner thickness on both sides of the imaged sheet, sheet thickness and the temperatures of the rollers and sheet.

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Introduction

A desirable feature in electrophotographic (EP) or laser printing is the ability to produce two-sided prints. It is further desirable that the two sides or images have the same print quality: gloss, density, no unwanted markings, etc. Printing one side of a sheet is done through a series of four steps:

(1) electrostatic image development,
(2) toner image development,
(3) electrostatic transfer of toner image to the sheet, and
(4) fusing.[1]

A two-sided print is made by printing one side of a sheet then repeating the process on the second side. As a naming convention in this article, the "simplex image" is the image placed on the sheet first and the "duplex image" is the second image placed.

When printing the duplex image, the main difference from the simplex image printing is the presence of the simplex image on the sheet. This can affect steps (3) and (4) in the electrophotographic printing process (see above). In this article, the focus is on the final step—fusing. By modeling the heat transfer in the nip, an insight on how the duplex image may be fused without degradation to the simplex image is obtained.

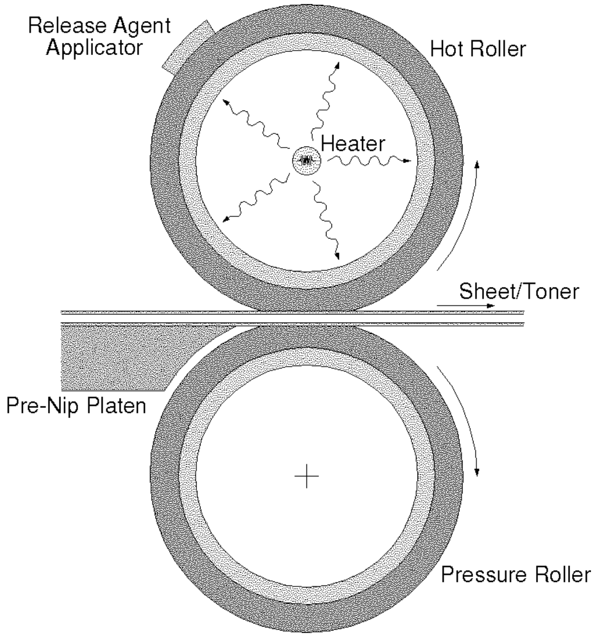

Figure 1. Hot Roll Fuser

Fusing Process and Apparatus

Fusing is the process of heating powder toner for the toner to bond with the sheet and itself. Heating allows the toner to become viscous and in turn flow into the sheet and coalesce. The toner becomes viscous when the temperature of the toner is above the "glass transition temperature." There are several different fusing methods. The most common method is hot roll fusing. Hot roll fusing consists of two rollers and a heat source as shown in Fig. 1. Other design elements include a pre-nip platen and a release agent applicator. In general, both the hot and pressure rollers have a metal core with a thermally stable rubber coating. The area of contact between the rollers caused by the deformation of the rubber is called the "nip." The difference between the hot and pressure rollers is that the hot roller contains

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Table I. Thermal Properties and Physical Dimensions

Material	Specific Heat Per Unit Volume 10^6 J/m^{3}K	Thermal Conductivity W/mK	Thickness μm
Silicon Rubber[4]	1.53	0.151	1,000
Fusing Toner[5]	Nonlinear	Nonlinear	0–40
Paper (Dry)[5,6]	1.59	0.110	60–160
Fused Toner[7]	1.70	0.600	10–40
Powder Toner[7]	1.04	0.106	

the active heat source for fusing. The pressure roller, with no direct heat source, acquires heats through the nip. This can become significant in a color process with a long processing time. Measurements of pressure roller temperature on a Tektronix Phaser 550 show that the pressure roller achieves a steady state temperature of 130–135°C in color print mode. For comparison, the same printer achieves a steady state temperature of only 105–110°C in monochrome print mode.

The pre-nip platen also plays a roll in the fusing process. The primary purpose of the platen is to guide the media into the roller nip. However, Prime[2] showed that the pre-nip platen, if heated, could accelerate fusing. Some amount of temperature rise will occur in the pre-nip due to its proximity to the hot roller. Therefore, the fusing process may begin even before the sheet enters the fuser.

