Discrete Element Method Simulation of Developer Flow Behavior and Toner Developing in Two-Component System

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Abstract

The magnetic brushes play an important role in a two component development system in order to realize high quality printing. Therefore, in the design of two-component development system, it is necessary to clarify the relationship between dynamic characteristics of magnetic brushes and design parameters. However, the empirical design and production by trial-and-error have been still applied to the real development procedure and they are time-consuming and expensive. A simulation tool of magnetic brush behavior and toner developing in a two-component electro-photographic system has been developed in this work. Most DEM (Discrete element method) simulation approaches have been restricted to a small area or volume, especially, the development zone between the magnet roller and the photoreceptor due to the limitation of number of particles for evaluation and extremely long calculation time. In this paper, a large scale-DEM simulation tool is proposed, which is able to analyze the magnetic brush behaviors in total region surrounding the magnet roller. Parallel computing with fast N-body algorithm has been applied to the DEM calculation of enormous particles in the total region surrounding the magnetic roller. The DEM simulation has been performed in the main functional areas of the magnet roller, e.g. regulation, developing and separation areas and its validity is confirmed by comparison of experimental results. The effects of the geometry of blade, positions of the blade and the magnetic flux density distribution on the flow behavior of developer are investigated in regulation area. Also, the developing behavior of toner particles is simulated according to electric field conditions between magnetic roller and photoreceptor. In the experiment, DMA (Developer mass per area on magnet roller) and TMA (Toner mass per area) are evaluated for simulation accuracy. Simulations are well matched with experimental results with lower than 10% error.

Introduction

Two-component development process is that the developer consisting of the toner and the carrier particles forms a magnetic brush on a magnet roll and then the toner particles are selectively attached to the electrostatic latent image when the magnetic brushes contact with the photoreceptor drum. Therefore, for the design of two-component development process, it is necessary to clarify the relationship between dynamic characteristics of magnetic brushes and design parameters. Because there are no commercial tools to simulate and analyze this developing process, the empirical design and production by trial-and-error have been still applied to the real development procedure and it is time-consuming and expensive process. Recently, thanks to improvement of computing technology, the DEM (discrete element method) approach has been studied as a powerful simulation tool for the analysis of the development system of electro-photography in many researches [1-5]. However, most DEM simulation approaches have been restricted to a small area or volume, especially, the development zone between the magnet roller and the photoreceptor due to the limitation of number of particle for evaluation and extremely long calculation time. In usual two-component development systems, the magnet roller has following functions: catch-up, regulation, image development and recovery. Therefore, in order to be utilized as a practical design tool of the two-component system, it is necessary to expand its analysis region into the total region surrounding the magnet roller. The flow behavior of brushes surrounding the magnet roller directly affects the performance of the two-component development system. For example, the flow behavior of the developer in the vicinity of the regulation blade such as the feed stability of the developer, the stress acting on it is an important factor for high quality imaging. Also, the recovery function of the magnet roller has direct influence on the stability of image density.

In this paper, a large scale-DEM simulation tool is proposed, which is able to analyze the flow behaviors of developer in total region surrounding the magnet roller as well as toner developing between the magnet roller and the photoreceptor. To overcome the difficulties in computation cost to calculate the motions of enormous developer particles surrounding the magnet roller, both novel parallel computing technology and fast N-body algorithm were employed. In addition, GUI- based simulation tool easy to use for the product engineers was developed. Both the developer flow behaviors and toner developing were simulated with an example of two-component system used to real product. Validity of the tool was investigated by comparison of transported developer mass on development roller and developed toner mass with the experimental results.

Simulation Method

Numerical model of DEM

DEM is one of the most popular and reliable simulation methods for the numerical analysis of particle behavior. In this simulation method, equations of motion are built by modeling all forces acting on each particle and are calculated at every discrete-time step. The trajectories of all particles are updated by Newton's law of motion. The basic equation of motion for each particle j with six degrees of freedom including rotations is as follows:

$$m_j \ddot{\boldsymbol{u}}_j = \boldsymbol{F}_j \quad , \boldsymbol{I}_j \ddot{\varphi}_j = \boldsymbol{M}_j \tag{1}$$

Where, $\boldsymbol{u}_j(=x_j,y_j,z_j)$ is the displacement vector, $\boldsymbol{F}_j$ is the summed force acting on a particle j, m_j means the mass of a particle ,and

