Effective Use of External Electric Field for Charging and Levitation of Particles Under UV Irradiation

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Effective Use of External Electric Field for Charging and Levitation of Particles under UV Irradiation

Mizuki Shoyama[1,2], Taiki Sugaya[2], and Shuji Matsusaka[2]

Abstract **Electrostatic forces can be used to control the motion of charged particles. In this study, particle charging and motion in an electric field under ultraviolet (UV) irradiation were investigated. When the particle layers deposited on an insulating substrate were irradiated with UV light in a downward electric field, photoelectrons were emitted, and positive charges moved to the bottom of the particle layers. Subsequently, by reversing the direction of the electric field, the positive charges in the bottom moved upward; thus, the particles in the top layer were positively charged and levitated by Coulomb forces. The flux of the levitated particles increased with an increase in the strength of the electric field (downward and upward). As the upward electric field strength increased, the number of agglomerated particles in the levitation increased; however, the particle charge decreased. As the thickness of the particle layers increased, the time delay for particle levitation increased; however, the flux of the levitated particles decreased. The ratio of agglomerated particles to the total levitated particles increased. These results can be explained by the mechanisms of charge transfer and particle levitation.**

***Index Terms*— Charging, electric field, levitation, negatively charged cloud, particle, photoemission, UV irradiation.**

NOMENCLATURE

D_p	Particle diameter (m).
$\boldsymbol{E}_{ex}$	External electric field generated by applied voltage (V/m).
$\boldsymbol{E}_n$	Electric field generated by negatively charged cloud (V/m).
$\boldsymbol{E}_p$	Electric field generated by positively charged particle layers (V/m).
$\vert E_{down}\vert$	Strength of downward electric field (V/m).
$\vert E_{up}\vert$	Strength of upward electric field (V/m).
$\boldsymbol{g}$	Gravitational acceleration (m/s^2).
h	Height of particle layers (mm).
J	Flux of levitated particles (pcs/(s·m^2)).
m_p	Mass of primary particle (kg).
q_p	Particle charge (C).
$\langle q_p \rangle$	Average charge of the levitated primary particles (C).
r_a	Ratio of agglomerated particles to total particles (–).
t	Time (s).
t_p	Thickness of particle layers (mm).
t_s	Time required to start particle levitation after applying an upward electric field (s).
V_{down}	Applied voltage for downward electric field (V).
V_{up}	Applied voltage for upward electric field (V).
$\boldsymbol{v}_p$	Particle velocity (m/s).

Greek symbols

μ	Fluid viscosity (Pa·s).
ρ_p	Particle density (kg/m^3).

I. INTRODUCTION

PARTICLE adhesion nd deposition in manufacturing processes can reduce productivity and lead to quality degradation [1]. Wet methods using chemical solutions are commonly used to remove particles; however, subsequent drying and wastewater treatment are required, which leads to a high environmental load [2]. When the particles are appropriately charged, their motion, for example, levitation and transport, can be controlled by electrostatic forces, which circumvents the requirement for wet methods [3]–[10].

Particles can be charged via photoemission induced by ultraviolet (UV) irradiation, which is more efficient than the common techniques of ion charging because it does not require the addition of extra ions or electrons [11]–[14]. When the surface of the particle layers is irradiated with UV light, the particles are positively charged by the emission of photoelectrons. The emitted photoelectrons are immediately attracted to the charged particles owing to Coulomb forces. Consequently, the concentration of photoelectrons is high in the space just above the particle layers, that is, a negatively charged cloud is formed in the equilibrium state. Based on the aforementioned series of phenomena, an upward electric field is formed between the negatively charged cloud and the surface of the particle layers. If the Coulomb force acting on the

