Numerical Simulation of Toner Concentration Distribution In Two-Component Developer By Diffusion-Convection Model

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Abstract

We propose a new method applying the diffusion-convection model for numerical simulation of toner concentration distribution so as to design development unit with stable toner concentration at the development area. Numerical calculation by the discrete element method using damper and spring model for individual particle is usual to analyze dynamic behavior of each particle, however it needs enormous calculation time because of the great number of particle to be treated and to account the interaction of them in development unit. To decrease the load of calculation, simple experimental data are introduced beforehand. As the result, knowing the diffusion coefficient and the convection speed of developer in a development unit, the toner concentration distribution can be estimated which shows good agreement with experimental results, and an actual machine can carry out appropriate toner concentration control by adopting this method.

Introduction

Two-component developer always circulates in a development unit by mixing and transporting mechanism such as screw feeders and development roller. However, toner is consumed by development process, and new toner should be supplemented to a part in mixing and transporting mechanism. Therefore toner concentration of developer always has distribution in development unit and it will change with time. In a development unit using two-component developer, agitation mechanism such as screw and paddle is required, 1) to prepare the two-component developer by contacting the supplied toner particles to the carrier particles, 2) to average the toner concentration distribution by diffusing the newly prepared developer, 3) to supply the prepared developer onto the developing roller, and 4) to deliver the developer which has experienced development process to the toner supply area. The prediction of toner concentration distribution by numerical calculation has been our great expectation, because it is useful to know how the toner concentration distribution in development unit will change, when we design the development unit and set up the unit conditions.

As an instance of handling the many-body problem, the discrete element method (DEM) will be mentioned, and it has been applied to the analysis of the diffusion function on the agitation paddle in a development unit.[1] This method could treat individual particle and has every possibility of establishing the guideline on designing the optimum agitation mechanism. However, in the present, it is not suitable for predicting the toner concentration distribution around the development unit because of the enormous calculation time and of the difficulty in reflecting the real developer property in it.

On the other hand, stochastic method which express the dispersion behavior of toner particles by a certain constant named mixing ratio has been investigated.[2] This method is very useful because not only the load for the calculation is comparatively low but also it applies real value given by an experiment. However, it can not treat when there is unidirectional flow of developer in the development unit.

Both of the numerical calculation methods above can handle only diffusion phenomenon of developer. On the other hand, the other method named dispersal model on toner amount and carrier amount has been proposed to treat the flow of developer.[3] However, it needs plural constants which would not be given by measurement directly, and there are no explanation for how to find out those constants.

Here the diffusion and the advection behavior of developer in a development unit has been modeled based on stochastic background, and the numerical calculation for the toner concentration distribution in a development unit has been carried out using diffusion-convection model, whose appropriateness has verified by some experiments.

Stochastic Preparation on the Diffusion and the Advection Property of Developer

Assuming that the one-dimensional velocity of a particle in a screw is composed of both the translation velocity $u(x,t)$ and the random velocity $v(x,t)\eta(t)$ and that the random velocity is Gaussian white noise, the Langevin equation on a particle position x is expressed as

$$\frac{\partial x}{\partial t} = u(x,t) + v(x,t)\eta(t) \ , \qquad (1)$$

$$where \ <\eta(t)> = 0, \ <\eta(t)\eta(t')> = 2\varepsilon\delta(t-t') \ .$$

In this case, applying the stochastic Liouville equation introduced by Kubo[4], the distribution function $\rho(x,t)$ is expressed as

$$\frac{\partial \rho(x,t)}{\partial t} = -\frac{\partial}{\partial x}u(x,t)\rho(x,t) - \eta(t)\frac{\partial}{\partial x}v(x,t)\rho(x,t) \ . \qquad (2)$$

Converting equation (2) into the expression using the density function $P(x,t) \equiv <\rho(x,t)>$,

$$\frac{\partial P(x,t)}{\partial t} = -\frac{\partial}{\partial x}u(x,t)P(x,t) + \varepsilon\frac{\partial}{\partial x}v(x,t)\frac{\partial}{\partial x}v(x,t)P(x,t) \ , \qquad (3)$$

which is called Fokker-Planck equation, is derived.

Here assuming both $u(x,t)$ and $v(x,t)$ are uniform both in time and in space, and putting

$$\left.\begin{aligned} u(x,t) &\equiv U = const \\ v(x,t) &\equiv \sqrt{D/\varepsilon} = const \end{aligned}\right\}, \qquad (4)$$

equation (3) can be expressed as

$$\frac{\partial P(x,t)}{\partial t} = -U\frac{\partial P(x,t)}{\partial x} + D\frac{\partial^2 P(x,t)}{\partial x^2} \ , \qquad (5)$$

which is generally called diffusion-convection equation.