$\varphi_j(=\varphi_{xj}, \varphi_{yj}, \varphi_{zj})$ is the rotation angle. $\boldsymbol{I}$ and $\boldsymbol{M}$ denote the moment of inertia and the applied moment to a particle j, respectively. The assumed external force $\boldsymbol{F}_j$ applied to the particle j consists of the contact force $\boldsymbol{F}_{CT}$ magnetic force $\boldsymbol{F}_m$, Coulomb force $\boldsymbol{F}_C$, electrostatic force $\boldsymbol{F}_E$, Van der Waals force $\boldsymbol{F}_w$, Air dag $\boldsymbol{F}_a$ and gravitational force $\boldsymbol{F}_g$. acting on carrier or toner particles in the two-component development process.

The contact force $\boldsymbol{F}_{CT}$ was estimated based on Voigt model from Hertzian contact theory in the normal direction and Mindlin contact theory in the tangential direction. Force and moment between particle to particle, particle to magnet roller, particle to photoreceptor drum and particle to blade are included in this contact force term.

Carrier particles on the sleeve form the magnetic brush in the magnetic field caused by the magnet roller. The magnetic force $\boldsymbol{F}_{mj}$ and rotational moment $\boldsymbol{M}_{mj}$ of the j^{-th} particle with the magnetic moment $\mathbf{p}_j$ are given by the following equations:

$$\boldsymbol{F}_{mj} = (\boldsymbol{p}_j \cdot \nabla)\boldsymbol{B}_j \quad , \boldsymbol{M}_{mj} = \boldsymbol{p}_j \times \boldsymbol{B}_j \tag{2}$$

The magnetic dipole moment $\boldsymbol{p}_j$ and magnetic flux density $\boldsymbol{B}_j$ are given by the following expressions:

$$\boldsymbol{B}_j = \boldsymbol{B}_{j,field} + \sum_{k=1, j\neq k}^{N} \boldsymbol{B}_{kj} \tag{3}$$

$$\boldsymbol{p}_j = \frac{4\pi}{\mu_0}\frac{\mu_r - 1}{\mu_r + 2}\frac{a_j^3}{8}\boldsymbol{B}_j \tag{4}$$

where N is the number of particles, μ_0 is the magnetic permeability of vacuum (=12.57×10^{-7} A/m^2), μ_r is the relative magnetic permeability of particles, a_j is the diameter of j-th particle. In the equation (3), $\boldsymbol{B}_j$ is the magnetic flux density of the j-th particle, which is used the summed value of the magnetic flux density from magnetic roller and the ones from magnetized particles. $\boldsymbol{B}_{j,field}$ is the magnetic field generated by the magnetic roller and $\boldsymbol{B}_{kj}$ is the magnetic flux density of j-th particle caused by the magnetized k-th particle. The $\boldsymbol{B}_{kj}$ is given by

$$\boldsymbol{B}_{kj} = \frac{\mu_0}{4\pi}\left(\frac{3\boldsymbol{p}_k \cdot \boldsymbol{r}_{kj}}{\left|\boldsymbol{r}_{kj}\right|^5}\boldsymbol{r}_{kj} - \frac{\boldsymbol{p}_k}{\left|\boldsymbol{r}_{kj}\right|^3}\right) \tag{5}$$

Where, $\boldsymbol{r}_{kj}$ is the position vector from the k-th particle to j-th one. The magnetic force on j-th particle can be obtained by solving the equations (3), (4) and (5) simultaneously and then by substituting the calculated results, $\boldsymbol{p}_j$ and $\boldsymbol{B}_j$ to the equation (2)

Coulomb force $\boldsymbol{F}_C$ acts on toner/toner or toner/carrier particles, because toners and carriers have triboelectric charge caused by developer agitating. $\boldsymbol{F}_C$ is calculated from the following equation.

$$\boldsymbol{F}_{C,ij} = \frac{1}{4\pi\varepsilon}\frac{q_i q_j \boldsymbol{r}_{ji}}{\left|\boldsymbol{r}_{ji}\right|^2\left|\boldsymbol{r}_{ji}\right|} \tag{6}$$

Where, ε is the permittivity of air (=8.86×10^{-12} F/m) and q denotes charge. The carrier particle has the opposite charge of toner on the surface.