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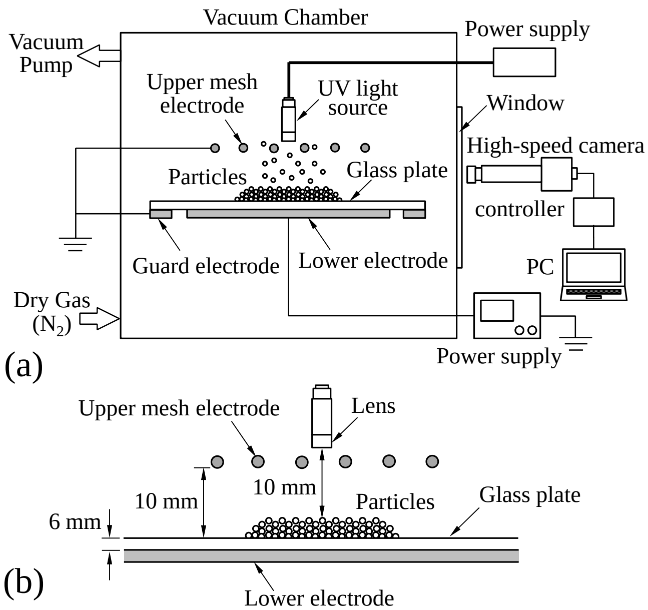

Fig. 1. Experimental setup: (a) UV irradiation system and (b) detailed dimensions.

charged particles is greater than the gravitational force, the particles levitate along the electric field direction [15]–[18].

Even when the Coulomb force acting on the particles is smaller than the gravitational force, the particles can be levitated by actively applying a strong external electric field [19]–[21]. The positive charges generated by the emission of photoelectrons are distributed within the particle layers; these positively charged particles can be levitated with the application of an upward electric field [22]–[24].

In this study, the particle layers on an insulating substrate were irradiated with UV light in the presence of an electric field. The motion of the levitated particles was recorded using a high-speed camera, and the flux of the particles was analyzed via digital image processing. The particle charges were estimated by fitting the particle positions calculated based on the motion equation to the observed particle motion. The effects of the direction and strength of the electric field on particle charging (induced by UV irradiation) and charged-particle motion were studied.

II. Experimental Method

Fig. 1 shows the experimental setup. An upper mesh electrode (material: stainless steel, external dimensions: 60 mm × 60 mm, diameter: 0.60 mm, opening: 3.63 mm) was placed parallel to the lower plate electrode (material: stainless steel, external dimensions: 60 mm × 60 mm) with a spacing of 16 mm between the electrodes in a chamber (external dimensions: 350×350×460 mm). The particles (glass beads) were placed on a glass plate attached to the lower electrode. The surface of the particle layers was irradiated by UV light with a peak wavelength of λ = 160 nm (S2D2-VUV, L10706, Hamamatsu Photonics K.K.) at a distance of 10 mm from the surface in all cases. Before each experiment, the chamber was vacuumed to

TABLE I
Properties of Sample Particles

Mass median diameter (μm)	59
Geometric standard deviation [–]	1.05
Particle density (kg/m^3)	2300
Work function (eV)	4.4–5.0

a pressure of 1 kPa and filled with dry nitrogen gas (N_2) to a pressure of ~101 kPa to remove oxygen and moisture. This allows the UV light (vacuum ultraviolet, VUV) to be irradiated directly onto the particles without being absorbed by oxygen [22].

To generate a downward electric field, a negative voltage from −5 kV to −3 kV was applied to the lower electrode using a power supply (610D, Trek Inc.); the upper electrode was grounded. Thus, the photoelectrons moved to the upper electrode, and the positive charges moved to the bottom of the particle layers. After 90 s of UV irradiation, a positive voltage from 3 kV to 5 kV was applied to the lower electrode to reverse the direction of the electric field and generate an upward electric field. This allowed the positively charged particles to levitate by Coulomb forces.

The motion of the levitated particles was recorded using a high-speed camera (FASTCAM Mini UX100, Photron Ltd.) with a high-magnification zoom lens (VSZ-10100, VS Technology Corporation) for <400 ms after reversing the direction of the electric field. The charge of each particle was estimated by fitting the particle position calculated based on the motion equation to the observed particle motion. Furthermore, the flux of the levitated particles was analyzed using digital image processing.

Table I lists the properties of the sample particles. The particles were dried at 120 °C for 12 h and cooled to 22 ± 2 °C in a desiccator before use. All experiments were conducted at a relative humidity of 40 ± 5 %.