A release agent applicator is in the fusing system to prevent a set of failures known as "offset."[3] At the end of the nip the still-viscous toner will experience a level of adhesion with the hot roller. If the adhesive force is too great, three forms of offset failure may occur:
(1) cold offset
(2) hot offset, or
(3) media wrap.

Cold offset is the result of the nip temperature being too low for complete fusing, thus leading to poor adhesion between the toner and sheet. Hot offset occurs when the toner's adhesion to the hot roller is greater than the adhesion to the sheet or greater than the cohesive force with in the toner. This leads to the image being pulled at least partially from the sheet at the end of the fuser nip. Media wrap occurs when the sheet's stiffness is too low to prevent the sheet from bending around the hot roller at the end of the fuser nip. A release agent added to the hot roll fusing process though a thin liquid coating of the hot roller will help prevent offset.

Defects During Duplex Image Printing

Fusing the duplex image complicates the fusing process over fusing of the simplex image because of the possibility of reaching the glass transition temperature within the simplex image and incomplete fusing of the duplex image. Passing the glass transition temperature within the simplex image is not a negative feature unless it occurs at the interface of the simplex image and the pressure roller. If the simplex image-pressure roller interface reaches the glass transition temperature, hot offset or media wrap can occur. To prevent offset and fully understand the process by which the simplex image-pressure roller interface reaches the glass transition temperature requires a heat conduction model of the nip under duplex fusing conditions or else experimental data.

Reaching the glass transition temperature in the simplex image-pressure roller interface is not the only concern. The duplex image may have unacceptable fusing quality. Prime's experiments[2] show the relationship of dwell time and nip pressure to fusing quality, but stop short of investigating the effects of media variation and duplex printing. To understand the effects of duplex printing and media thickness variation on the duplex image fusing quality requires an analytical solution or experimental data.

To limit the scope of this article, only the mechanisms causing offset defects on the simplex image-pressure roller interface are investigated using analytical methods. There is no open literature on offset of the simplex image during duplex fusing at this time.

Modeling

The purpose of an analytical model for the offset of the simplex image during duplex printing is to predict the hottest temperature on the interface of the simplex image-pressure roller interface. This will occur at the end of the nip. The simplex image-pressure roller interface at the end of the nip is defined as the "release point". The temperature at the release point—specifically a temperature greater than the glass transition temperature—is an indicator of when offset failure will occur. This section develops an approximate heat conduction model of the fusing nip. The model will then be used to study release point temperature as a function of sheet thickness, toner thickness and the pre-nip pressure roller temperature.

Thermal Properties

This section discusses the thermal properties of the various materials in the fusing model. The thermal properties include the specific heat per unit volume and the thermal conductivity.

Rubber. Material properties and relative insensitivity to environmental changes govern the selection of the rubber coatings of the hot and pressure rollers. Typical rubbers used are silicon rubber or a fluoroelastomer. These materials typically exhibit constant thermal properties over the operating temperature range of a hot roll fuser system. The model uses published values for the thermal properties of silicon rubber as shown in Table I.

Toner. The model requires the investigation of the thermal properties of toner for both the fused toner in the simplex image and the fusing toner in the duplex image. The simplex image is assumed to be below the glass transition temperature and that it has homogeneous properties with no inclusions from carrier beads, dirt, air, etc. This allows for the use of constant thermal properties of solid toner for the simplex image. The model uses the published values for black toner presented in Table I.

During fusing, the toner in the duplex image undergoes a transition a particulate amalgam to a uniform visco-elastic layer. Clearly, this will give variable thermal properties, and Mitsuya and co-workers[5] further showed that these properties are nonlinear with temperature. The specific heat and thermal conductivity of the duplex image fundamentally change from the powder toner values to the fused toner values while passing through the fusing nip (see Table I). Currently, there is no model available for this nonlinear transition in a hot roll fuser. To conservatively estimate the simplex image-pressure roller interface temperature response to duplex toner, it is assumed that the duplex image is at its most conductive state—fused—entering the nip.

Media. There are extreme amounts of variability in the sheet that an operator can use, as becomes clear at any large office supply store or print shop. To bring this variation to a manageable level, only paper is modeled. Paper, due to its complex structure, absorbs water from the environment, as much as 10% by weight.[1] The moisture adds the complication of evaporation to the fusing system.