The toner particles are selectively attached to the latent images on the photoreceptor from the magnetic brushes under the influence of the electrostatic force $\boldsymbol{F}_E$. The electrostatic force $\boldsymbol{F}_E$ is estimated by the product $\boldsymbol{F}_E = q \cdot \boldsymbol{E}$ of the electric field $\boldsymbol{E}$ and the charge q of the developer. The electric field $\boldsymbol{E}$ and the charge density ρ of the nip area were determined by solving the following equations:

$$\boldsymbol{E} = -\nabla\Phi \tag{7}$$

$$-\nabla \cdot (\varepsilon\nabla\Phi) = \rho \tag{8}$$

Where, Φ denotes the electric potential distribution, which is assumed to be unchanged by the magnetic brushes and the charge of toners.

Magnetic Field of Magnet Roller

The magnet roller with 5-pole permanent magnets is widely used in two-component development devices as developing roller and it is applied to the DEM simulation domain. The magnets produced by in-process magnetization of injection molding have complex magnetization distribution. This distribution is required for the calculation of magnetic field but generally not known and difficult to express by a formula. In this paper, the magnetization distribution of magnet is modeled and the magnetic field $\boldsymbol{B}_j$,field generated by the magnet roller is calculated by using FEM tool, COMSOL.

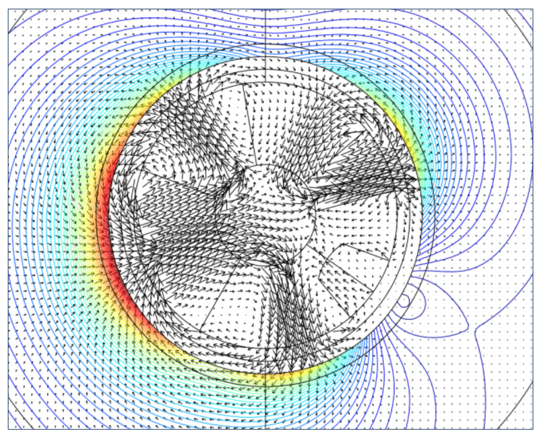

***Figure 1**. The magnetic field surrounding the sleeve of the magnet roller by COMSOL models*

For the FEM calculation of magnetic field around the magnetic roller, the vector field is applied for modeling the magnetization distribution of the magnet, which is assumed as follows:

$$\mathbf{M}_{PMi} = \begin{bmatrix} -M_{PMi}(x,y)\dfrac{x}{\sqrt{x^2+y^2}}\left(\cos(2\phi_i\pi/180)+\sin(2\phi_i\pi/180)\right) \\ M_{PMi}(x,y)\dfrac{x}{\sqrt{x^2+y^2}}\left(\sin(2\phi_i\pi/180)+\cos(2\phi_i\pi/180)\right) \end{bmatrix} \tag{9}$$

$$(-180 \le \phi_i \le 180^{\circ},\ i = 1,2,\ldots 5)$$

Where, ϕ_i is the pole angle of i-th magnet and $\boldsymbol{M}_{PMi}$ is the magnetization vector field distributed in i-th magnet. Magnetization at the position (x,y) in the magnet area, $\boldsymbol{M}_{PMi}(x,y)$ is given by

$$M_{PMi}(x,y) = M_{PMi} e^{-\alpha\left[\phi_i - \cos^{-1}\left(\frac{x}{\sqrt{x^2+y^2}}\right)\right]^2} \qquad (10)$$

Where α is the shape factor, which determines the sharpness of the magnetic flux density distribution in normal direction on the sleeve of magnetic roller. It is decided in the manufacturing process of magnet roller. Fig.1 shows the magnetic flux density vectors surrounding the sleeve of the magnet roller, which is obtained from the FEM calculation. The calculated and measured distribution of the magnetic flux density on the sleeve is plotted in Fig.2. It is confirmed that the distribution of the calculated magnetic flux density in both normal and tangential direction agree well with measured ones on the sleeve as shown in Fig.2.

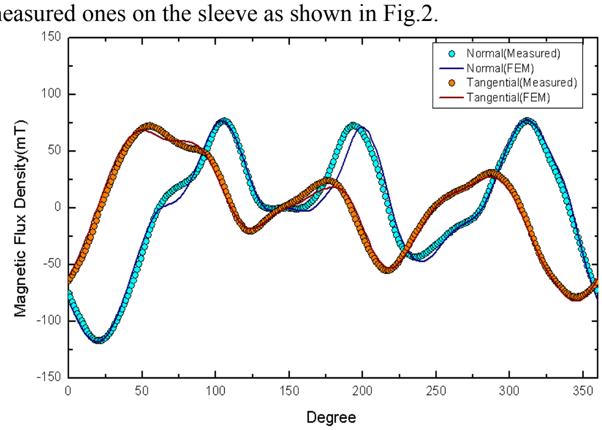

Figure 2. *The calculated and measured distribution of the magnetic flux density on the sleeve of magnet roller*

