A Numerical Study for Fusing Process Including Moisture Phase Change in The Porous Media

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Abstract

A numerical study has been conducted for accurate prediction of temperature in the toner layer including moisture phase change in porous media (paper). The moisture contents, in previous study, have been found experimentally to influence the heat transfer behavior significantly in the fusing process. Heat and mass transfer equations were incorporated into fusing processes analysis to consider the energy loss due to the evaporation of moisture in the paper. The effects of moisture content, dwell-time, fusing temperature, paper grammage, and heating energy from heater on fusing behaviors were numerically investigated by using the present numerical model.

Introduction

In electrophotographic printer, fusing process is fixing technique where the conveyed toner particles on the paper are heated up and pressed simultaneously in the fuser nip to be fixed on the media via softening, coalescence, melting and sintering of the powder [1]. Since these changes occur in a few milliseconds and are difficult to track the transient heat transfer characteristics, considerable numerical efforts have been devoted to understand the fusing processes by using discrete element modeling [2], considering toner rheology [3], or including the existence of air gap [4].

Although 99% of the heat energy in fusing processes is consumed by heating the paper and 14% among that energy is dissipated to evaporate the moisture in the paper [5], the existing numerical models generally ignored the moisture content effect. Thus, understanding of moisture content should be critical for accurate simulation of fusing processes. In this study, a numerical model was developed including moisture phase change in the paper, especially for the sorbed water [5]. And evaporation rate equation [6] was formulated into heat and mass balance equations to consider the moisture content change during fusing processes. Then, the effect of moisture content was studied and the results were discussed in detail.

Theories and calculation

Physical model

The physical model of fusing processes including moisture phase change in the paper is depicted in Figure 1. Initially, at the state I, the heat roller is heated up to the target temperature by the radiative heat transfer from the infrared halogen heater. By the rotating configuration of fusing system, the pressure roller also reaches to the energy balanced temperature, usually lower than the target temperature. Then, the transferred toner on the paper is fed into the fuser nip. Subsequently, the toner, paper, and moisture begin to heat up by the thermal energy due to conductive heat transfer from the heat roller, the pressure roller, and heat flux from halogen heater during the dwell time.

While the paper is in the fuser nip, the surfaces of heat roller and pressure roller are impermeable thus the moisture flux is captured in the paper between the rollers. However once the paper with fixed toner layer comes out from the fuser nip (state II to III, Figure 1), the vapor flux within the paper is released into the atmosphere through the pores of the paper.

Note that we divided the physical model into six layers for fusing phase (form state I to II) and two layers for evaporating phase (from state II to III).

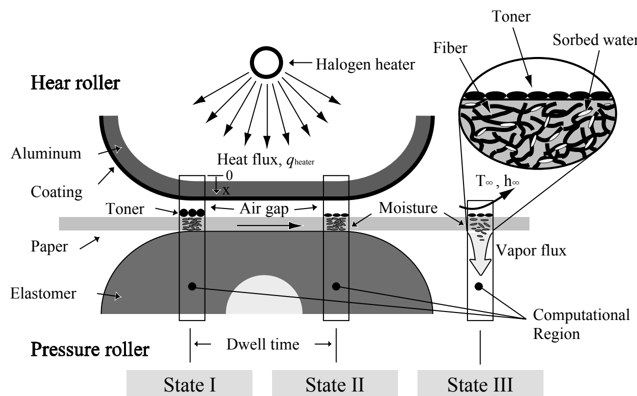

Figure 1. *Physical model for fusing processes with sorbed water in the paper.*

Properties

Paper: moisture ratio, content, and weight based properties

For proper evaluation thermophysical properties in the fusing processes, the amount of moisture in the paper should be quantified first. In this regard, moisture ratio in a paper volume cell is defined as

$$\phi = \frac{m_w}{m_{dp}} \tag{1}$$

where m_w is the mass of water content in the paper and m_{dp} is the mass of dry paper, whereas moisture content is defined as

$$x = \frac{m_w}{m_w + m_{dp}} . \tag{2}$$

Due to its linearity and better reflection of variations of water content, in this study, the moisture ratio is used for calculation while the moisture content is used for all figures. Then, the weight based properties of paper can be calculated as [7]

$$c_{p,paper} = \frac{c_{p,fiber} + \phi c_{p,w}}{1+\phi} \tag{3}$$

where $c_{p,fiber}$ and $c_{p,w}$ are the specific heat of fiber and water.

