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PIV Measurement of Toner Particle Motion in a Micro-gap in the Development Process of Electrophotography

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Abstract : In the development process of electrophotography, charged dielectric toner particles move in a micro-gap between the photoreceptor and the development roller to form images by the action of electrostatic force. To improve image quality, it is important to clarify the toner particle motion and the effects of the electric field on this motion. In the present study, Particle Image Velocimetry (PIV) was applied to measure the toner particle motion and the results were compared to calculated results. It was confirmed that the toner velocity increased with increasing electric field intensity, and that the measurement results agreed with the calculated results. These results indicated the usefulness of PIV in analyzing toner particle motion in the development process.

Keywords : PIV, Micro-flow, Electrophotography, Development, Toner.

1. Introduction

Electrophotography is a well-known image forming method used in, for example, copiers, printers, and fax machines. In the electrophotography, charged particles called toner particles, which are approximately 10 μm in diameter, are moved by electrostatic force in an electric field to form images on a recording media. The electrophotography process is described schematically in Fig. 1. The electrophotography process consists of six sub-processes—charging, exposure, development, transfer, fusing and cleaning—which take place in the vicinity of the photoreceptor. In the present study, we focused on the toner particle motion in the development process, in which toners are moved to electrostatic latent images formed on the photoreceptor from the development roller by electrostatic force.

The configuration of the development process is also described in Fig. 1. A development roller is set against a photoreceptor with a narrow space (typically 100-500 μm) between them. Dielectric toner is provided on the development roller, and these toner particles are negatively charged by the friction between a blade and the particles on the development roller. The negatively charged toner particles are transported into the development area (the rectangular box indicated by broken lines in Fig. 1) by rotation of the roller. The electrostatic latent images are formed on the photoreceptor surface in the charging and exposure sub-processes. In addition, the electric field is formed between the latent images and the biased development roller. The toners in the development area are moved to the photoreceptor surface from development roller to form real images by the action of electrostatic force in an electric field. The toner particle motion is thought to be controlled primarily by electrostatic force, and the variation in toner particle motion in a disturbed field is thought to cause image degradation. Quantitative clarification of the motion and clarification of the mechanism of the image degradation are very important in order to achieve high-quality imaging. Numerical studies (Ito et al., 2000; Kubota et. al., 2000; Nakano, 2000) have been performed in place of experimental studies because of the difficulty involved in the direct measurement of high-speed particle motion in a micro-gap. However, the appropriateness and accuracy of the numerical studies has not been confirmed directly or quantitatively. As a result, direct observation of toner particle motion has been attempted in recent years (Hirabayashi, 2002; Hirooka et al., 2001; Howard et al., 2000; Uchida, 2002).

In this study, PIV was applied to measure the toner particle motion in the development area. First, toner characteristics and motion, including population, size and direction of movement of toner particles, were measured and discussed to confirm the applicability of PIV measurement. Then, the velocity distribution of toner particles was measured and the results were compared to the theoretical and numerical results for verification of quantitative accuracy and applicability of the technique.

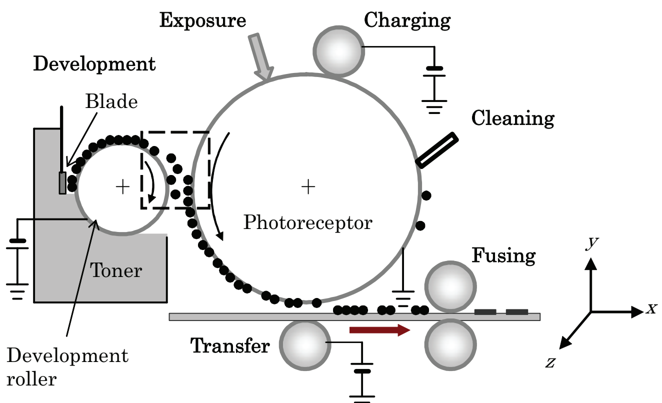


Fig. 1. Development process of electrophotography.

