Electrostatic Manipulation of Particle

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Abstract

We have been investigating an electrostatic manipulation of a small particle, such as toner and carrier particles. A manipulator consisted of two parallel pin electrodes. When voltage was applied between the electrodes, electrophoresis force generated in non-uniform electrostatic field was applied to the particle near the tip of the electrode. The particle was captured by the application of the voltage and released from the manipulator by turning off the voltage application. It was possible to manipulate not only insulative but also conductive particles. However, if the particle was charged, Coulomb force and adhesion force prevented to release the particle when the voltage was turned off. This condition was apt to take place for small particles, less than 200 μm in diameter. The third electrode was introduced near the dipole electrodes to blow off the particle by the ionic wind and the validity of this system was demonstrated. An uneven electrode system without the additional separation electrode was also developed to release the attached particle independently of the position of the manipulator. Three-dimensional calculation was conducted by the Finite Difference Method and compared to the measured force.

Introduction

We have been investigating an electrostatic manipulation of a small particle [1], such as toner and carrier particles, because it is indispensable for the basic research on particle dynamics [2]. A manipulator consists of two parallel wire electrodes. When voltage is applied between the electrodes, the dielectrophoresis force generated in the non-uniform electrostatic field is applied to the particle near the tip of the electrode [3]. The particle is captured by the application of voltage and released by turning off the voltage application [4]-[8]. In this study, we have investigated fundamental characteristics of the system.

Experimental

A setup shown in Figure 1 was constructed to manipulate small particles. Two parallel wire electrodes, both 300 μm in diameter made of stainless steel, were insulated by insulation tubes and spaced in 1 mm between the wire centers. The electrodes were connected to a xyz mechanical stage through an arm to control the position of the manipulator manually. High voltage was applied to the electrode by a DC power supply (Matsusada Precision, HEOPT-1B30). The performance of the manipulation was observed by a high-speed camera (Photoron, FASTCAM-MAX 120K model 1) with a back light (Sanei Electric, XEF-501S).

Numerical

The dielectrophoresis force $\boldsymbol{F}$ applied to the particle is calculated by the integration of Maxwell's stress $\boldsymbol{f}$ over the surface S of the particle in the non-uniform electrostatic field $\boldsymbol{E}$.

$$\boldsymbol{F} = \boldsymbol{n}\int_S f\, dS , \quad (1) \qquad f = \frac{1}{2}\varepsilon_0\varepsilon_r\left(\boldsymbol{n}\cdot\boldsymbol{E}\right)^2 , \quad (2)$$

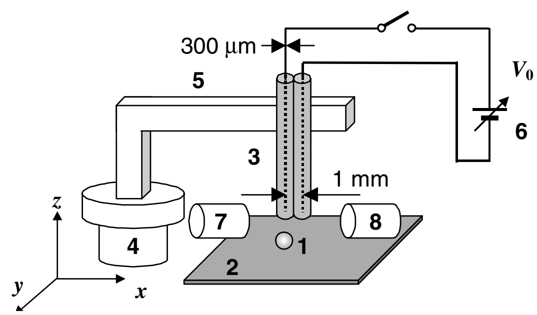


***Figure 1.** Experimental set-up of electrostatic manipulation with dipole probe (1: particle, 2: plate, 3: dipole electrodes coated with insulator, 4: xyz mechanical stage, 5: arm, 6: power supply, 7: high-speed camera, 8: light)*

where ε_0 is the permittivity of free space, ε_r is the relative permitivity, and $\boldsymbol{n}$ is a unit normal vector to the particle boundary. The electrostatic filed $\boldsymbol{E}$ ($= -\nabla\phi$) is determined by the Poisson equation and the conservation of charge.

$$\nabla\cdot\left(-\varepsilon_0\varepsilon_r\nabla\phi\right) = \rho , \quad (3) \qquad \nabla\cdot\left(-\sigma\nabla\phi\right) + \frac{\partial\rho}{\partial t} = 0 , \quad (4)$$

where ρ is the charge density, ϕ is the potential, σ is the conductivity, and t is time. Boundary and initial conditions are as follows.

$\phi = V_0$	on one side of the electrodes, where V_0 is the applied voltage,
$\phi = 0$	on the other side of the electrodes,
$\boldsymbol{n}\cdot\nabla\phi = 0$	on other insulated boundaries,
$\rho = 0$	at $t = 0$.

Distributions of the potential ϕ and the charge density ρ were calculated numerically with the three-dimensional iterative Finite Differential Method. Figure 2 shows the geometries for the FDM calculation. Instead of the infinite boundaries, large distances from the tip of the pin (x, y, z = 5 mm) are determined as the insulated boundary.