Toner: Specific heat

Although the actual specific heat of toner can be measured using DSC (Differential Scanning Calorimeter), in this study, along with the 4 stages of toner in the fusing processes (warming, softening, melting, and liquid like behavior), the temperature dependent specific heat is modeled as shown in Figure 3. [2]

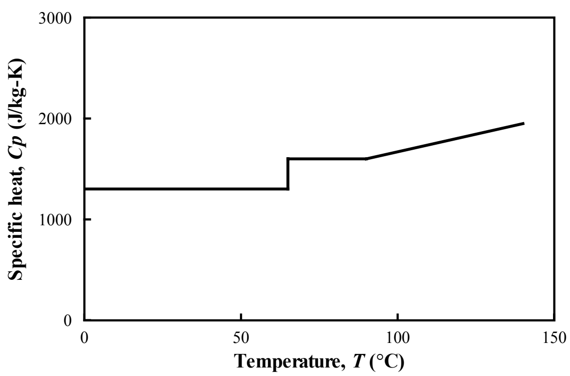

Figure 2. *Temperature dependent specific heat of toner.*

Mass conservation equation

The conservation of mass for moisture in a porous media can be written as

$$\frac{\partial \phi \rho}{\partial t} + \nabla \cdot \phi \rho u = 0 \tag{4}$$

The mass flux by evaporation between the paper surface and surrounding air can be expressed as Stefan equation [6]

$$\phi \rho u = \frac{p_g K M_w}{R(T+273.15)} \log\left(\frac{p_g - p_{v,air}}{p_g - p_{v,paper}} \right). \tag{5}$$

where K is the mass transfer coefficient, M_w is the molecular weight of water, p_g is the pressure of air air, T is the temperature, and R is the gas constant.

The partial pressure for water vapor in the air is given by [8]

$$p_{v,air} = \frac{\phi_{air}}{\phi_{air} + 0.62} p_g . \tag{7}$$

where ϕ_{air} is moisture ratio of air and the partial pressure for water vapor for paper surface is given by [9]

$$p_{v,paper} = \eta p_{v,free} . \tag{8}$$

where $p_{v,free}$ is partial pressure for free water and η is sorption isotherm which has value zero to one. The partial vapor pressure for free water is determined using Antoine's equation

$$p_{v,free} = 10^{\left(10.127 - \frac{1690}{T+230}\right)} . \tag{9}$$

The empirical sorption isotherm for paper is written as [10]

$$\eta = 1 - \exp(-47.58\phi^{1.877} - 0.10085\, T\phi^{1.0585}) . \tag{10}$$

Equation (8) state that the partial pressure at the paper surface is equal to the partial pressure for free water so long as capillary transport can bring new water to the paper surface but becomes zero as the paper is dryer.

Energy conservation equation

The conservation of energy is written as

$$\frac{\partial \rho c_p T}{\partial t} + \nabla \cdot (-k\nabla T) = \nabla \cdot \phi \rho u (\Delta H_s + \Delta H_{vap}) \tag{11}$$

where ΔH_s is the heat of sorption needed to evaporate the sorbed water besides ΔH_{vap} is the latent heat of vaporization for water. The heat of sorption is defined using Clausius-Clapeyron relation and obtained by applying the relation to Eq. (10) as [9]

$$\Delta H_s = 0.10085\phi^{1.0585}(T+273.15)^2 R \frac{1-\eta}{M_w \eta} \tag{12}$$

During the iterative calculation for a time step to solve the nonlinearity of the Eqs. (11) and (12), the moisture ratio ϕ in the computational region was calculated first by solving the mass conservation equation of Eqs. (5), (6), (7), (8), (9), and (10). Then, the energy conservation equation of Eq. (11) was solved to obtain the temperature with the heat of sorption energy, Eq. (12), calculated at previous iterative step. Once the predetermined level of accuracy was satisfied, the iterative calculation for a time step terminated and that of the next time step began.