S-DEM/EP with H/W and S/W acceleration

S-DEM/EP is developed for simulating of particles behavior in electro-photography by Samsung. It has massively parallel multithreaded devices capable of executing a large amount of active threads. S-DEM/EP uses multiple streaming multiprocessors, each of which contains multiple scalar processor cores. A function that executes on the H/W acceleration device consists of multiple threads executing code in a single instruction, multiple data (SIMD) fashion. That is, each thread in a kernel executes the same code, but on different data. Presently, the raw computational power of these multiprocessors can reach one Teraflop, which is several hundred times the throughput of a modern scalar CPU. To accelerate DEM simulation of our model, hardware acceleration and software acceleration using the cell-linked list algorithm was implemented. The simulation space is partitioned into cells and the particles are then assigned to the cells by virtue of their position in the simulation space. A linked list of the particle indices is created during the sorting procedure. Also, at the beginning of a simulation, an array that contains a list of cell neighbors for each cell is created. This method dramatically reduces the number of unnecessary inter-particle distance calculations. Therefore entire region surrounding magnetic roller including entrance of regulating blade and recovery area can be simulated in one boundary model.

GUI system for simulation

GUI-based tool has been developed so that the process design engineers may easily perform the simulation and analysis of two-component development process. The simulation tool consists of three parts as follows:

1. Excel sheet to set design parameters such as magnet geometry, magnetic pole conditions, wall geometry of blade and guide around the magnet roller.
2. FEM tool to calculate magnetic field around the magnet roller with parameters settled in Excel sheet.
3. DEM simulation tool to visualize and analyze the motions of carrier and toner particles in total region of the magnet roller and the developing nip.

The schematic diagram of GUI-tool is shown in Fig. 3.

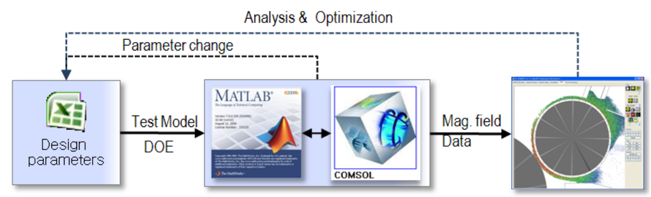

Figure 3. *The schematic diagram of GUI-tool*

Simulation results and discussions

Experimental evaluating for simulation validity

Experimental set up was used to evaluate simulation validity. The motion of the developer brushes on the magnet roller was observed by the high-speed microscope camera (Photoron, FASTCAM-SA1.1). Real scale mock-up machine was used for precise measurement instead of a full set commercial printer. The mock-up machine comprises a pseudo-photoreceptor, a magnet roller and driving systems. Because of the effect of high-intensity light of the high speed camera on toner developing, the pseudo-photoreceptor drum, wrapping FPC (flexible printed circuit) with copper electrode patterns on an aluminum drum, was used to form latent image. The electrode patterns generated the electric field similar to the latent image by applying voltage to the electrodes.

Developer mass per area (DMA) and toner mass per area (TMA) were chosen as parameters for evaluating the simulation accuracy. DMA was measure by traditional method and new accurate method. New method could measure DMA with less than 2% error during rotating the sleeve of magnetic roller. TMA was converted from toner thickness measured by optical measurement system. Toners are transferred from magnetic roller to latent image which is controlled by applied potential from external voltage set up. The DC development voltage was applied between the drum and the sleeve. The AC voltage was not superposed on the DC voltage in simulation and experiment. Due to this experimental set-up, DMA and TMA can be measured without transfer and fusing process into paper.

Flow behavior of magnetic brush

The simulated flow behavior of brushes in entire area surrounding the magnet roller after certain period time is shown in Fig.4. The motions of more than 45,000 particles were calculated and it took about 24hours in one personal computer with single H/W acceleration device. In this study, as case study using the simulation tool, the flow behavior of developers in the regulation and separation area was simulated. As is shown in Fig.5, the case of type (a) shows flow behavior that the developer particles forms a accumulative flows in the vicinity of blade, on the other hand, the case of type (b) shows smooth flows without accumulation. Since the simple geometry with large space in front of blade causes turbulence of developer flow, change to geometry with auxiliary wall can help improve the flow of developer. The improvement of flow can reduce stress of developer and instability of DMA.