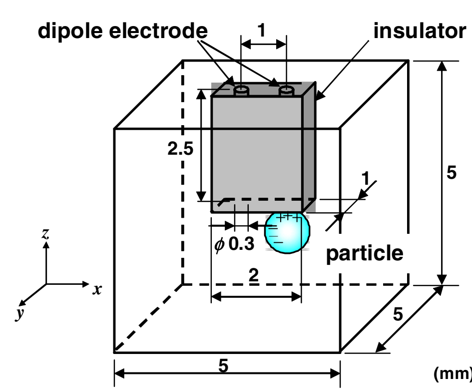
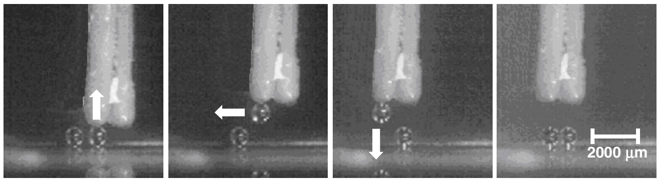
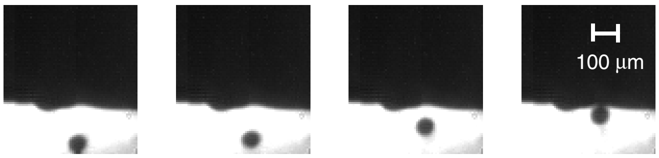


***Figure 2.** Geometries of three-dimensional FDM calculation to calculate polarized electrostatic field.*



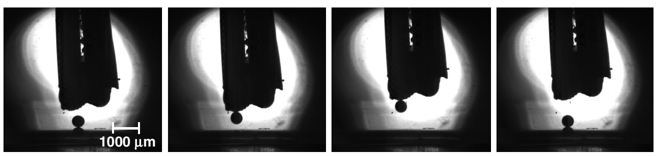
(a) capture, 0 s (b) move, 4 s (c) separate, 8 s (d) release, 9 s

Figure 3. *Manipulation of glass particle. (1,000 μm, 1.6 kV)*



(a) 0 ms (b) 0.2 ms (c) 0.4 ms (d) 0.6 ms

Figure 4. *Manipulation of carrier particle. (100 μm, 1.6 kV)*



(a) approach, 0 s (b) capture, 3 s (c) move, 6 s (d) release, 9 s

Figure 5. *Manipulation of zinc particle. (100 μm, 1.6 kV)*

Demonstration of Particle Manipulation

It was demonstrated that an insulative glass particle was captured by the application of voltage higher than the threshold, 800 V in this case, and released by turning off the voltage application as shown in Figure 3.

It was also demonstrated that a highly resistive carrier particle, 10^7-10^9 Ωcm, was also possible to manipulate as shown in Figure 4. The particle was used in the two-component magnetic development system in electrophotography. However, particles smaller than 50 μm diameter could not be released even when the voltage application was turned-off. Adhesion force and/or Coulomb force might be larger than the weight of the small particle.

Lastly, manipulation of conductive particle was demonstrated as shown in Figure 5. These experiment was conducted not only in air but also in oil.

In conclusion, not only insulative but also conductive particles can be captured both in air and in oil. However, adhesion force and Coulomb force, if the particle was charged, prevented to release the particle even if the voltage was turned off. This condition was apt to take place for small particles.

Measurement and Calculation of Force

Force to the particle was measured by a setup shown in Figure 6. The dipole electrodes were upended and the glass particle connected to the free end of the cantilever through a fine wire was approximated to the manipulator. The displacement of the cantilever was measured by a laser displacement meter (Keyence, LK-080) just when the particle was captured to the manipulator and the force to the particle was derived multiplying the measured displacement and the stiffness of the cantilever. The stiffness was statically measured dividing weights put on the free end of the plate by the static displacement measured by the laser displacement

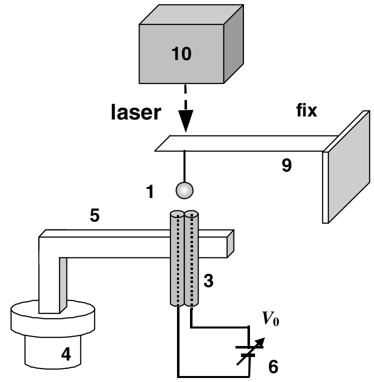
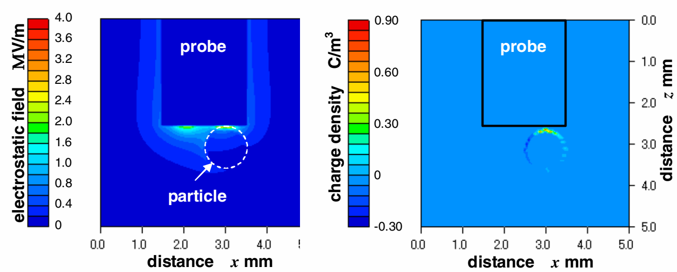