Results and discussion

Fusing processes behavior

The general fusing process behaviors with moisture phase change in the paper were investigated for the operating conditions in Table 1 and 2. Figure 3 shows the evolution of the moisture content and the temperature of each computational layer (heat roller, coating, air gap, toner, and paper) of present numerical model during the fusing phase and evaporation phase. In Figure 3a showing the result in 0.1 sec, the moisture content is found to be a dominant effect on the heating rate of the toner and the paper comparing to the result of simulation excluding moisture content effect. By including moisture in the paper, the overall heat capacity of the paper increases, and then the temperature at the end of the fusing phase dropped by approximately 5 °C on the paper and 2 °C on the toner, respectively. Since the temperature of the toner layer is the criteria for the adhesive and cohesive characteristic of the powder, the degree of fusing, crucial print quality, can be affected by the including moisture content in the paper. Note that, during the fusing phase, due to the impermeable boundary condition, the mass transfer in the paper is not allowed and thus the moisture content is uniform.

In Figure 3b, illustrating the result in 20sec, the moisture content in the paper is observed to be significantly changed from 7% to 1.9% due to its evaporation. However, the dramatic falling of the moisture content is occurring right after the paper brings out from the fuser nip and recovers in a few seconds to the saturated condition. This result indicated that, when the moisture content is experimentally measured, the result can be affected by the measuring point.

Table 1. Geometry and properties of layers [2, 3].

Layer	δ [mm]	k [W/m-K]	ρ [kg/ m^3]	c_p [J/kg-K]
Roller	1.0	210	2698.9	900
Coating	0.03	0.22	2120	1050
Air gap	0.005	0.0263	1.1614	1007
Toner	0.014	0.15	1200.0	1300-1900
Paper(fiber)	0.1	0.08	800.0	1450
Elastomer	4.0	0.281	1120.0	1546.1

Table 2. Parameters and expressions for the fusing process.

h_∞	15.0 W/m^2-K
K	0.06 m/s [a]
M_w	0.01801528 kg/mole
P_g	101300 Pa (=1atm)
q_{heater}	50525.3 W/m^2
t_{dwell}	40 ms
T_∞	23 °C
$T_{initial,\ HR\&Coating}$	170 °C
$T_{initial,\ Air,Toenr,\&Paper}$	23 °C
$T_{initial,\ PR}$	100 °C
ΔH_{evap}	2260000.0 J/kg
ϕ_{air}	0.00888 at 23 °C and HR 50%
$\phi_{paper,initial}$	0.075268 at $x_{paper} = 7\%$,

a Åkesson et al (2006)

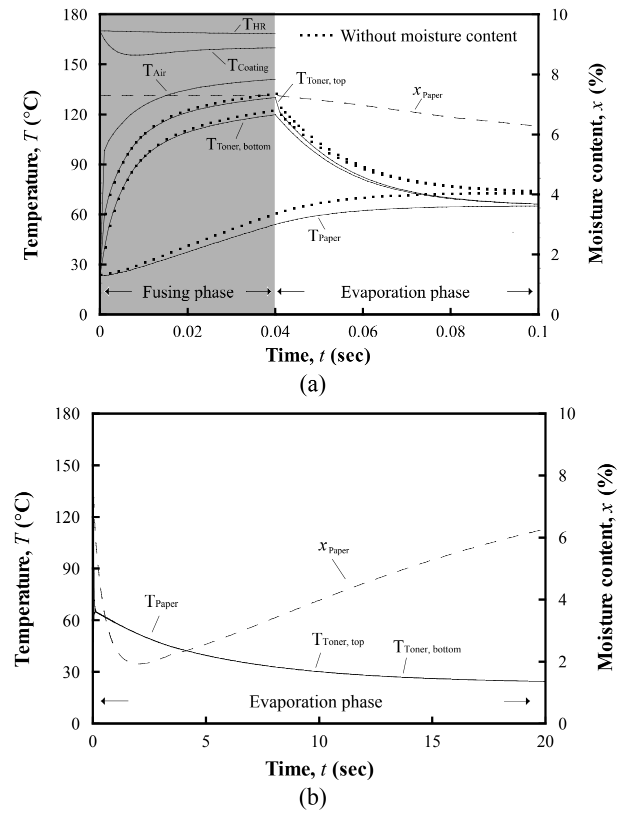

Figure 3. *Fusing behavior simulated with or without the moisture content inside the paper: the evolution of the temperature and moisture content displayed (a) in 0.1 seconds and (b) in 20 seconds.*