Reviewing the duplex process, the simplex image fusing removes most of the moisture. Assuming an automatic document feed system processing the duplex image immediately after the simplex image, little time will pass before the duplex fusing will take place. In the Tektronix Phaser 740 printer, the automatic document feed delay is about 15 seconds for color printing.[8] With the rate that the moisture enters paper, 15–30 min for a single sheet to reach equilibrium,[9] a sheet will absorb negligible amounts of water in those 15 sec. The lack of moisture in the paper during the duplex image fusing, allows for the use of the properties of dry paper in the model, Table I. The source[5] providing these values does not elaborate on the specifics of the paper; recycled, cotton, wood, etc.

Physical Properties

The thickness of the toner and paper is determined by the desired images (front and back) and by the “weight” of paper chosen by operator of the printer. Using “weight” to denote paper thickness is a colloquial expression from the pulp and paper industry. The weight of 500 sheets measuring 17 inches wide and 22 inches long (432 mm × 559 mm) gives the connection to sheet thickness. Paper used in copiers and laser printers typically have a “weight” falling between 16 and 32 lbs (60–120 g/cm^2). Above 32 lbs. the sheet is generally regarded as “card stock” and is too thick and stiff for most office printers. The investigation focuses on the 16 to 32 pound range. The thickness of any “weight” paper will vary with density, but the thickness range given in Table I shows the variation within the 16 to 32 lb. range.

The toner layer thickness varies with operator’s desired image, especially when the image is in color. Each of the nine possible color combinations has a characteristic thickness. During the image accumulation step in the color EP process, the component colors are layered on top of one another combining to form the total thickness.[10] For example, layering yellow and magenta toner forms the composite color red. The toner thickness of a red area will be the sum of the yellow and magenta toner thickness. The toner thickness range given in Table I is from thickness measurements on various color prints from a Tektronix Phaser 550.

Beyond the dimensions listed in Table I, two other parameters are in the model, nip velocity and nip width. These values link through dwell time,[1]

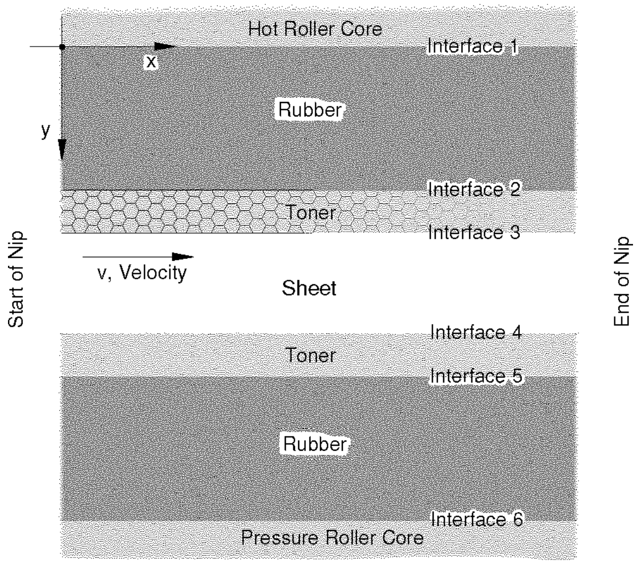

Figure 2. Fuser Model

$$\text{Nip Width} = (\text{Nip Velocity})\,(\text{Dwell Time}). \quad (1)$$

Dwell times in the range of 18–23 ms have been considered by other authors.[4,11] Measurement of the nip dimensions from a Tektronix Phaser 550 verifies the appropriateness of this range in color printing. The Phaser 550 has a dwell time of about 21 ms from a nip width of about 2 mm and a nip velocity of 0.095 m/s. The example results below use a 20ms dwell time.

Governing Equation

Previous attempts to model the temperature profile in the fusing nip under one sided printing have used a transient model with one-dimensional conduction perpendicular to the plane of the nip.[4] The one-dimensional model produces errors of 10–20°C from ignoring conduction and convection parallel to the nip plane. It was suggested in the earlier work that a two-dimensional model might be more appropriate. With this in mind, the fusing system is modeled as a steady-state two-dimensional system with a moving medium, see Fig. 2.