Furthermore, when the weight distribution of developer in a screw is regarded as uniform, $P(x,t)$ expresses the toner concentration: TC.

$$\frac{\partial TC}{\partial t} = -U\frac{\partial TC}{\partial x} + D\frac{\partial^2 TC}{\partial x^2} \qquad (6)$$

The TC distribution can be numerically calculated by replacing the form of equation (6) with the form of difference equation.

Diffusion-Convection Effect by a Screw

In the first place, using a screw installed in a U-drain and putting suitable amount of developer with initial toner concentration distribution as shown in equation (7), an experimental system shown in Fig.1 (a) was prepared.

$$\left.\begin{aligned} TC &= 15[wt\%] \ \ (|x| \le 0.01[m]) \\ TC &= 5[wt\%] \ \ (|x| > 0.01[m]) \end{aligned}\right\} \qquad (7)$$

Next, the screw is rotated with appropriate rotational speed, and the results shown in Fig. 2 is obtained by measuring the toner concentration distribution at $t=t_0$[s], $2t_0$[s], and $4t_0$[s]. On the other hand, by a convergent calculation of equation (6) on the experimental plots in Fig. 2, $U=0.050$[m/s] and $D=0.00012$[m^2/s] is found.

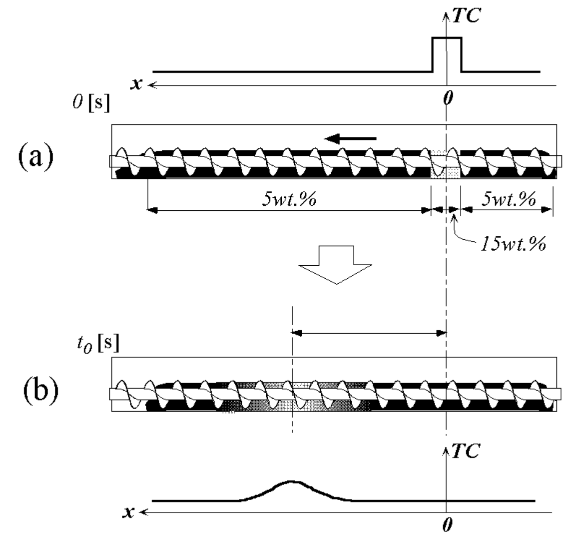

Figure 1. Measurement of screw function

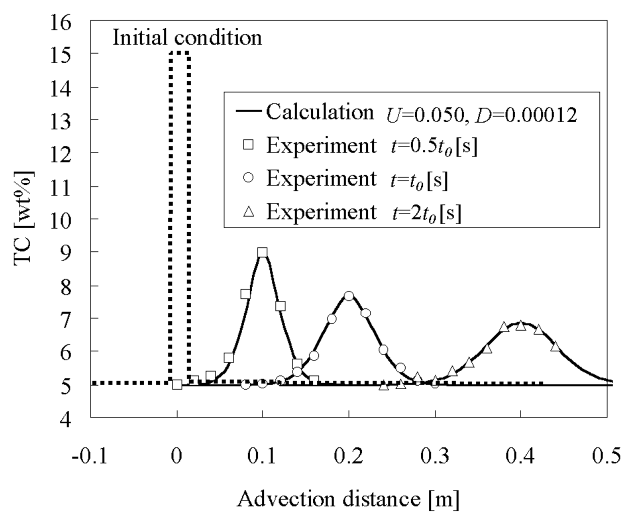

Figure 2. Capability of equation (6) on various agitation time

From these results, it can be understood that the screw function can be identified by only two type of constant (the advection speed U and the diffusion coefficient D) when the screw conditions (such as screw shape, developer level, and rotational speed) has been fixed. That is, the variation of the toner concentration distribution with time on the developer put in arbitrary shape of screw is predictable by knowing only the advection speed U and the diffusion coefficient D.

Application of Diffusion-Convection Model on the Reflux Developer At Sleeve

Let us now consider about the developer attracted to sleeve by magnetic force from agitation area. Figure 3 is the chart diagram of an experiment and shows the cross section of development sleeve, doctor blade, and reflux developer. In the initial state, the toner concentration of the reflux developer is set at *0*[wt%].