2. Toner Particle Motion in the Development Process

Toner particle motion is expressed by Eq. (1).

$$m\frac{d\boldsymbol{u}}{dt} = \boldsymbol{f}_t \tag{1}$$

where m, $\boldsymbol{u}$ and $\boldsymbol{f}_t$ are the mass, velocity vector and total applied force vector, respectively, of an individual toner particle. In this study, electrostatic force $\boldsymbol{f}_e$, aerodynamic drag $\boldsymbol{f}_a$ and gravitational force $\boldsymbol{f}_g$ are considered in the calculation of $\boldsymbol{f}_t$.

The electrostatic force $\boldsymbol{f}_e$ acting a toner particle with charge q in electric field $\boldsymbol{E}$ is calculated as

$$\boldsymbol{f}_e = q\boldsymbol{E} \tag{2}$$

The electric field in the development area depends on the voltage and on the gap between the photoreceptor and the development roller and can be numerically calculated by, for example, the Finite Element Method (FEM). In addition, the field intensity can be approximated by V/d, where V is the voltage and d is the horizontal gap (in the x-direction) between the development roller and the photoreceptor surface at each y-position.

The theoretical values, V/d in the case of a minimum gap of 300 μm, are plotted in Fig. 2. The horizontal axis is in the y-direction ($y = 0$ at the closest point to the rollers) and the vertical axis is the relative field intensity ($E = 1.0$ at a voltage of 1600 V). The field intensity varies with voltage and the gap width, as is obvious from Eq. (2). The charge of a typical toner particle is approximately 10^{-15} C, thus the electrostatic force is 10^{-9}～10^{-8} N. Aerodynamic drag and gravitational force are much lower than this range of forces. This means that toner particle motion is controlled primarily by electrostatic force, and we can estimate the velocity distribution of moving toner particles from the figure. Toner velocity near the position $y = 0$ mm tends to increase due to the high electric field intensity, and that near the position $y = 6$ mm tends to become relatively slower due to the low electric field intensity.

If we consider only the electrostatic force in Eq. (1), one-dimensional toner particle motion can be easily determined analytically. The calculation should provide valuable information. However, numerical procedures are required in order to solve Eq. (1) more precisely. The Distinct Element Method (DEM) (Cundall and Strack, 1979) was used to calculate the motion of a large number of toner particles. The motion of each toner particle is determined by solving Eq. (1) considering the contact force between particles in addition to the electrostatic force. In the DEM calculation, the contact force between particles is evaluated by assuming the Foigt model. The property of the spring in the model is estimated by the Hertzian contact theory according to a previous study (Nakayama and Mukai, 1999). Aerodynamic drag was calculated using Stoke's law.

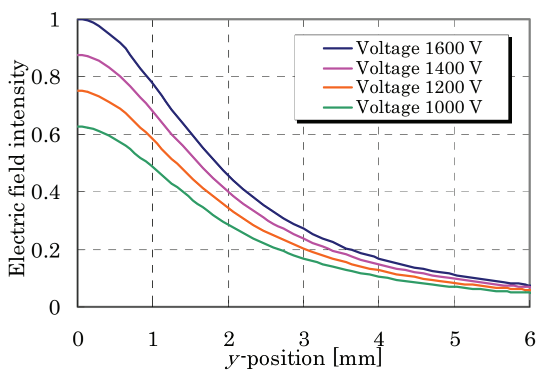


Fig. 2. Calculated electric field dependence on voltage and gaps.

3. Measurement Method

The PIV system used in the experiment is described schematically in Fig. 3. The diameters of the development roller and the photoreceptor are 16 and 40 mm, respectively, and the gap between the rollers was set at 300 μm. The development roller and the photoreceptor rotate at 49.5 rpm (circumferential velocity: 41.4 mm/sec) and 12.5 rpm (circumferential velocity: 26.2 mm/sec), respectively.

