

Modeling of Heat Transfer Phenomena with Air Existing in Fusing Region

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Abstract

Computational treatment of the effects of air existing in a nip region is studied for accurate temperature estimation during toner fusing process in electrophotographic printers. Thermal resistance of the existing air in paper surface roughness and between toner particles is evaluated and thermally equivalent air layer with uniform thickness is introduced based on the amount of the air. Four models are proposed to discuss an adequate setting position of the air layer in a computational region. Toner surface temperatures estimated by the models are compared with measured ones during fusing process. It is clarified that the estimated temperature shows a good agreement with the measured ones with the following two models: 1) The air layer based on paper surface roughness is positioned at toner-roller interface and that based on the toner particles arrangement is in the midst of toner layer. 2) The air layer based on paper surface roughness is the same position with model 1) and the toner is treated as a porous uniformly including air. The above two models are applied to another two kinds of print media with different surface roughness, offering good estimations. The results confirm the usefulness of the treatment of existing air for temperature estimation during fusing process. Effects of toner particle sizes for color printing on the temperature field are also discussed with the estimating calculation. It is expected that the smaller size of toner particles offers an improvement of fuse quality for high-speed color printing with lower energy consumption.

Introduction

Higher-speed printing has been required to electrophotographic printers with higher print quality and lower energy consumption. The print quality is determined during the fusing process and strongly affected by thermal and pressure conditions in the nip region between heat and pressure rollers. One of the measures to the requirement concerning with the high-speed printing is supplying a larger heat flux to the toner fusing region, while excessive heat supply however shorten a fuser lifetime.

A method for optimizing fuser parameters is thus necessary to overcome the conflict, method which offers a good estimation of temperature filed in the nip region and final fuse quality, as measurement of the temperature is difficult due to small dimensions of the nip region.[1]

The authors have proposed a method [2] for evaluating a magnitude of the thermal resistance of the existing air and reducing it to a uniform air layer thermally equivalent to the air, an adequate setting position of the air layer in a computational region has however remained to be discussed.

In this study, several layer-setting models for numerical estimation will be proposed and adequate models discussed by comparing the estimated results with the measured ones. It will be further discussed the effects of toner particle size on color print quality in high-speed printing.

Thermal Resistance of Existing Air in Nip

A certain amount of air exists in the nip region as illustrated in Fig.1, which strongly affects the temperature field during the toner fusing process due to its much smaller thermal conductivity than those of toner material, paper and fuser members. Since the amount of air depends on toner dimension, layer arrangement of toner particles and surface roughness of the paper, a precise estimation of those has been carried out based on their geometrical configurations in the previous report [3].

By modeling the toner arrangement deposited on the paper as a two-storied hexagonal closed packed lattice, thermally equivalent thickness of air layer was evaluated.[3] For toner particles with the mean size, $\overline{d}$, of 7.6 μm, the thickness and void fraction of the toner layer, δ_t^* and ε_t, were 13.8 μm and 0.334, respectively.[3] Based on the properties, the thickness of thermally equivalent air layer, δ_{at} and that of bulk toner, δ_t, were determined as 4.6 μm and 9.2 μm, respectively.[3]

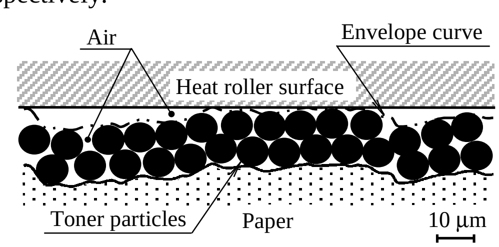

Figure 1. Schematic of air existing in the nip region

The same treatment is also carried out for determining thermal resistance of air existing in paper surface roughness. Geometrical properties of surface roughness are measured by using a contact profile meter on a paper for color print (paper A, 100 μm in thickness) with isotropic texture.[3] The results showed that the maximum height of the surface roughness, R_y, was 12.5 μm and the three-dimensionally calculated void fraction of the paper surface, ε_p, was 0.46.[3] Based on the evaluations, the thickness of thermally equivalent air layer, δ_{ap}, and that of smooth paper, δ_p, were evaluated 5.7 μm and 88.4 μm, respectively.[3]

Computational Models and Estimated Results

Setting Position of Air Layers in Computational Region

Since the air existing in the nip region significantly affects the heat transfer phenomena during the toner fusing, the thermally equivalent air layer evaluated in the previous chapter should be introduced into an adequate setting position in the computational region. By considering the state of the nip region illustrated in Fig.1, four setting models are proposed as shown in Fig. 2. In Model 1, the air layers based on both toner particle arrangement and paper surface roughness are together positioned at the toner-roller interface. Model 2 arranges the air in paper surface roughness at the toner-roller interface with considering the state illustrated in Fig.1 and that between toner particles in the midst of toner layer. In Model 3, the air layer based on paper surface roughness is set in the same position with Model 2 and the toner layer is treated as a porous including air. Model 4 is the one, in which the air existing in the nip region is neglected for comparison with the other air including models. The thickness of the layers composing these computational models is listed in Table 1.

