Numerical Simulation of Electrophotography Processes

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Outline

- Overview of the recent progress of simulation technology for the development of electrophotography processes
  - especially developed in Japan

- Promotion of simulation technology and education of young engineers in Japan
Charging, Exposure and Fusing Systems

- based on the mechanics of continuous media
- formulated as a set of multi-component, nonstationary, and nonlinear partial differential equations
- numerically solved by the iterative FEM or FDM.
Development, Transfer and Cleaning Systems

- dynamics of toner and/or carrier particles
- the discrete element method (DEM)
- direct observation with a high-speed microscope camera
1. Charging
Charging Devices

contact charger roller

micro-discharge

BCR

OPC

corona discharge

corotorn/ scrotron
Modeling of Contact Charging
(one-dimensional analytical)

\[ V_c(t) = q(t) \frac{d}{\varepsilon_0 \varepsilon_r} \]

- charged voltage

\[ q(t + \Delta t) = \frac{\varepsilon_0 \varepsilon_r}{\varepsilon_r} \left\{ V_a(t) - \frac{d + z(t) \varepsilon_r}{z(t) \varepsilon_r} V_{th}(t) \right\} \]

charge density

Micro discharge takes place when (gap voltage) > (Paschen \( V_{th} \))

H. Kawamoto (Fuji Xerox) 1993
Calculated and Measured Charging Characteristics

\[ V_{\text{DC}} = -750 \text{ V} \]

\[ V_{\text{DC}} = -500 \text{ V} \]

\[ V_{\text{critical}} - V_{\text{DC}} = 73 \text{ V} \]

\[ V_{\text{critical}} = 573 \text{ V} \]

\[ \omega/2\pi = 1,000 \text{ Hz} \]

H. Kawamoto (Fuji Xerox) 1993
Analysis of Strip Image Defect due to AC Voltage Application

Period: \( v/(\omega/2\pi) = 224 \mu \text{m} \)
when \( v = 56 \text{ mm}, \omega/2\pi = 250 \text{ Hz} \)

\( V_{AC} = 0.75 \text{ kV} \)
\( 1.25 \text{ kV} \)

H. Kawamoto (Fuji Xerox) 1993
Analysis of Image Defect due to DC Voltage Application

- expanded to 2D field
- circumferential transport of charge

M. Kadonaga (Ricoh) 1999
Analysis of Image Defect due to DC Voltage Application

observed image defect  calculated charge density

M. Kadonaga (Ricoh) 1999
Plasma Ozone Synthesis

- Ozone Synthesis

\[ e^- + O_2 \rightarrow 2O + e^- \quad O + O_2 + O_2 \rightarrow O_3 + O_2 \]

- Plasma Reaction Rate

\[ S = 2\pi \int_{r_o}^R K_r n_e n_o r dr \quad (O_3/\text{sec}) \]

- based on Townsend theory

H. Kawamoto (Fuji Xerox) 1994
Measured and Calculated Ozone Concentration

<table>
<thead>
<tr>
<th>AC voltage (kV)</th>
<th>Ozone concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 Hz</td>
<td>exp. cal.</td>
</tr>
<tr>
<td>450</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td></td>
</tr>
</tbody>
</table>

H. Kawamoto (Fuji Xerox) 1994

Ozone Generation

- corotron 100
- contact charger roller 2
Modeling of Corona Charging

- conservation of charges

\[ \frac{\partial n_p}{\partial t} + \text{div} \left( \mu_p E n_p \right) = -R_e n_p n_n \]

\[ \frac{\partial n_n}{\partial t} + \text{div} \left( -\mu_n E n_n \right) = -R_e n_p n_n \]

- Poisson's equation

\[ \text{div} (\varepsilon E) = e \left(n_p - n_n\right) \]

- boundary condition

\[ E = E_{p0} \text{ (threshold of corona onset) at wire} \]
Numerical Result

effects of rotation and resistivity of OPC

\[ J_\rho = \sigma E + \rho v_0 \]

\[ \frac{\partial \rho}{\partial t} + \text{div} J_\rho = 0 \]

initial 0 V

cal. - 863 V

exp. - 900 V

initial - 250 V

cal. - 886 V

exp. - 925 V

Y. Watanabe (Ricoh) 1990
Flow Analysis of Ionic Wind

**Discharge Field (2D, unipolar)**

\[
\frac{\partial \rho}{\partial t} + \nabla \left( \mu \rho \left( -\nabla \phi \right) \right) = 0 \\
\nabla \left( \varepsilon \left( -\nabla \phi \right) \right) = \rho
\]

**Aerodynamics (3D)**

\[
\frac{\partial \rho_g u}{\partial t} + \rho_g \left( u \cdot \nabla \right) u = -\nabla p + \mu_g \Delta u + F
\]

Navier-Stokes
Calculated Velocity Distribution

utilized to improve blur of toner dust

H. Okamoto (Fuji Xerox) 2002
2. Exposure
Formation of Latent Image
(3D, time-dependent, 3-unknowns)

- conservation of charges
\[ \frac{\partial n_p}{\partial t} + \text{div}(\mu_p E n_p) = \Gamma - R e n_p n_n \]

- Poisson's Equation
\[ \text{div}(\varepsilon E) = e(n_p - n_n) \]
• Calculated field strength can predict threshold of development.
• Latent image created by an isolated dot spreads even if the thickness of OPC is 10 \( \mu \text{m} \).
• Latent image created by one-by-one dot is suppressed by adjacent dots.
3. Development
Two Approaches for Toner/Carrier Dynamics