Figure 6. *Setup to measure force to particle. (9: cantilever, 10: laser displacement meter)*



(a) electrostatic field (b) charge density

Figure 7. *Distributions of electrostatic field and charge density. (1,000 μm glass particle, 1.6 kV).*

meter. The adhesion force was also measured using this setup when the applied voltage was settled to be zero after the attachment.

Figure 7 shows calculated distributions of the electrostatic field and the charge density. High electrostatic field was generated at the tip of the electrode [refer to Figure 7(a)] and the particle was polarized [refer to Figure 7(b)].

Figure 8 summarizes measured and calculated forces. Although the qualitative feature that the force is proportional to the square of the applied voltage was in good agreement with each other, the measured force (exp. B: measured total force minus measured adhesion force) was much smaller than the calculated electrophoresis force (cal. A: calculated electrophoresis force).

Because the particle is assumed to be charged in contact with the insulator of the wire electrode, the charge of the attached particle was measured utilizing the setup shown in Figure 1 to estimate the Coulomb force. After the particle was captured to the manipulator, the applied voltage between the electrodes was turned off and then the voltage was applied between the capture electrode and the lower plate so that the captured particle separated from the manipulator by the Coulomb force. The motion of the particle from the manipulator to the plate was measured by the high-speed camera and the charge of the particle q was determined by the following equation.

$$m\boldsymbol{a} = q\boldsymbol{E} + m\boldsymbol{g} - 6\pi\eta r\boldsymbol{v} \ , \qquad (5)$$

where m is a mass of particle, $\boldsymbol{a}$ and $\boldsymbol{v}$ are an acceleration and velocity of particle measured by the high-speed camera, respectively, $\boldsymbol{g}$ is the acceleration of gravity, η is the viscosity of air, and r is the

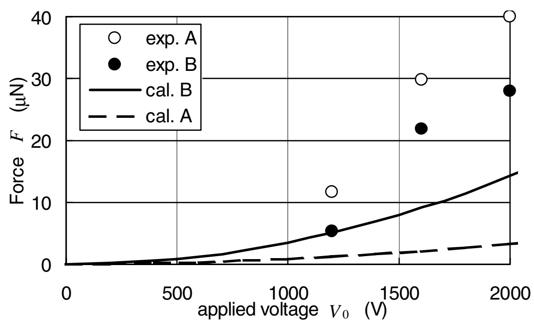


Figure 8. *Measured and calculated force applied to particle. (1,000 μm glass particle) exp. A: measured total force, exp. B: measured total force minus measured adhesion force, cal A: calculated electrophoresis force, cal. B: calculated electrophoresis force plus Coulomb force*

radius of the particle. The electrostatic field $\boldsymbol{E}$ was calculated to the corresponding boundary condition, i.e., $\phi = V_0$ on one side of the electrodes and $\phi = 0$ on the plate electrode, by the Finite Differential Method. The Coulomb force was calculated using the measured charge by this procedure, 2.0×10^{-6} μC for the 1,000 μm glass particle, and the calculated force added to the electrophoresis force was shown as 'cal. B' in Figure 8. A large discrepancy still exists between the measured and calculated, even if the adhesion and Coulomb forces were evaluated. Further investigation, such as the effect of charge distribution, is necessary to evaluate forces applied to the particle during manipulation more accurately.

Release of Particle

We have developed a new system to control the release of a small particle. The system utilizes ionic wind as shown in Figure 9 [9]. The third pin electrode was placed between the parallel electrodes. After turning off the voltage application between the parallel electrodes and if a small particle did not released from the electrode, DC voltage higher than the corona onset was applied between the third electrode and the plate electrode. Ionic wind was generated from the tip of the third electrode to the plate electrode and the particle was blown off by the wind as demonstrated in Figure 10.

Figure 11 shows another miniaturized system based on the similar principle with that of Figure 9.