In this experiment, toner particles are used as tracer particles in general PIV measurement. The mean diameter of toner particles, which is equal to the sum of particle diameters divided by the toner particle population, used in the measurement is approximately 4.54 μm, and the charge per unit mass is approximately -0.011 C/kg. A double-pulsed Nd:YAG laser (New Wave Research, Inc., Solo-Ⅲ, wavelength: 532 nm, maximum energy: 50 mJ/pulse, thickness of sheet: 0.14 mm) was used to supply the pulsed laser sheet and illuminate toner particle motion at intervals of 10-20 μs. Images were captured through zoom lens (Keyenece Corporation, VQ-Z50, depth of field: 611 μm and VH-Z35, depth of field: 1 mm) and a CCD camera (Eastman Kodak Co., ES1.0, 1008×1018 pixels, 8 bits, or Hamamatsu Photonics K.K., C7300, 1280×1024 pixels, 12 bits). To analyze a pair of images, the successive abandonment algorithm (Kaga et al., 1994) and the algorithm for particle tracking velocimetry using binary pixels (Uemura et al., 1990) were employed. The former algorithm is used in Particle Image Velocimetry (PIV), and the latter algorithm is used in Particle Tracking Velocimetry (PTV).

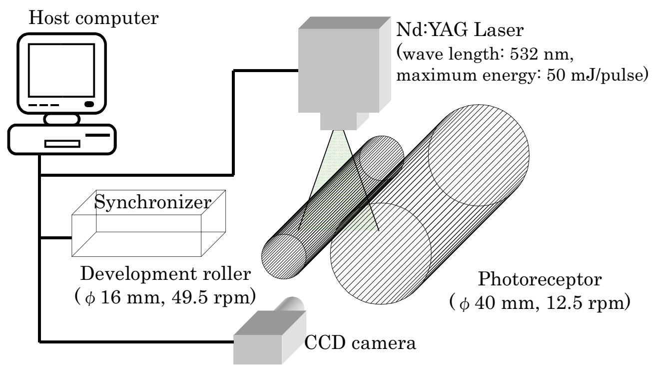


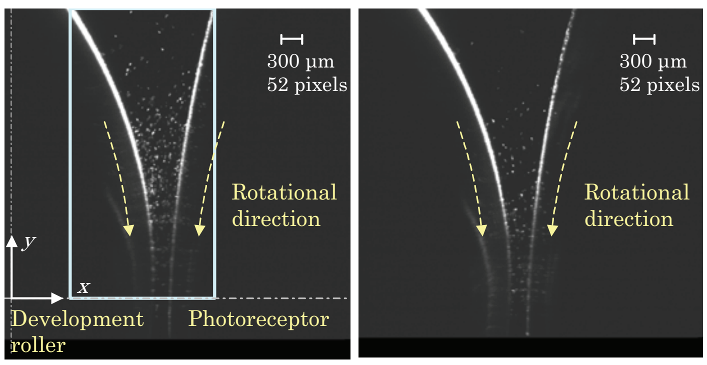
Fig. 3. Experimental set-up.

4. Results and Discussion

4.1 Captured Images

In this experiment, a CCD camera (Eastman Kodak Co., ES1.0, 1008×1018 pixels, 8 bits) and a zoom lens (Keyenece Corporation, VQ-Z50, depth of field 611 μm) were used. Examples of captured images are shown in Fig. 4. These images show toner particle motion in the axial plane (*xy*-plane) of the development area. Thick white lines indicate roller surfaces, and the numerous white spots between the rollers are toner particles.

From the figure it is clear that toner particles vary in size and that the toner particle population has a spatial distribution. In addition, comparison of Figs. 4(a) and (b) reveals that the total number of toner particles decreased and the distribution of toner particle population varied with the decrease in the applied voltage. The difference in toner particle motion is thought to correspond to the difference in the electric field intensity.



(a) Voltage 1600 V (b) Voltage 1200 V

Fig. 4. Examples images of toner particles in the development area.

4.2 Distributions of Size and Population of Toner Particles

Distributions of toner particle size and population, shown in Fig. 4(a), were investigated. A histogram of toner particle size is shown in Fig. 5(a). The horizontal axis is the toner particle size obtained based on an image analyzed by an image processor. The standard deviation of toner particle size on the image is 12 µm. Here, the unit (pixel) is converted to µm for a spatial resolution of 5.77 µm/pixel. Moreover, toner diameter in the image plane is converted to actual toner diameter (Nishino, 2000).