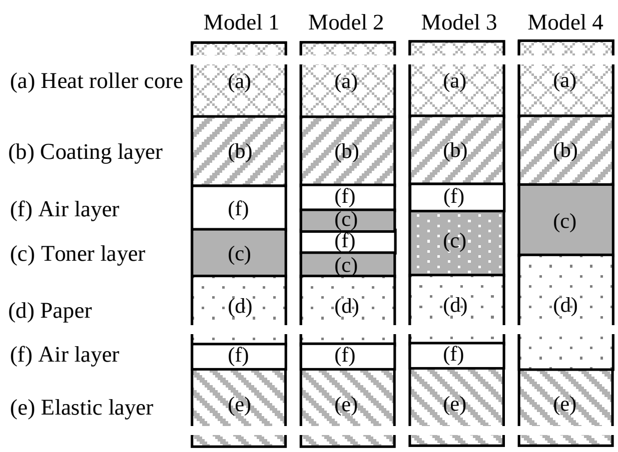

Figure 2. Layer construction models for numerical estimation

Table 1. Layer Thickness in Calculation

Layer	Model 1 δ [μm]	Model 2 δ [μm]	Model 3 δ [μm]	Model 4 δ [μm]
Heat roller core	1500	1500	1500	1500
Coating layer	30	30	30	30
Equivalent air layer	10.3	5.7	5.7	—
Toner layer (*porous)	9.2	4.6	*13.8	13.8
Equivalent air layer	—	4.6	—	—
Toner layer	—	4.6	—	—
Paper	88.6	79.4	79.4	100
Equivalent air layer	5.7	5.7	5.7	—
Elastic layer	200	200	200	200

Numerical Method

For the temperature changes during the fusing process in two-dimensional heat transfer field illustrated in Fig. 3, the governing equation is

$$\rho c \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial \theta}{\partial y} \right) \quad (1)$$

where θ is the temperature, ρ is the density, c is the specific heat and λ is the thermal conductivity. Equation 1 is discretized on a rectangular grid system and solved by the alternating direction implicit (ADI) method in the region illustrated in Fig.2, in which vectors of heat flux are defined on the boundaries of each cell and scalars of temperature at the center of that. For a simple treatment of the transferring filed of the nip elements, a calculating method[2] has been proposed on the fixed computational grid system.

Boundary conditions to the region are given as constant heat flux spilled on the inner surface of the heat roller core (y=0), q_h, and adiabatic on the remaining three boundaries.

Results and Discussion

Figure 4 shows the estimated results of temperature changes on the toner surface through the nip region with the Model 1, 2, 3 and 4. The initial temperature, θ_0,, properties of the layers and the fusing parameters are listed in Table 2 and 3, respectively. In the calculation, paper surface uniformly deposited by toner and a sudden contact of the heat roller, the paper and the pressure roller just at the start of the calculation are presumed.

Plotted in the figure by solid circle is the toner surface temperature[2] measured by an infrared radiation thermometer just behind the nip outlet varying fusing speed, v, in the range listed in Table 4. In the experiment, toner (melting

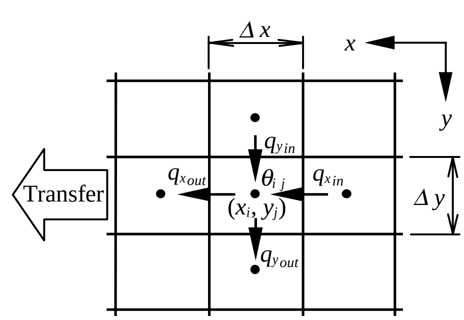

Figure 3. Two-dimensional heat conduction in the transferring field

point, θ_m, of 125°C) is deposited uniformly on the whole surface of the paper corresponding to the state in the estimating calculation.

Compared with the measured temperature changes, the estimated results offer good agreements by both Model 2 and 3. The estimation by Model 1 shows lower temperature than the measured one, while that of Model 4 gives higher one. The discrepancies between these estimated results indicate the importance of both appropriate positioning for introducing the equivalent air layers and the precise evaluation of the thermal resistance.