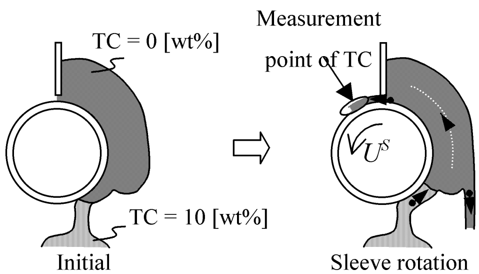

Figure 3. Measurement of sleeve function

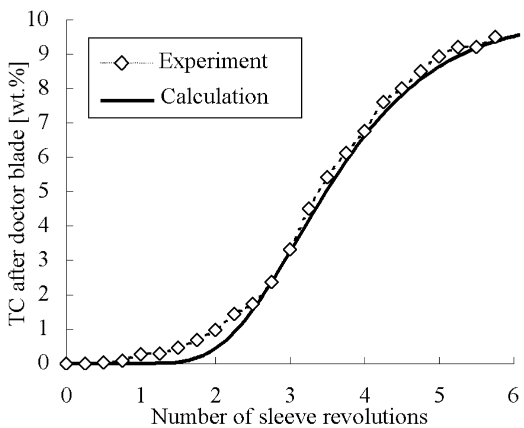

Figure 4. Characteristic curve of sleeve function

As the sleeve rotate, only the developer with *TC=10*[wt%] is attracted onto the sleeve. By measuring the *TC* of the developer metered by the doctor blade, the plotted marks in Fig.4 is obtained. It is very interesting that the *TC* of the developer after the metering process hardly changes when the sleeve takes only one revolution. To understand such phenomena numerically, here the diffusion-convection model is applied. Because the motion of the developer at the reflux area on the sleeve is very complicated, here the simplest system is supposed. That is, considering that the developer may basically has translation velocity followed by the sleeve movement and random velocity caused by the magnetic field on the sleeve, Eq. (6) will also hold in this case. This model is based on the assumption that the diffusion in the normal direction is accomplished immediately and that the advection speed is given by averaging the velocity component of all particles in the reflux area. This apparent advection speed can be derived by considering the conservation of the developer weight between at the attracted area and at the reflux area, which is given as

$$U^* = \frac{\rho \cdot l}{W} U^S \tag{8}$$

where W[kg/m] is developer weight at the reflux area per unit length of the sleeve, l[m] is circumferential length of the reflux area, and ρ[kg/m^2] is the developer amount per unit area attracted by the magnetic force onto the sleeve. By giving such an advection speed, the only parameter identifying the effect of the reflux developer is diffusion coefficient D^*[m^2/s]. The possibility of applying the diffusion-convection model to the experimental result shown in Fig.4 by giving suitable diffusion coefficient is investigated. Using $W=0.67$[kg/m], $l=0.026$[m], and $\rho=1.8$[kg/m^2] as experimental conditions, and numerically solving the diffusion-convection equation on the reflux developer as the solution would fit the experimental result, then diffusion coefficient D^* is found to be ~1×10^{-4}[m^2/s], also showing in Fig.4. The slope of the graph at *TC=5*[wt%] is thought to be mainly determined by D^*, and the needed time (sleeve revolutions in Figure 4) to reach *TC=5*[wt%] will be mainly determined by U^*. If U^* is not appropriate value, then the simulation result would not agree with experimental result. As is shown in Fig.4, the results are in good agreement indicating the validity of how to give the advection speed U^* defined by equation (8).

Next, the function of the reflux developer is investigated by a numerical calculation applying D^* and U^* given above. The simulation is carried out by giving *TC=3.4*[wt%] to the initial toner concentration at the reflux developer, and giving the *TC* fluctuation (frequency; f^{noise}[Hz], amplitude; *0.2*[wt%]) at the attracted developer onto the sleeve as equation (9).

$$TC[wt\%] = 3.4 + 0.2\sin(2\pi f^{noise} t) \tag{9}$$

Figure 5 shows that the reflux developer has a role as low-pass filter which will reduce the high-frequency hysteresis of toner concentration.