III. Motion Analysis of the Levitated Particles

The charge q_p of each levitated particle can be controlled via two mechanisms: photoemission caused by UV irradiation and charge transfer caused by emitted photoelectrons. Photoemission can positively charge the particles, whereas charge transfer can negatively charge them.

To estimate the charges of the levitated particles, particle motion must be analyzed. The particles moving in the electric field experience drag, gravitational, and electrostatic forces. For a stationary fluid, the equation of motion of the particle is expressed as

$$m_p \frac{d\boldsymbol{v}_p}{dt} = 3\pi\mu D_p \boldsymbol{v}_p + m_p \boldsymbol{g} + q_p \left(\boldsymbol{E}_{ex} + \boldsymbol{E}_p + \boldsymbol{E}_n \right), \quad (1)$$

where m_p, $\boldsymbol{v}_p$, μ, D_p, $\boldsymbol{g}$, q_p, and t are the particle mass, particle velocity, fluid viscosity, particle diameter, gravitational acceleration, particle charge, and time, respectively. The electrostatic force consists of the Coulomb force related to the external electric field $\boldsymbol{E}_{ex}$ generated by the applied voltage, electric field $\boldsymbol{E}_p$ generated by the positively charged particle

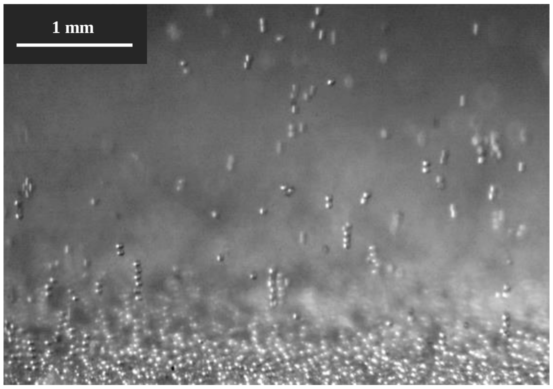

Fig. 2. Particles levitated from the surface of the particle layers ($|E_{down}|$=188 kV/m, $|E_{up}|$=313 kV/m, h =1 mm).

layers arising from photoemission, and electric field $\boldsymbol{E}_n$ generated by the negatively charged cloud arising from the emitted photoelectrons. m_p is given by

$$m_p = \frac{\pi D_p{}^3 \rho_p}{6}, \tag{2}$$

where ρ_p is the particle density.

In this study, particle motion was calculated assuming that $|\boldsymbol{E}_p + \boldsymbol{E}_n| << |\boldsymbol{E}_{ex}|$. Each particle charge q_p was estimated by fitting the calculation results based on the equation of motion to the particle trajectory obtained using the high-speed camera [7].

IV. Results and Discussion

Fig. 2 shows the particles levitated from the surface of the particle layers. When the particle layer was irradiated with UV light in the presence of an external electric field, single or chain-agglomerated particles were levitated. Because each particle was polarized in the electric field, dipole moment interaction generated chain agglomerates.

A. *Effect of downward electric field on particle levitation*

Fig. 3 shows the effect of the strength of the downward electric field $|E_{down}|$ on the flux of levitated particles J. Here, the application of the upward electric field $|E_{up}|$ was kept constant at 188 kV/m. The J value increased with an increase in $|E_{down}|$ because the total quantity of positive charges in the particle layers increased with an increase in $|E_{down}|$.

Fig. 4 shows the effect of $|E_{down}|$ on the ratio of levitated agglomerates r_a to total levitated particles. The r_a value was constant at 0.13 at $|E_{up}|$ = 188 kV/m regardless of $|E_{down}|$ because agglomerated particles were formed when the particles levitated in the upward electric field. As $|E_{up}|$ was constant, the state of agglomeration did not change.