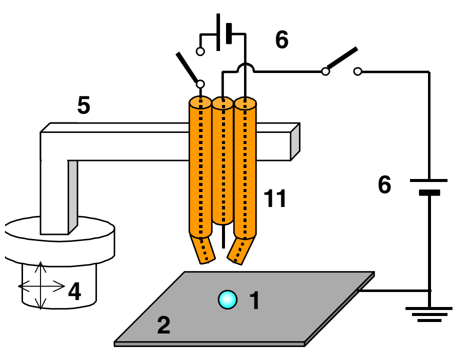


Figure 9. *Experimental set-up of separation system utilizing ionic wind. (11: triple electrodes coated with insulator)*

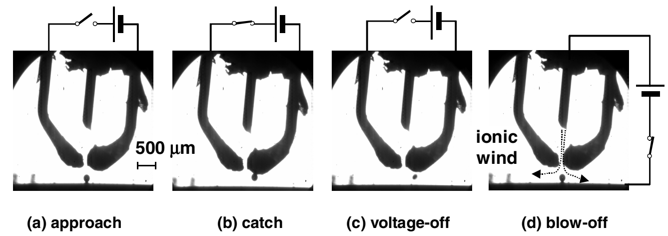


Figure 10. *Separation of captured particle utilizing ionic wind.*

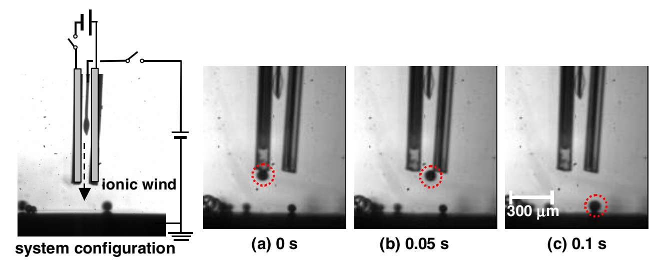


Figure 11. *Miniaturized manipulation system with separation electrode utilizing ionic wind. (electrode diameter: 50 μm, particle: 88 μm carrier particle, capture voltage: 800 V, release voltage, 2,000 V)*

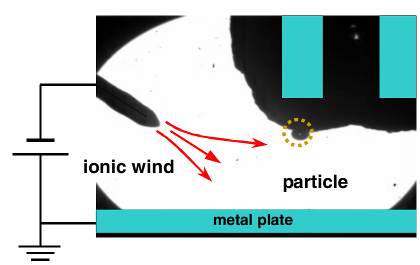


Figure 12. *Manipulation system with leaned separation electrode utilizing ionic wind.*

On the other hand, when the separation electrode was located outside of the manipulation and leaned to the plate as shown in Figure 12, particle can be blown off to the lateral direction, because the ionic wind flows almost parallel to the leaned separation electrode [10].

All of these triple-electrode systems have a demerit that the corona onset voltage and the release force depend on the gap between the separation electrode and the plate electrode. An uneven electrode system without the additional separation electrode was developed as shown in Figure 13 to improve this disadvantage. After turning off the voltage application between the wire electrodes and if a small particle did not released from the electrode, DC voltage higher than the corona onset was applied between the electrodes. Ionic wind was generated from the tip of the electrodes and the particle was blown off by the wind as demonstrated in Figure 13. Because the corona onset voltage and the strength of the ionic wind are independent to the gap between the manipulator and the plate, the attached particle can be released independently of the position of the manipulator.

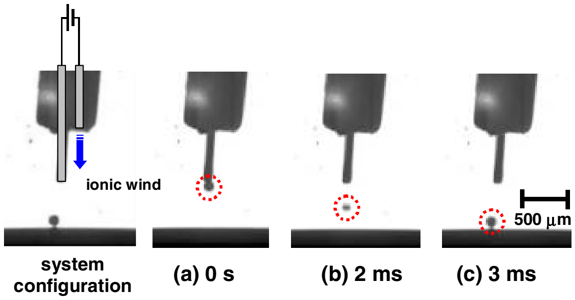


Figure 13. *Separation of captured particle utilizing uneven two-electrode system. (electrode diameter: 50 µm, particle: 150 µm glass particle, capture voltage: 300 V, release voltage, 2,000 V)*

Conclusion

An electrostatic manipulator was developed to manipulate small particles. The manipulator consisted of triple or dual wire electrodes. The particle was captured to the tip of the electrode by the application of the voltage over the threshold between two electrodes and released from the manipulator by turning off the voltage application. It was demonstrated that insulative, highly resistive, and conductive particles can be manipulated not only in air but also in oil.

However, Coulomb and adhesion force prevented to release the small particle when the voltage was turned off. An effective method to get off the particle was proposed. The system utilized ionic wind from the tip of the electrode.

Three-dimensional FDM calculation was conducted to calculate the dielectrophoresis force but it was smaller than the measured. Further investigation is necessary to clarify the force applied to the particle during manipulation.

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Author Biography

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