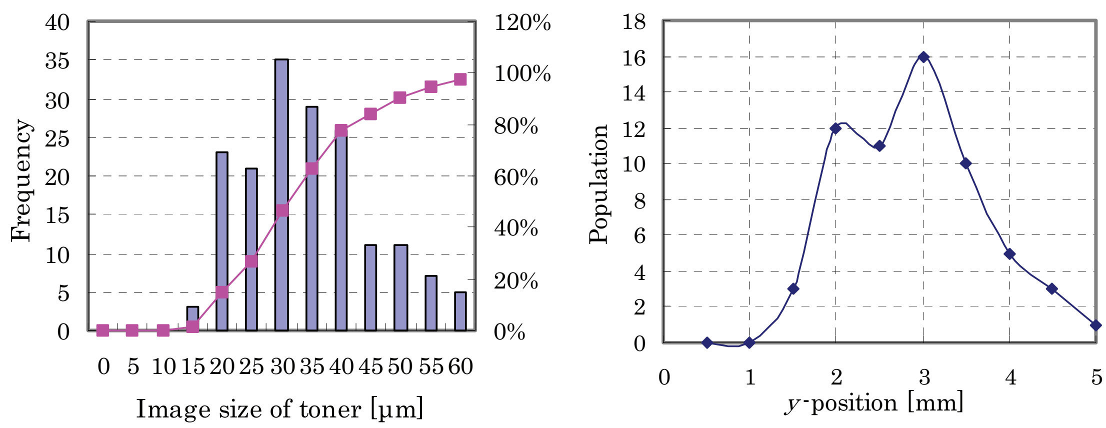
The diameter of the diffraction-limited point spread function d_a in the image plane, is given by

$$d_a = 2.44\lambda(1+M)F \tag{3}$$

where λ is the wavelength of the light, M is the total magnification of the microscope and F is the F-value.

Particle size in the image plane d_e is expressed by

$$d_e = \sqrt{M^2 d_p{}^2 + d_a{}^2} \tag{4}$$



(a) Histogram of toner sizes (b) Distribution of toner population along *y*-axis

Fig. 5. Measured characteristics of moving toner particles.

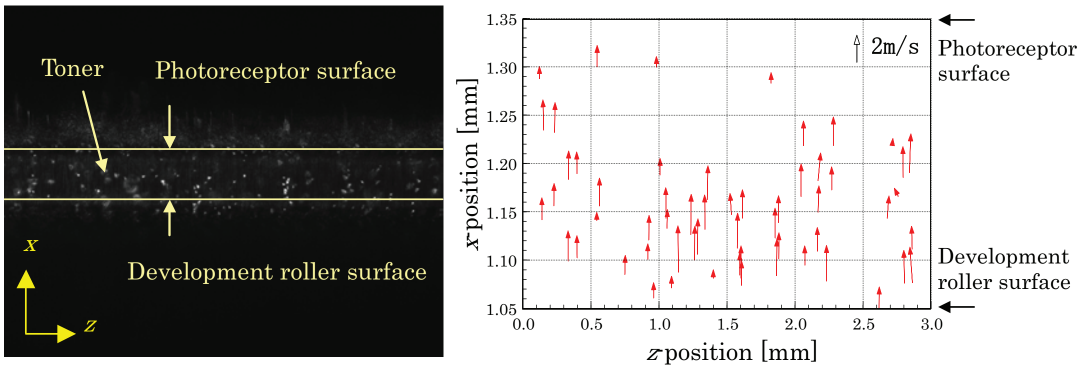
where d_p is the particle diameter. The mean diameter of the toner particles is approximately 4.54 µm, which is equivalent to 31.9 µm on the obtained images. Figure 5(a) shows that more than half of the toner particles move independently; whereas, the rest are formed by clusters of toner particles. For precise calculation, the distribution of particle size in the numerical study should be considered.

The distribution of toner particle population along the *y*-axis is shown in Fig. 5(b). The horizontal axis is the position in the *y*-direction, and the vertical axis is the toner particle population at every 0.5 mm along the *y*-axis. The figure shows that most toner particles began to move before reaching the point closest to the rollers ($y = 0$ mm). The distribution of toner particle population is thought to shift according to the magnitude of the electric field intensity, as described in Figs. 4(a) and (b).