Fig. 5 shows the effect of $|E_{down}|$ on the average charge of the levitated primary particles $<q_p>$. Each plot represents the average of the five measurements. The $<q_p>$ value was constant

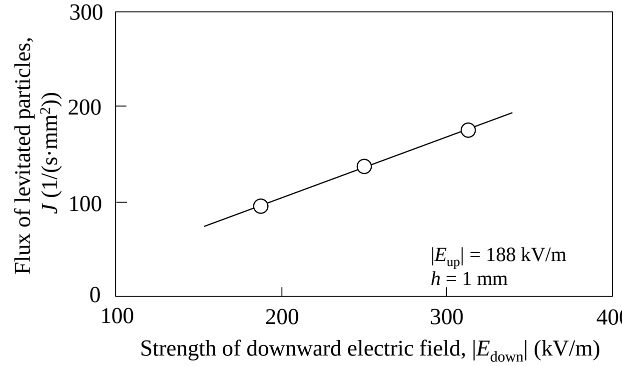

Fig. 3. Effect of strength of downward electric field on the flux of levitated particles.

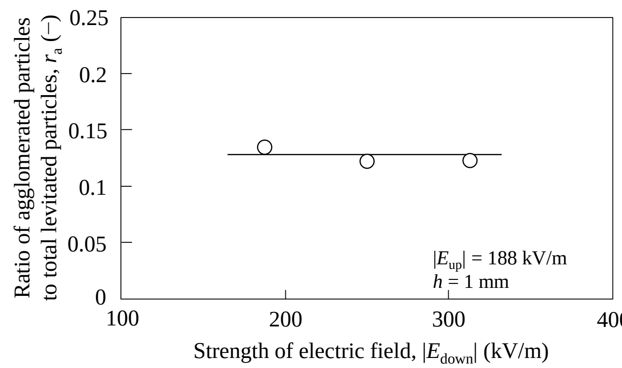

Fig. 4. Effect of strength of downward electric field on the ratio of agglomerated particles.

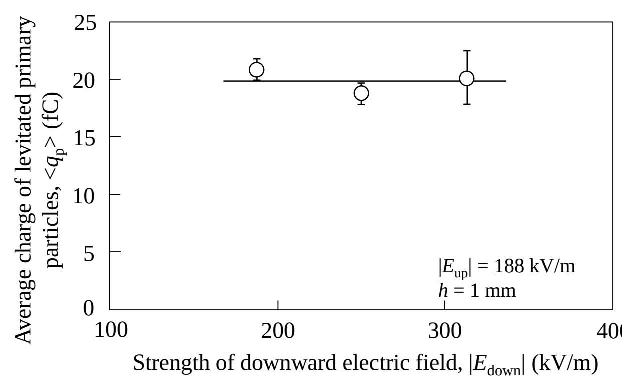

Fig. 5. Effect of strength of downward electric field on the average charge of levitated particles.

at 20 fC at $|E_{up}|$ = 188 kV/m regardless of $|E_{down}|$ because particle levitation was controlled by balancing the upward Coulomb force related to $|E_{up}|$, gravitational, and adhesion forces. In other words, because the latter forces were constant, the upward force represented by the Coulomb force (= $<q_p>|E_{up}|$) was also constant. Furthermore, as $|E_{up}|$ was constant, $<q_p>$ was also constant.

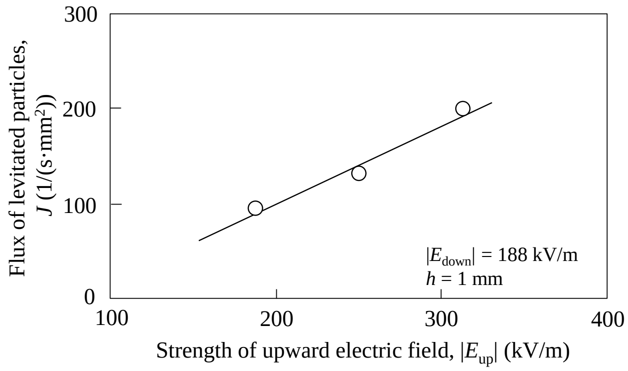

Fig. 6. Effect of the strength of upward electric field on the flux of levitated particles.