Model 2 and 3, both of which offer good estimations of the temperature field, are applied to another two kinds of print media with different surface roughness, paper B and C. Geometrical properties of the two papers, the maximum height of profile, R_y, the void fraction of the paper surface, ε_p, the thickness of thermally equivalent air layer, δ_{at}, and that of smooth paper, δ_t, are obtained in the same manner for paper A and listed in Table 5. While both of the papers are 100 μm in thickness, the surface of paper B is sufficiently smooth to be regarded as completely flat and the paper C has two times deeper roughness than that of paper A. Table 6 shows the thickness of each layer of Model 2 and 3 in the calculation.

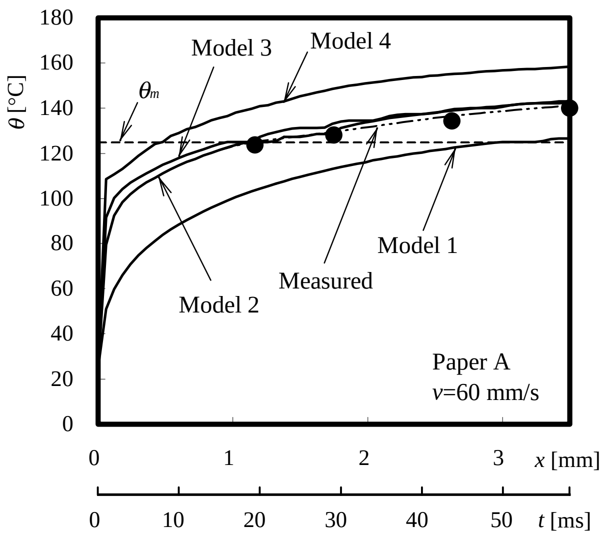

Figure 4. Comparison between measurements and estimations

Table 2. Initial Temperature and Thermal Properties

Layer	θ_0 [°C]	λ [W/(m°C)]	ρc [MJ/(m^3°C)]
Heat roller core	180	228.6	2.50
Coating layer	180	0.181	1.64
Toner layer (bulk) (porous)	25	0.151 0.065	1.51
Paper (A, C) (B)	25	0.080 0.141	1.16 1.88
Elastic layer	25	0.281	2.01
Equivalent air layer	25	0.030	0.0012

Table 3. Fusing Parameters in Calculation

Parameter	Value
Nip region w [μm]	3.5
Fusing speed v [mm/s]	60.0
Heat flux from heater q_h [kW/m^2]	34.0

Table 4. Measured Toner Surface Temp. vs. Nip Period

Fusing speed v [mm/s]	60.0	80.0	120.0	180.0
Nip period t [ms]	58.3	48.3	29.2	19.4
Toner surface temp. θ [°C]	140.0	134.3	128.1	123.7

In Table 7, the estimated toner surface temperature at the nip outlet is compared with the measured one for each paper. Each of estimations shows a good agreement with that obtained in the experiment. These good agreements also certify the availability of the estimating method of the temperature field during the fusing process.

The above results together confirm that the proposed models, Model 2 and 3, are useful for introducing the thermal resistance by air in the nip region determined based on the geometrical properties of the paper surface roughness and toner particles.

Effects of Toner Particle Size on High-Speed Color Printing

The thickness of the toner layer for color printing is thicker due to the amount of toner particles multi-layered on the paper. Effects of the toner particle size on the fuse

Table 5. Roughness Properties and Air Layer Thickness

Type	R_y [μm]	ε_p [−]	δ_{ap} [μm]	δ_p [μm]
Paper A	12.5	0.459	5.7	88.4
Paper B	0.2	—	0	100
Paper C	20.5	0.502	10.3	79.4

Table 6. Layer Thickness for Paper B and C in Calculatio

Layer	δ [μm] (Paper B)		δ [μm] (Paper C)	
	Model 2	Model 3	Model 2	Model 3
Heat roller core	1500	1500	1500	1500
Coating layer	30	30	30	30
Equivalent air layer	0	0	10.3	10.3
Toner layer (*porous)	4.6	*13.8	4.6	*13.8
Equivalent air layer	4.6	—	4.6	—
Toner layer	4.6	—	4.6	—
Paper	100	100	79.4	79.4
Equivalent air layer	0	0	10.3	10.3
Elastic layer	200	200	200	200

Table 7. Compared with Measured and Estimated Result

Type	Measured [°C] at v=60mm/s	Estimated [°C]	
		Model 2	Model 3
Paper A	140.0	143.1	142.7
Paper B	153.1	151.4	151.0
Paper C	133.7	131.8	131.9

quality for high-speed color printing are discussed by numerical estimations of the temperature field in the fusing region, method for which estimations has been developed in the preceding chapter.