4.3 Direction of Movement of Toner Particles

If we wish to observe the toner particle motion in the *xy*-plane, the toner particles must move in the *x*-direction only. Therefore, toner particle motion was observed on the *xz*-plane with an applied voltage of 1600 V, and the velocity vectors in the *xz*-plane were analyzed. In this experiment, a CCD camera (Hamamatsu Photonics K.K., C7300, 1280×1024 pixels, 12 bits) and a zoom lens (Keyenece

Corporation, VH-Z35, depth of field: 1 mm) were used. An example image is shown in Fig. 6(a). The surfaces of the rollers are not clear because the laser was illuminated in the z-direction. Although toner particles in the area between the photoreceptor and the development surface were in focus, toner particles in other areas were out of focus due to the narrow depth of field. Velocity vectors are shown in Fig. 6(b). Four pairs of toner images, which were acquired under the same experimental conditions, were analyzed by PTV and the results are described in the same figure. It follows that most toners move straight from the development roller to the photoreceptor.

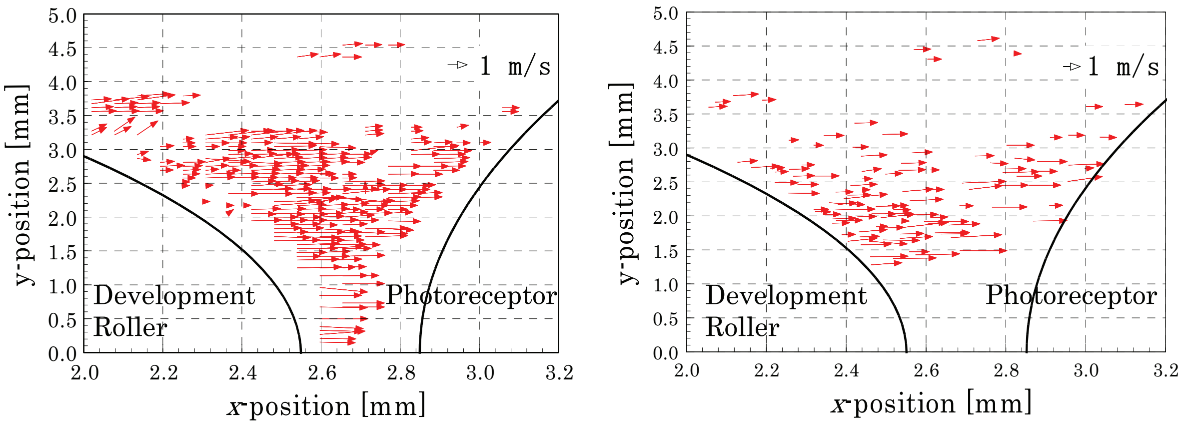


(a) Toner image in *xz*-plane (b) Velocity vectors in *xz*-plane

Fig. 6. Measurement results for the direction of movement of toner particles.

4.4 Velocity of Toner Particles

Velocity vectors in the xy-plane are plotted in Fig. 7. Figures 7(a) and (b) show instantaneous velocity vectors at a voltage of 1600 V as analyzed by the PIV and PTV algorithms, respectively. The area described in each figure corresponds approximately to the rectangular box indicated in Fig. 4. Each figure shows the velocity vectors from the development roller to the photoreceptor. The velocity in the narrower gap and near the photoreceptor is thought to be higher, and the directions of velocity vectors is thought to vary depending on the position of the moving toner particles.



(a) Velocity distribution analyzed by PIV (b) Velocity distribution analyzed by PTV

Fig. 7. Velocity vectors of toner particles in the development area.

4.5 Comparison with Calculated Results

In order to verify the accuracy of the measured velocity, the experimental results described in Figs. 7(a) and (b) were compared to the theoretically and numerically calculated results.