Modeling in two dimensions as shown in Fig. 2, assumes that conduction parallel to the axis of the rollers is negligible. As depicted in Fig. 2, the nip shape is approximated as flat. The nip shape will be slightly curved due to variation in the durometer and thickness of the rubber coatings. However, it is believed that the flat nip approximation is acceptable provided the defection in the y direction is much smaller than the nip width.

The partial differential equation for two-dimensional heat conduction with variable material properties and motion in the x direction is[12]

$$uC_p \frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right). \quad (2)$$

where u is the nip velocity, C_p is the specific heat per unit volume, k is the thermal conductivity, and T is temperature.

Boundary Conditions. Each of the materials in the fusing nip requires four boundary conditions, two in the x direction and two in the y direction. The two x direction boundary conditions come from assuming complete knowledge of the temperatures of the fusing materials—paper, toner and rollers, ahead of the fusing nip. Mathematically this equates to

$$T(x,y) = \Omega(x,y) = \text{a known function for } x \le 0. \quad (3)$$

Therefore, at the start of the nip, $x = 0$, the temperature and temperature gradient of the material entering the nip are

$$T(0,y) = \Omega(0,y) \quad (4)$$

and

$$\frac{\partial T(0,y)}{\partial x} = \frac{\partial \Omega(0,y)}{\partial x}. \quad (5)$$

These equations give the two required boundary conditions in the x direction. In this case both are at the start of the nip, $x = 0$.

For this modeling, the temperature function $\Omega(x, y)$ is approximated by the stepwise constant profile

$$\Omega(x,y) = \begin{cases} T_h = \text{constant for hot roller} \\ T_{dup} = \text{constant for duplex image} \\ T_m = \text{constant for the sheet} \\ T_{simp} = \text{constant for simplex image} \\ T_p = \text{constant for pressure roller} \end{cases}. \quad (6)$$

Specifying the function $\Omega(x, y)$ in this manner gives a similar boundary condition as used in the previous simplex printing work.[4] Applying Eq. 6 to the x direction boundary conditions, Eqs. 4 and 5 gives

$$T(0,y) = \begin{cases} T_h = \text{Interface } 1 \le y < \text{Interface } 2 \\ T_{dup} = \text{Interface } 2 \le y < \text{Interface } 3 \\ T_m = \text{Interface } 3 \le y < \text{Interface } 4 \\ T_{simp} = \text{Interface } 4 \le y < \text{Interface } 5 \\ T_p = \text{Interface } 5 \le y < \text{Interface } 6 \end{cases}, \quad (7)$$

and

$$\frac{\partial T(0,y)}{\partial x} = 0. \quad (8)$$

This temperature function, $\Omega(x, y)$ neglects a certain amount of heat conduction that would come from the actual non-zero temperature gradients at the start of the nip. The diffusive nature of Eq. 2, which governs the heat conduction, tends to minimize the transmission of errors over time and distance. With the end of the nip being approximately twenty paper-thicknesses away from the start of the nip, the error from the ignored temperature gradients at the start of the nip will have little consequence at the end of the nip.

An additional assumption about the toner layers is that they enter the nip at the same temperature as the sheet,

$$T_{dup} = T_{simp} = T_m \quad (9)$$

The toner layers have a thermal conductivity approximately 6 times that of paper and a thickness of about one-third that of paper per Table I. This physical information on the toner layers combined with the fact that toner layers and paper are in contact prior to the fusing nip makes the toner layer temperature assumption appropriate.

In the y direction, an energy conservation boundary condition is used for Interfaces 2 through 5 in Fig. 2,

$$k\left(\frac{\partial T(x,y@\text{Interface})}{\partial y}\right)_{\text{Material 1}} + k\left(\frac{\partial T(x,y@\text{Interface})}{\partial y}\right)_{\text{Material 2}} = 0. \quad (10)$$

Kuo[11] showed the appropriateness of this type of boundary condition for interfaces with rubber rollers, Interfaces 2 and 5. At the simplex toner–paper interface, Interface 4, the energy conservation boundary condition is appropriate due to the penetration of the toner into the media during the simplex image fusing. The duplex toner–paper interface, Interface 3, does not perfectly fit the energy conservation boundary condition as shown in Eq. 11. This is a result of the duplex image transitioning from a powder to a solid through the general fusing process. Using Eq. 11 at Interface 3 will allow more heat to pass through the interface and induce an increased temperature over Interface 5. Therefore, design choices based on the assumed boundary condition on Interface 3 will provide a "conservative" margin of safety against the occurrence of offset from the simplex image.