• **Continuous Model**
  
  Navier-Stokes
  - (Hitachi Printing, Ricoh, Fuji Xerox, ---), 2000

• **Discrete Model**
  
  Discrete Element Method (DEM)

\[
m_i \ddot{x}_i + c_i \dot{x}_i + k_i x_i = F_{\text{mechanical}} + F_{\text{electrostatic}} + F_{\text{magnetic}} +
\]

\[
x = (x, y, z, \theta_x, \theta_y, \theta_z)
\]
Mechanical Interaction between Beads (Voigt model)
Mixing of Toner and Carrier Particles in Auger

H. Mio (Kyoto Fine Particle Technology) 2007
Magnetic Interaction

- magnetic force

\[ f_{mj} = (p_j \cdot \nabla)B_j, \quad M_{mj} = p_j \times B_j \]

- magnetic dipole moment

\[ p_j = \frac{4\pi}{\mu_0} \frac{\mu - 1}{\mu + 2} \frac{a_j^3}{8} B_j, \]

\[ + \frac{\mu - 1}{\mu + 2} \frac{a_j^3}{8} \sum_{i=1}^{N} \left( \frac{3p_i \cdot r_{ij}}{|r_{ij}|^3} r_{ij} - \frac{p_i}{|r_{ij}|} \right) \]

due to other particles
Design of Magnetic Roller

utilized to improve pole pattern of magnetic roller that can efficiently mix toner/carrier particles.
Magnetic Brushes

Simulation

Experiment

Photoreceptor

Development Sleeve

H. Kawamoto (Waseda) 2007
Two-Component Development

H. Mio (Kyoto Fine Particle Technology) 2007
Direct Observation of Development by High Speed Camera

H. Kawamoto (Waseda) 2007
4. Transfer
Electrostatic Field in Transfer Process

- **OPC**
- **Transfer roller**
- **Paper**
- **Nip area**
- **Discharge**
- **Potential distribution**

Discharge: 10mm
Toner Dynamics in Roller Transfer System

Toner particles scatter due to electrical discharge.

on OPC

on paper

M. Kadonaga (Ricoh) 2004
Hollow Defect and Toner Scattering

Hollow defects

Toner scattering

hollow defect

toner scattering
Hysteresis of Toner Compression

non-linear (Hertz contact)

N. Nakayama (Fuji Xerox) 1997
Hollow Defect and Toner Scattering

on OPC (before transfer)

(b) Compressed low compression ($\varepsilon_h=0.045$, $p=0.7$ kPa)

(c) Compressed medium compression ($\varepsilon_h=0.134$, $p=31.7$ kPa)

(d) Compressed high compression ($\varepsilon_h=0.259$, $p=168.8$ kPa)

N. Nakayama (Fuji Xerox) 1997
5. Fusing
Visco-Elasticity of Toner

S. Hasebe (Fuji Xerox) 2007
6. Cleaning

- generation of acoustic noise
- low cleaning performance of spherical toner
Acoustic Noise from Cleaner Blade

- **Low Speed**
  - stick-slip
  H. Kawamoto (Fuji Xerox) 1995

- **Rated Speed**
  - coupled non-linear vibration
  M. Kasama (Fuji Xerox) 2006
Cleaning Performance of Spherical Toner Particles

\[ \mu = 0.96, \ \theta = 30\text{deg}, \ k_w = 10\text{N/m}, \ a/b = 1.0 \]

\[ \mu = 0.96, \ \theta = 30\text{deg}, \ k_w = 10\text{N/m}, \ a/b = 1.23 \]

N. Nakayama (Fuji Xerox) 2004
7. Paper Handling
Improvement of Paper Path for Image Scanner

output image

O. Takehira (Ricoh) 2000
Application for Paper Feeder

H. Seki (Ricoh Printing Systems) 2006
Promotion of Simulation Technology and Education of Young Engineers in Japan
Academic Committees

Three Japanese academic committees to promote the modeling and numerical simulation of electrophotography processes

- The Imaging Society of Japan (ISJ)
  - education of young engineers
  - publish of textbook

- The Japan Society of Mechanical Engineers (JSME)
  - technology exchange on a give-and-take basis

- The Japan Society for Precision Engineering (JSPE)
  - paper handling
Simulation Seminar

The seminar is conducted every year for 15 students. Students are young engineers in industries. They do exercise with their own note PC.
Example of Exercise
(Thermal Analysis of Belt Nip Fuser)

Students must complete the calculation at the end of one-day lecture!!
Electrophotography

Process & Simulation

Published by The Imaging Society of Japan

Edited by Hirakura (Ricoh) & Kawamoto

Textbook
Concluding Remarks

Simulation technology has been developed and widely utilized for the development of electrophotography machines, although it had been believed that the simulation is ineffective for the electrophotography.

The electrophotography processes are no longer a black box.
Acknowledgement

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end
Electrophotography Processes
History of Electrophotography Technology

Technology:
- Automatic improvement
- Digital/color
- Multi-function

Approach:
- Analytical
- Numerical
  - Continuous mechanics (FDM, FEM)
  - Particle dynamics (DEM)

Timeline:
- '50
- '60
- '70
- '80
- '90
- 2000

Events:
- Xerox 914

Methods:
- Trial and Error
- Analytical Modeling
- Numerical Simulation