Figure 8 shows the numerically calculated results of potential, electric field and toner particle motion with two-dimensional FEM and DEM. In Fig. 8(a), potential contours are described. Blue indicates relatively lower potential and red indicates relatively higher potential. Equipotential lines are approximately parallel to roller surfaces. Figure 8(b) shows the x-component of the electric field. As mentioned earlier, the field in the x-direction increases as the gap between the rollers decreases. Figure 8(c) describes the transient motion of toner particles. In this numerical calculation, mean diameter, charge per unit mass and volume density were 4.54 μm, -0.011 C/kg and 1200 kg/m^3, respectively. The voltage was 1600 V, and, with the exception of the standard deviation, the parameters for the numerical calculation were those obtained via measurement. The standard deviation was assumed to be 10% of the mean toner particle diameter.

First, toner particles are deposited on the development roller under the gravitational field, and an electric field is then applied. Toner particles are transferred by electrostatic force to the photoreceptor as a sheet. The sheet of toner particles is dispersed somewhat during this transfer due to differences in size, mass, and charge of the toner particles. The toner particles closest to the rollers reach the photoreceptor surface 0.2 ms after the application of the electric field. In contrast, toner particles near the left side of the figure require more time to reach the photoreceptor.

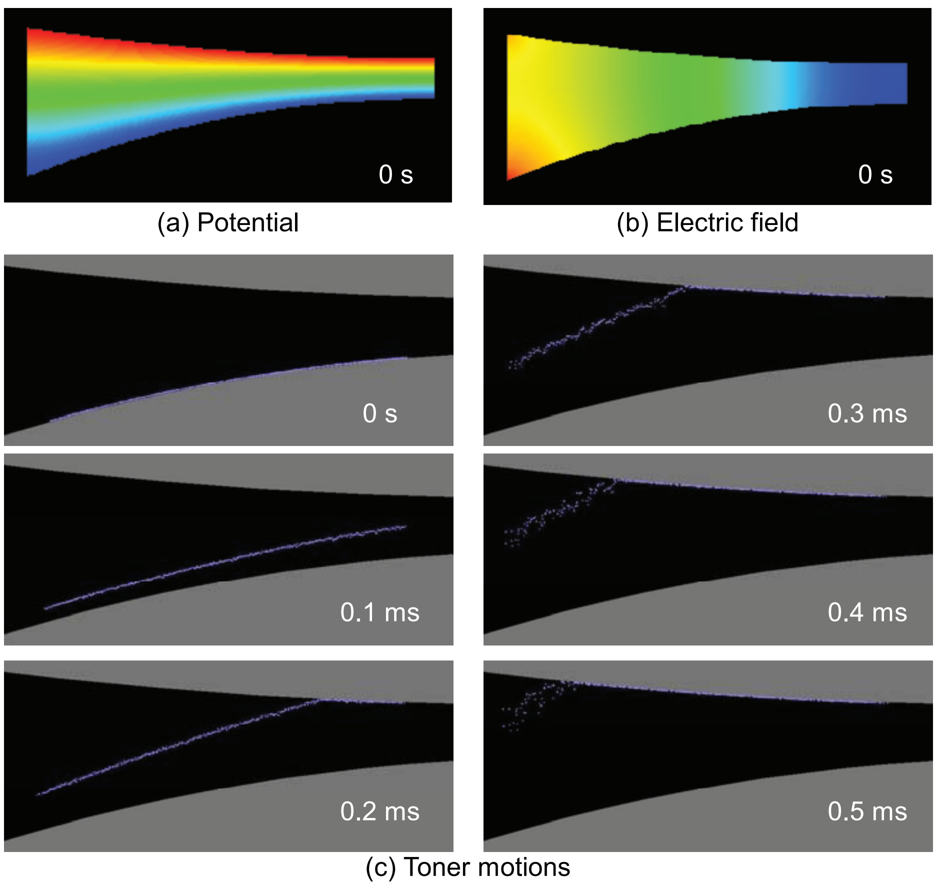
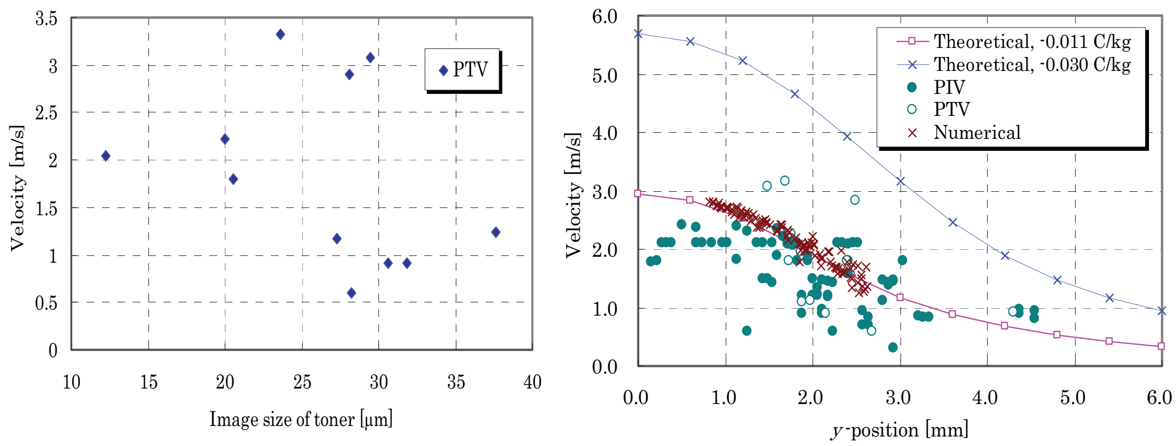