Only the two interfaces with the roller cores still require boundary conditions, Interface 1 and 6. The boundary conditions at Interface 1 and 6 are set as a constant prescribed temperature equal to the respective roller's start of nip temperature,

$$T(x,y\ @\ \text{interface } 1) = T_h \quad (11)$$

and

$$T(x,y\ @\ \text{interface } 6) = T_p. \quad (12)$$

These equations assume that the roller cores are sufficiently massive so that the temperature variation is negligible through the nip and/or that an active control system is maintaining the temperature.

Normalization of Temperature. All gauge temperatures are referenced with respect to the temperature of the pre-nip paper and toner. The hot roller gauge temperature then provides a base for the non-dimensionalization,

$$\theta = \frac{T - T_m}{T_h - T_m}. \quad (13)$$

Non-dimensionalizing in this manner reduces the problem to only one input temperature specification—the non-dimensional pressure-roller temperature, θ_p. A value of $\theta_p = 0\%$ indicates that the pressure roller has the same temperature as the entering sheet. A value of $\theta_p = 100\%$ indicates that the pressure roller has the same

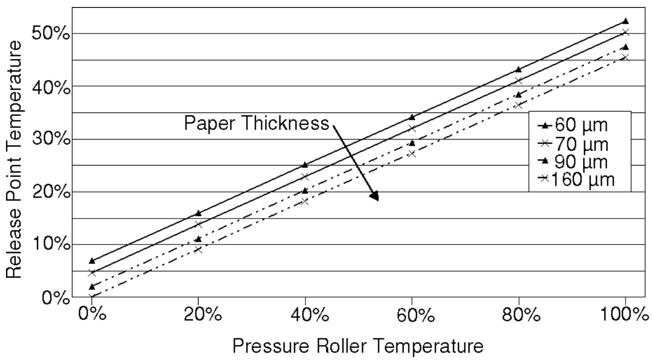

Figure 3. Release Point Temperature versus Pressure Roller Temperature

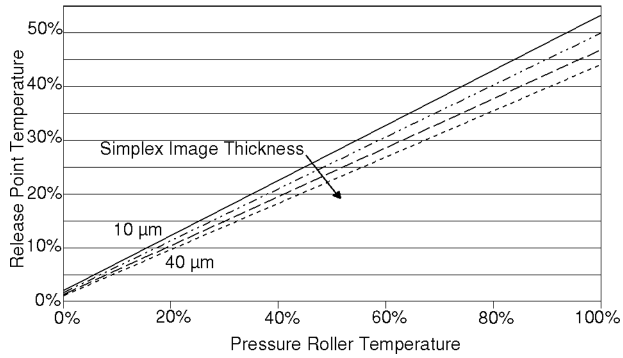

Figure 5. Release Point Temperature versus Pressure Roller Temperature for Various Simplex Image Thicknesses

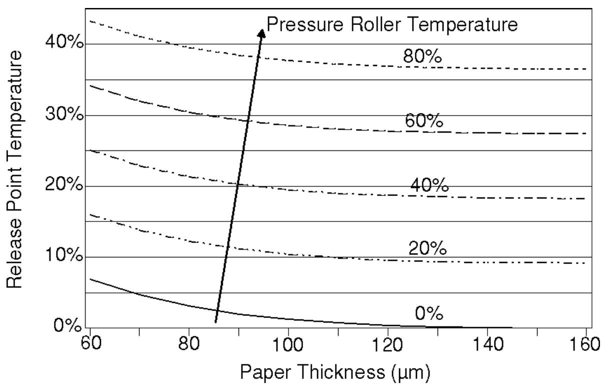

Figure 4. Release Point Temperature versus Paper Thickness

temperature as the hot roller. The resulting partial differential equation for the system with non-dimensional temperatures is

$$uC_p \frac{\partial \theta}{\partial x} = \frac{\partial}{\partial x}\left(k \frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial \theta}{\partial y}\right). \quad (14)$$