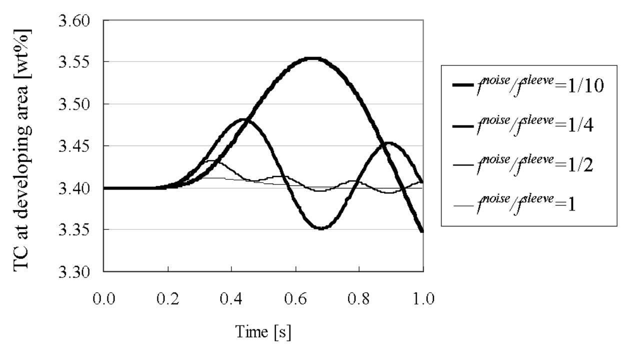

Figure 5. Sleeve operation as low-pass filter (f^{sleeve}[Hz] is the rotational frequency of sleeve)

Toner Concentration Distribution in Development Unit

A numerical simulation on the toner concentration distribution in a development unit is carried out considering both the developer in agitation screw and the reflux developer on sleeve. Subjected development unit is consist of two agitation screws (Screw 1 and Screw 2), toner supply unit at the upstream of Screw 2, and toner concentration sensor at the downstream of it (Fig. 6).

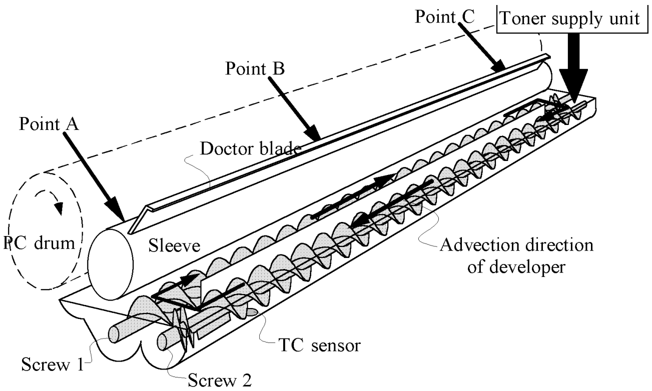

Figure 6. Schematic drawing of developer unit

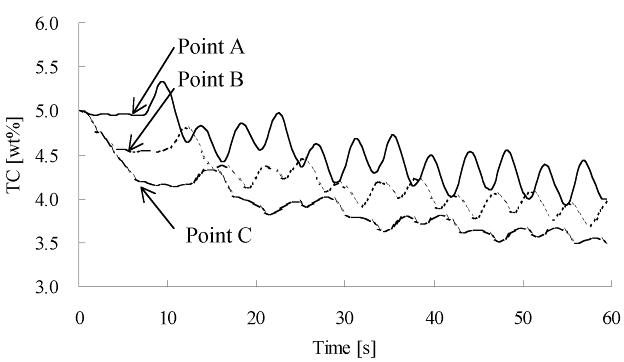

Figure 7. Simulation of TC at development area on sleeve

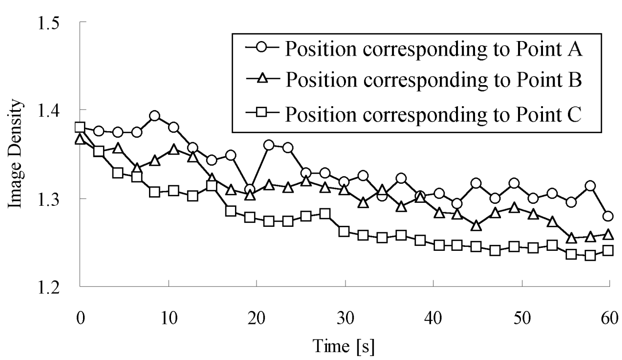

Figure 8. Experimental results of image density on printed paper

Toner in the development unit is consumed at the development area, and new toner is supplied from the toner supply unit in response to the signal from the toner concentration sensor. The simulation is carried out with the condition of continuous printing mode with 100% solid image pattern on A4 size paper, and the result is shown in Fig.7. On the other hand, Fig.8 shows the experimental result of the variation of the image density on printed paper. Although there is a difference in axis of ordinates between Fig.7 and Fig.8, the both results are considered to be in good agreement because the image density on the printed paper is thought to correlate closely with the toner concentration of the developer at the development area.

Conclusions

The developer behavior in a development unit can be expressed by diffusion-convection model followed by Fokker-Planck equation. Characterizing the behavior of developer in agitation mechanism and on sleeve by two parameters such as diffusion coefficient and advection speed, and constructing the numerical simulator based on diffusion-convection model, thus the quantitative prediction of the variation of the toner concentration distribution in a development unit is succeeded. The value of each parameter can be given not only by the simple experiment above but also by some analytical methods or some other approaches. It is useful for designing and analyzing the actual development system due to the simple scheme.

References

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Biography

Takeo Tsukamoto received his B.S. and M.S. degrees in Physics from Keio University in 1992 and 1994, respectively. He joined Ricoh in 1994 as a member of research scientist, and has been working in the area of electrophotography. Firstly, he studied the liquid development process, and recently he has been working on the dry development process.