Fig. 8. Calculated electric field and toner particle motion in the development area.

The velocity vectors of the toner particles near the center of the gap are plotted in Fig. 9. Figure 9(a) shows the velocity distribution analyzed by PTV with respect to toner particle image size. Large toner particles tend to move relatively slowly compared to small toner particles. Figure 9(b) shows the velocity distributions obtained via calculated results and measurement results as functions of the *y*-position. Circles indicate the measured velocity and solid lines indicate the theoretically calculated velocity of toner particles having different charges (typical case: -0.011 C/kg, highly-charged case: -0.030 C/kg). In theoretical estimation, particle motion in the electric field, which was calculated by *V*/*d*, was approximated using the difference method while considering aerodynamic drag. The diameter of toner particles was assumed to be 4.54 μm, and the other properties assumed in the theoretical calculation are in the same as those used in numerical calculation. Diagonal crosses indicate numerically calculated velocities.

These results clearly show the dependency of toner particle velocity on the *y*-position. Experimental, numerical and theoretical results for typical charged toner particles agree quantitatively. However, measured toner particle velocity varies in the range from 0.3 to 3 m/s. This variation is thought to result primarily from differences in toner properties, because the theoretical results for highly-charged toner particles give values that are twice as large as those for typical toner particles. These results indicate satisfactory quantitative accuracy and the applicability of PIV measurement.



(a) Velocity distribution analyzed by PTV (b) Comparison of velocity distribution of toner particles

Fig. 9. Velocity distribution of toner particles at the center of the development area.

5. Conclusion

PIV was applied to measure toner particle motion in the development process to clarify the usefulness of the PIV method in studies on the development process and for the improvement of image quality. Fundamental characteristics of toner particle motion were observed and the measured velocity was discussed by comparison with calculated results. The investigation clarified the following:

(1) More than half of the toner particles move independently, and the rest are considered as larger toner particles or clusters of toner particles.

(2) The population of moving toner particles has a spatial distribution. Under the experimental condition adopted herein (voltage: 1600 V, minimum gap: 300 μm), most toner particles began to

move before reaching the closest point between the rollers. The distribution shifts according to electric field intensity.

(3) Toner particles move straight from the development roller to the photoreceptor.

(4) The toner velocity is on the order of 1 m/s and varies widely depending on the properties of the toner. The measurement results agree quantitatively with the calculated results. These results indicate satisfactory quantitative accuracy and demonstrate the usefulness of PIV measurement.

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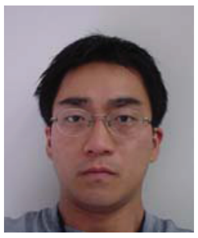

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