Toner particles of the same size arrayed on the paper in four-storied hexagonal closed packed lattice are considered as one of the general states for color printed images. For toner particles with the mean sizes of 5 μm, 7.6 μm and 10 μm, toner layer properties are evaluated and listed in Table 8. The melting point of bulk toner, θ_m, for color printing is 100°C.

Figure 5 shows the estimated temperature changes on the toner surface and the toner-paper interface. Conditions for the estimating calculation are the same to the one in the previous chapter. The surface temperature changes are almost the same, not showing dependency on the toner particle size. The toner-paper interface temperature, on the other hand, has a tendency to increase with the decrease of toner particle size. Listed in Table 9 are the quantity of heat changes during the fusing process for each layer, ΔQ. The

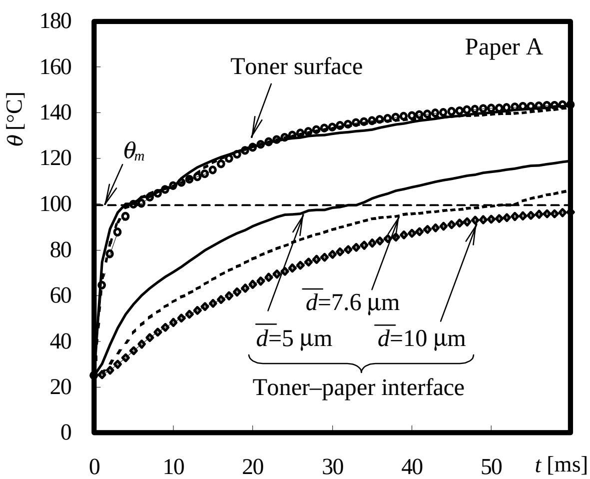

Figure 5. Effects of toner particle size on the toner layer

Table 8. Effects of Toner Particle Size on Air Layer Thickness

$\overline{d}$ [μm]	δ_t^* [μm]	ε_t [–]	δ_{at} [μm]	δ_t [μm]
5.0	17.3	0.298	5.2	12.1
7.6	26.2	0.298	7.8	18.4
10.0	34.5	0.298	10.3	24.2

Table 9. Quantity of Heat Changes during the Fusing Process

Layer	$\overline{d}$=5 [μm] ΔQ [kJ/m^2]	$\overline{d}$=7.6 [μm] ΔQ [kJ/m^2]	$\overline{d}$=10 [μm] ΔQ [kJ/m^2]
Heat roller core	-7.22	-7.26	-7.36
Coating layer	-1.31	-1.31	-1.31
Toner layer	3.75	5.13	6.19
Paper	6.07	4.90	4.05
Elastic layer	0.69	0.52	0.40
Equivalent air layer	2.1×10^{-4}	2.0×10^{-4}	2.0×10^{-4}

results shows that larger portion of the heat supplied from the heat roller is employed to heat the paper with the smaller tone, which improvement is due to smaller specific heat of the toner layer. In addition, the slight decrease of ΔQ in the heat roller core for the smaller toner suggests the decrease of energy for heat supply to the fusing process.

As the high fuse qualities of color printed images are obtained by sufficiently heated toner and paper, an increase of paper surface temperature offers a more favorable condition. The above results together indicate that the adoption of the smaller size of toner particles is an effective approach for obtaining high fuse quality in high-speed printing with lower energy consumption.

Conclusions

To establish an estimating method for the temperature field in the fusing region of electrophotographic printers, construction models to introduce thermal resistance due to the air existing in the region is proposed. Four models are proposed and the evaluated results obtained by the models are discussed. The results are summarized as follows:

(1) By the models adequately determining the setting position of thermal equivalent air, the estimated toner surface temperature changes show good agreements with the measured ones. The importance of adequate position for introducing the equivalent air layer is pointed out.
(2) The usefulness of the models is certified by being applied to print media with different surface roughness.
(3) The effects of the toner particle size on the temperature field are quantitatively examined. Adoption of the smaller size toner is expected to improve color printing with high-speed and lower energy consumption.

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Biography

Masahiro Samei received his B.E. and M.E. degrees in Mechanical Engineering from Kyushu University in 1987 and 1989, respectively, and his Dr. Eng. in Mechanical Engineering from Kyushu Institute of Design in 1999. Since 1989 he has worked in Documents Technology Research Lab. at Kyushu Matsushita Electric Co., Ltd., Fukuoka, Japan. His work has primary focused on the development of a highly optimized design method and the improvement of fuser performance.