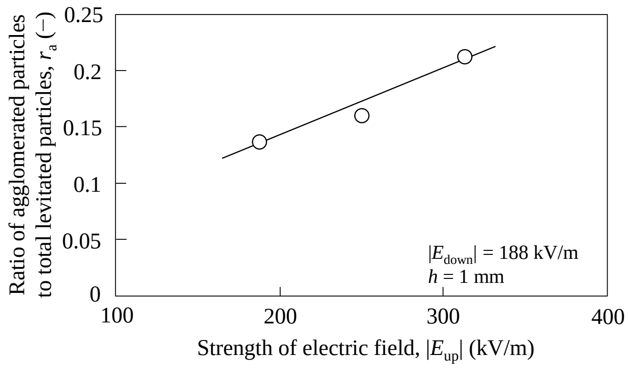

Fig. 7. Effect of strength of upward electric field on the ratio of agglomerated particles.

B. Effect of upward electric field on particle levitation

Fig. 6 shows the effect of the strength of the upward electric field $|E_{up}|$ on the flux of levitated particles J. Here, the $|E_{down}|$ value was kept constant at 188 kV/m, whereby the positive charge in the particle layers was kept constant. The J value increased with an increase in $|E_{up}|$. Assuming that the particles can be levitated by fewer charges at a higher value of $|E_{up}|$, it follows that the quantity of levitated particles is higher.

Fig. 7 shows the effect of $|E_{up}|$ on the ratio of agglomerated particles r_a to total levitated particles. The r_a value increased with an increase in $|E_{up}|$. For a higher value of $|E_{up}|$, the interaction force between the polarized particles is larger, which facilitates particle agglomeration.

Fig. 8 shows the effect of $|E_{up}|$ on the average charge of the levitated primary particles $\langle q_p \rangle$. The $\langle q_p \rangle$ value decreased with an increase in $|E_{up}|$ because particle levitation was controlled by balancing the upward Coulomb force and downward gravitational and adhesion forces. The Coulomb force $\langle q_p \rangle |E_{up}|$ must be constant under these conditions. Therefore, as the $|E_{up}|$ value increased, the $\langle q_p \rangle$ value decreased. This result proves the validity of the assumption shown in Fig. 6.

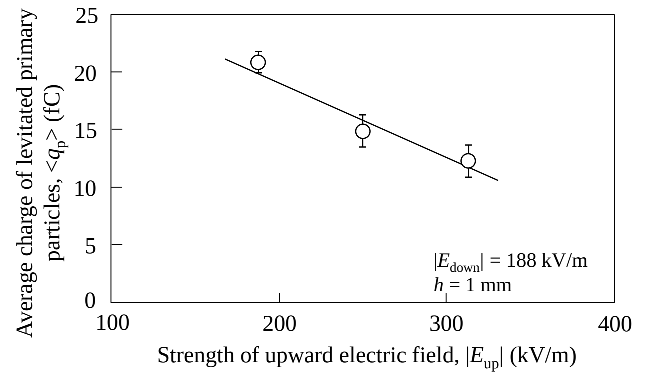

Fig. 8. Effect of strength of upward electric field on the average charge of levitated particles.

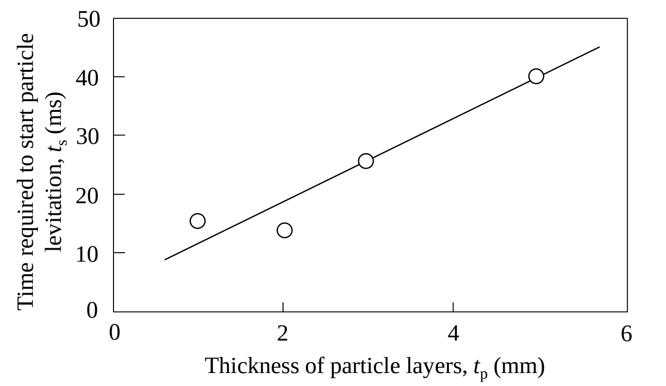

Fig. 9. Effect of thickness of particle layers on the time required to start particle levitation ($V_{down} = -4$ kV, $V_{up} = 4$ kV)