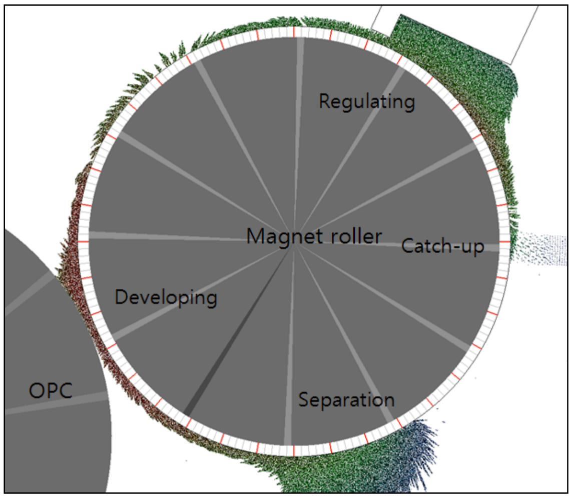

Figure 4. *The simulated flow behavior of brushes in entire area surrounding the magnet roller*

The recovery function of the magnet roller has direct influence on the stability of image density. If the low toner concentration developer used for image development is re-supplied to the magnet roller, this can cause image density fluctuation. Fig.6 shows the developer flow behavior in separation area. As shown in Fig.6 (a), since the magnetic flux density is not optimized, the developers came from the developing area are re-supplied to magnet roller, whereas, when it optimized, the developers can be almost entirely separated.

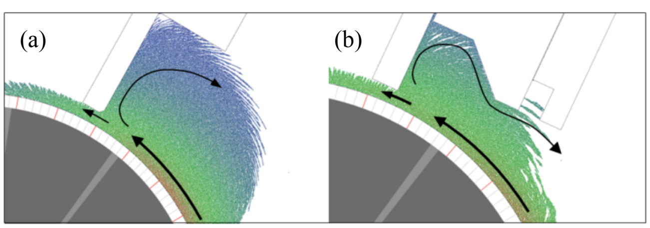

Figure 5. *The simulated flow behavior of brushes in vicinity of blade*

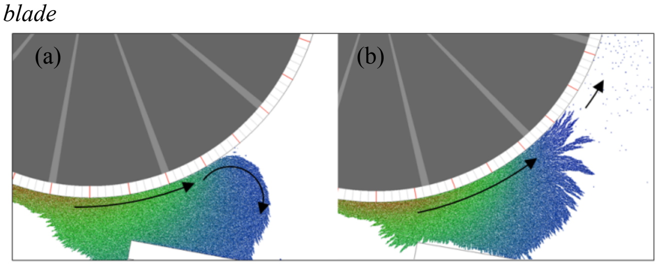

Figure 6. *The simulated flow behavior of brushes in separation area*

Developer mass per area

DMA is one of important parameters in the design of two-component development systems. DMA decide mass quantity per unit area on the surface of sleeve rotated around magnetic roller. If toner concentration is fixed, the toner amount is proportional to developer amount in the developing nip area. Therefore, the instability of DMA causes the difficulty of image density control. We have tested two different cases of blade with different blade gap shown in Fig.7. Normally, larger gap gives more DMA but it has complicate relation with other parameters. From these evaluation experiments, we found out that the simulation results are well matched within 10% of differences with experimental ones. Because this parameters can be measured quantitatively system during developing printer, DMA prediction with simulation is useful for developer system designer.

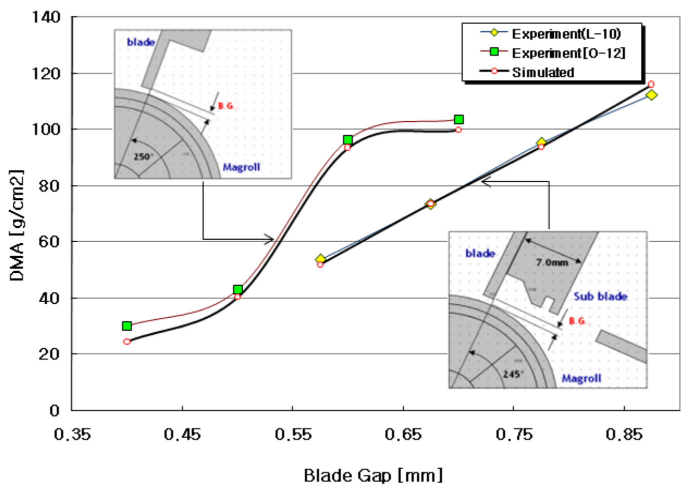

Figure 7. *Comparison of calculated developed mass per (DMA) with experimental results*