The set of boundary conditions with non-dimensional temperature is

$$\theta(0, y) = \begin{cases} 100\% = \text{Interface } 1 \le y < \text{Interface } 2 \\ 0\% = \text{Interface } 2 \le y < \text{Interface } 3 \\ 0\% = \text{Interface } 3 \le y < \text{Interface } 4 \\ 0\% = \text{Interface } 4 \le y < \text{Interface } 5 \\ \theta_p = \text{Interface } 5 \le y < \text{Interface } 6 \end{cases}, \quad (15)$$

$$\frac{\partial \theta(0, y)}{\partial x} = 0, \quad (16)$$

$$k\left(\frac{\partial \theta(x, y @ \text{Interface})}{\partial y}\right)_{\text{Material 1}} + k\left(\frac{\partial \theta(x, y @ \text{Interface})}{\partial y}\right)_{\text{Material 2}} = 0, \quad (17)$$

$$\theta(x,y @ \text{interface } 1) = 100\%, \quad (18)$$

and

$$\theta(x,y @ \text{interface } 6) = \theta_p. \quad (19)$$

Solution Approach

Due to the amount of variability on physical dimensions and number of different materials in the system, the numerical finite difference approach provides the desired solution method. Menzel[13] provides details on the formulation of the finite difference model.

Results

The temperature at the release point, the end of the nip on the simplex image-pressure roller interface, is used to determine whether offset will occur, Fig. 2. There are four specifications in the model for which a range is defined:

- Non-dimensional pressure roller temperature, 0%–100%
- Paper thickness, 60–160 µm
- Simplex image thickness, 10–40 µm
- Duplex image thickness, 0–40 µm

These will be analyzed, in turn, for their influence on offset.

Simulation Data

The first input specification to be assessed is the pressure roller temperature. Figure 3 shows how the release point temperature varies with pressure roller temperature for several papers thickness. Pressure roller temperature variation shows a linear dependence on the release point temperature. As paper thickness varies, the linear relationship remains with essentially no change in slope. This shows that the paper thickness and pressure roller temperature independently affect the temperature at the release point.

Figure 4 presents the same data as Fig. 3, but this time plotted using the paper thickness as the horizontal axis. The independent influences from paper thickness and pressure roller temperature are again seen. The interface temperature varies exponentially with paper thickness, with the thicker paper producing the lower temperatures. This intuitively makes sense as the thinner paper will have less thermal mass and will allow faster heating of the simplex image.

Figure 5 shows the release point temperature as a function of the pressure roller temperature. Results for four different simplex image thicknesses are plotted. The

Table II. Effects of Duplex Toner on the Release Point Temperature

	Extremes of Variation							
	A	B	C	D	E	F	G	H
Simplex Image Thickness (μm)	10	10	10	10	40	40	40	40
Non-dim. Pressure Roller Temp.	0%	0%	100%	100%	0%	0%	100%	100%
Paper Thickness (μm)	60	160	60	160	60	160	60	160
Duplex Image Thickness (μm)	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
0	9.997%	0.081%	61.242%	51.395%	5.781%	0.031%	48.883%	43.142%
10	8.198%	0.056%	59.380%	51.370%	4.646%	0.021%	47.730%	43.132%
20	6.764%	0.040%	57.896%	51.354%	3.759%	0.015%	46.833%	43.126%
30	5.600%	0.029%	56.703%	51.343%	3.056%	0.011%	46.126%	43.121%
40	4.646%	0.021%	55.731%	51.335%	2.492%	0.008%	45.559%	43.118%

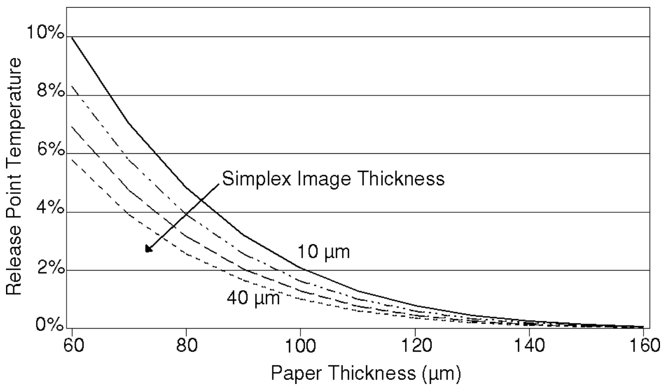

Figure 6. Release Point Temperature versus Paper Thickness for Various Simplex Image Thicknesses