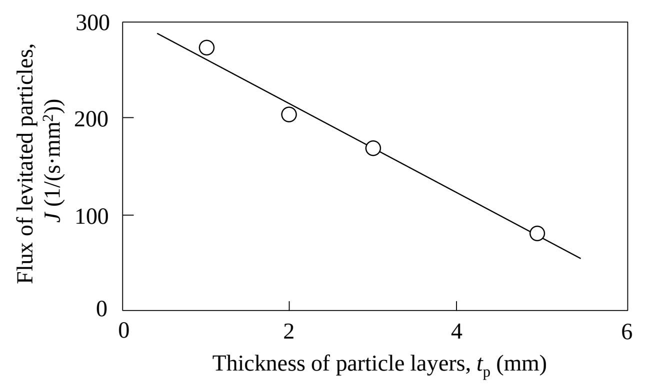

Fig. 10. Effect of thickness of particle layers on the flux of levitated particles ($V_{down} = -4$ kV, $V_{up} = 4$ kV)

C. Effect of the thickness of the particle layers on particle levitation

Fig. 9 shows the effect of the thickness of the particle layers t_p on the time t_s required to start particle levitation after applying

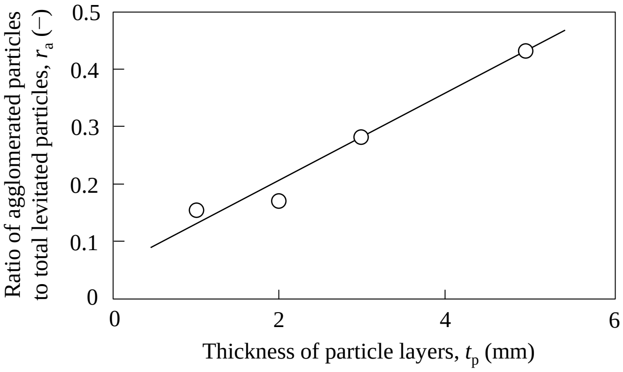

Fig. 11. Effect of thickness of particle layers on the ratio of agglomerated particles to total levitated particles (V_{down} = −4 kV, V_{up} = 4 kV).

an upward electric field. The t_s value increased with an increase in t_p. This implies that time is required for the positive charges accumulated at the bottom of the particle layers to move to the surface of the particle layers. After the top layer was sufficiently charged, particle levitation occurred.

Fig.10 shows the effect of t_p on the flux of the levitated particles, J. The J value decreased with an increase in t_p. This implies that as the thickness of the particle layers increases, the flux of positive charges moving upward decreases.

Fig. 11 shows the effect of t_p on the ratio of agglomerated particles r_a to total levitated particles. The r_a value increased with an increase in t_p. The ratio at t_p = 5 mm was three times larger than that at t_p = 1 mm. This is probably due to variations in the electric field. As the thickness of the particle layers increases, the distance between the positively charged surface of the particle layers and the upper electrode decreases; consequently, the electric field strength increases [7]. As shown in Fig. 7, r_a increased with an increase in $|E_{up}|$.

V. Conclusion

Glass beads deposited on an insulating substrate were charged and levitated. When the surface of particle layers was irradiated by UV light with a peak wavelength of λ = 160 nm in a downward electric field, the positive charges generated by photoemission moved to the bottom of the particle layers. Subsequently, by reversing the direction of the electric field, the positive charges moved to the top layer, and the charged particles levitated. The flux of the levitated particles increased with an increase in the strength of the electric field (downward and upward). With an increase in the strength of the upward electric field, the ratio of agglomerated particles to total particles increased because of the enhanced interaction forces between the polarized particles; the charge of the levitated particles decreased to keep the Coulomb force constant. As the thickness of the particle layers increased, the time required for the positive charges at the bottom of the particle layers to move to the top layer increased. Consequently, the time delay for particle levitation after the application of the upward electric field increased; however, the flux of the levitated particles decreased. The ratio of agglomerated particles to total levitated particles increased with an increase in the thickness of the particle layers.

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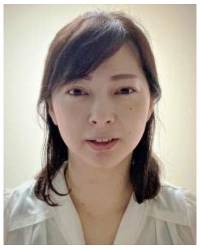

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