Sensitivity analysis

Sensitivity analysis is conducted for the bottom temperature of the toner layer corresponding to the five operating parameters (moisture contents, dwell time, fusing temperature, paper grammage, and heating energy) varying values listed in Table 3.

Table 3. Parameters for sensitivity analysis.

x_{paper}	2%, 7%, and 12%
t_{dwell}	30 ms, 40 ms , and 50 ms
T_{fusing}	160 °C, 170 °C, and 180 °C
g_{paper}	70 g/m^2, 80 g/m^2, and 90 g/m^2
d_{duty}	0%, 50%, and 100%

The function of the toner's bottom layer temperature can be expressed as

$$T_{toner,bottom} = f(x,t,T,g,d) \qquad (13)$$

where t is the dwell time, g is the paper grammage, and d is the duty controlling the heat energy from heater. By assuming the superposition principle for the operating parameters, the partial derivative form of Eq. (13) is written as

$$\Delta f = \frac{\partial f}{\partial x}\Delta x + \frac{\partial f}{\partial t}\Delta t + \frac{\partial f}{\partial T}\Delta T + \frac{\partial f}{\partial g}\Delta g + \frac{\partial f}{\partial d}\Delta d \ . \quad (14)$$

where the sensitivities of each parameter are displayed in Figure 4.

Figure 4 shows that the temperature of toner layer was more sensitive to the moisture content effect rather than the effect of paper grammage, and thus considering moisture content effect is required for the accurate temperature prediction.

Moreover, Eq. (14) states that the linear summation of each change of the operating parameter results in the change of the bottom temperature of the toner layer. In other words, for $\Delta f = 0$, if the paper grammage changed from 70 g/m^2 to 90 g/m^2, fusing temperature should be increased by 3.5 °C to attain the desired fusing quality while 2 °C increase is needed for the change of the moisture content, from 7 % to 12 %.

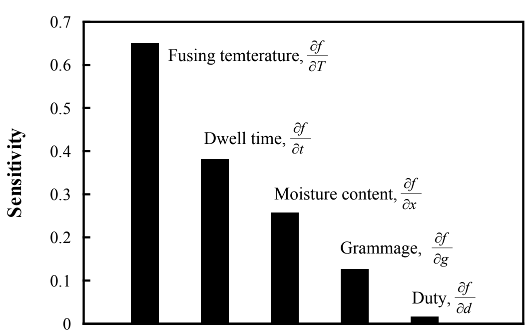

Figure 4. *Sensitivity of the operating parameters for the bottom temperature of the toner layer.*

Conclusion

A numerical study, considering moisture content in the porous media, was conducted for accurate simulation of the fusing processes. Present numerical model was developed on the basis of the previous numerical framework [2, 4]. In addition, an evaporation model for sorbed water [7] was combined with the numerical framework for detailed consideration of moisture content effect on fusing behaviors.

The effect of moisture contents in the paper was found to significantly drop the temperature in both paper and toner layer, which can affect the print quality. It was also observed that the amount of moisture content in the paper was dropped rapidly right after the paper brought out from the fuser nip and gradually recovered to the saturated condition. In addition to the effect of moisture content, the effect of dwell-time, fusing temperature, paper grammage, and heating energy from heater on fusing behaviors were numerically studied using sensitivity analysis. It was found that the temperature of toner layer was more sensitive to the moisture content effect rather than the effect of paper grammage, and the result of sensitivity analysis was able to suggest the guidelines to attain the desired print quality.

In conclusion, the numerical model proposed in this study is expected to be a useful tool for predicting and optimizing fusing processes.

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