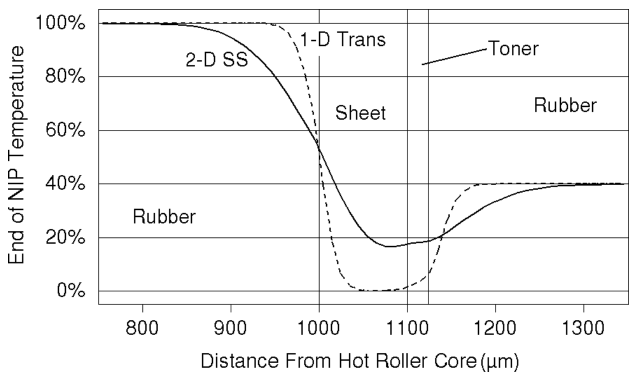

Figure 7. 1-D Transient Model versus 2-D Steady State Model

release point temperature is again seen to depend linearly on the pressure roller temperature. The slopes of these curves increase as the simplex image thickness is decreased. In other words, the release point temperature becomes more sensitive to the pressure roller temperature as the thermal mass of the simplex image is decreased.

Figure 6 shows the release point temperature as a function of the paper thickness. Four different simplex image thicknesses are shown. The release point temperature becomes more sensitive to sheet thickness as the thermal mass of the simplex image is decreased.

Table II gives the effect of the duplex image on the eight conditions defined by the extremes of the variation on paper thickness, simplex image thickness, and pressure roller temperature. In all cases, the addition of the duplex image reduces the release point temperature. Table II also shows that there is little sensitivity to duplex image thickness variation with thick paper against the release point temperature.

The combined results show that the non-dimensional pressure roller temperature is the most important variable affecting the release point temperature. This is an important result because non-dimensional pressure roller temperature is one of only two parameters that are controlled by the designer; dwell time is the other. This gives guidance on how to design a fuser that will not produce offset defects from the simplex image-pressure roller interface.

The variables controlled by the operator are nevertheless important, as the fuser design must be robust enough to handle the operator-induced variation. Of the operator-controlled variables, the paper thickness variation produces the greatest change in the release point temperature. This result may not be as critical as the variation that might be seen from changes in the thermal properties of the media. Further evaluation of the thermal properties of media is needed to understand if the variation is significant.

One-Dimensional Transient versus Two-Dimensional Steady State

The two-dimensional steady-state model of the present article was compared to a one-dimensional transient model of the sort used by Mitsuya and co-workers.[4]

$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y} \right) \qquad (20)$$

using the same initial conditions and boundary conditions. A finite difference numerical solution was used for both models. Figure 7 depicts the two temperature profiles along a line perpendicular to the plane of the nip and passing through the release point at the nip exit. In the region of 900–1000 μm, the approximate measurement point of the earlier work, the error in temperature between the two models is similar to the error previously shown between the one-dimensional transient model and experimental data.[4]

Conclusions

The investigation has developed a two-dimensional steady state finite difference model of a hot roll-fusing nip for the analysis of offset onto the pressure roller during duplex printing. The investigation used published material properties; limited the media to smooth paper; and evaluated a limited range on the pressure roller temperature. This will obviously not represent all fusing systems or fusing materials. To evaluate other fuser systems, the geometrical specifications and material properties required in our model would have to be determined.

The example results given here are useful for revealing the likelihood of offset due to the values of the pressure roller temperature, the paper thickness and the simplex image thickness. The results suggest that the designer's best approach to preventing offset in the simplex image is by controlling the pressure roller temperature. Another change is to lower the sheet temperature or hot roll temperature therefore raising the offset temperature. Lowering the sheet temperature would also require the reduction of pre-nip platen heating of the sheet. Adjusting the hot roller temperature for increased non-dimensional offset temperature could degrade the duplex image fuse quality. Any change to the hot roller temperature requires careful evaluation of fusing quality.

In summary, any design change that reduces the chance of simplex image offset may produce duplex image fusing quality issues. It is believed a design window will develop from the investigation of duplex image fusing quality and the data presented in this article. This topic is left for future research.

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