Toner developing

Simulation of toner developing requires higher number of particles than magnetic brush behavior simulation with only carriers, because toner particles are larger number than carrier and the size of toner is smaller than carrier in several times. This means calculation needs more time. Simulated result of image forming process near developing area is shown in Fig.8. Latent image pattern was formed on the photoreceptor numerically and the motions of approximately 30,000 carriers and toners were calculated.

Comparison plot shows simulations are reasonably accurate with experimental evaluation. Toner particles developed on the predefined latent image of photoreceptor surface in the post-nip is shown in the figure. Developed toner mass was calculated using 2D model for various DC-bias voltage between magnet roller and photoreceptor (500 ~ 800 V) and then converted to 3D results by multiplying the 3D conversion factor. Compared results of developed toner mass in the calculation and experiment are plotted in Figure 9. The results show good correlation of calculated and experimental values and the accuracy of simulation tool is good enough for the estimation of TMA .

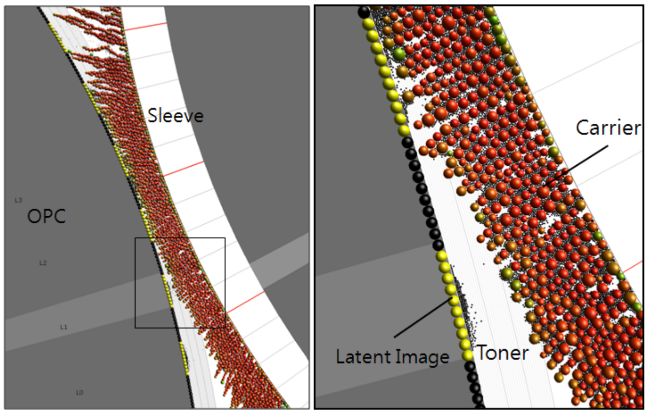

Figure 8. *The Simulated toner and carrier behavior near development nip.*

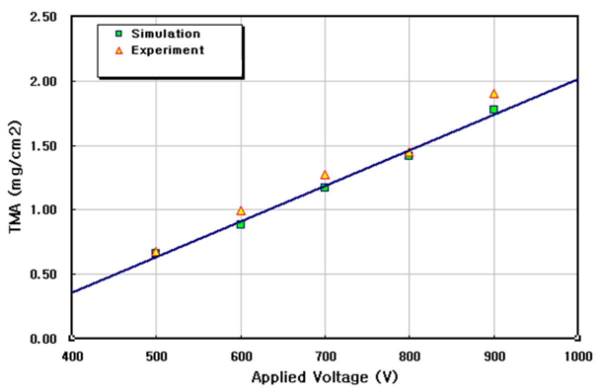

Figure 9. *TMA estimation according to applied DC bias voltage.*

Concluding Remarks

In this paper, a large scale-DEM simulation tool has been developed, which is able to analyze the magnetic brush behaviors in total region surrounding the magnet roller as well as toner imaging process in developing nip. The simulation tool equipped with novel parallel computing method showed remarkably high computational power even in one personal computer. Validity of the tool was confirmed by comparison of calculated developer mass per area (DMA) and developed toner mass(TMA) with the experimental results The simulated results of developer behavior in regulating area and toner behavior in developing nip are agreed with the experiment. From the current research, simulator can be able to estimate characteristics of developer unit more closely with allowable speed. Most of simulation cases have less than 10% of error in DMA and TMA case.

We were able to reduce developing period and easy to analyze developer design problems. Especially blade shape and relative positions with magnetic field distribution of develop roller. Also, optimized design of magnetic roller becomes more important because of reducing size and increasing speed of system. It can also be adapted for simulation of mono component developing process independent with magnetic characteristics. Refining post-process and some material properties will give more accurate information matched with experimental measurement. The simulation of auger system for carrier and toner mixing and charging process are investigating based on this work. With this prior process of current work will improve accurate and convenience of simulation for developer unit in electro photography, but number of particles should be enormously increased. Also, toner developing behavior with 3-dimensional and AC developing with large number of particles are good subject of this novel fast computation technology.

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