Charging and Levitation of Particles Using UV Irradiation and Electric Field

Mizuki Shoyama, Hironobu Yoshioka, and Shuji Matsusaka

***Abstract*— The charging and levitation of particles using UV irradiation in an upward electric field were investigated. Glass beads with a mass median diameter of 61 μm were used for the experiments. The particle layers formed on a glass plate were irradiated by UV light with wavelengths ranging from 240 to 400 nm. The particles in the top layer were positively charged by photoemission and levitated by the electrostatic forces. The fluxes and motions of the levitated particles were analyzed by digital processing of the images obtained with a high-speed camera. The charge of each levitated particle was determined by fitting the results calculated using the equation of motion to the experimentally obtained particle motion. The charge of the particles beginning to be levitated was determined by the force balance and thus was not affected by the UV irradiance. The positive charge of the levitated particles could be increased by continuous photoemission from the particles and decreased by the capture of photoelectrons emitted by other particles. Approximately 40% of the levitated particles descended because of the negative charge clouds formed by the photoemission from the particle layers and the levitated particles. Furthermore, in a second set of experiments, an upward electric field was applied after UV irradiation. In these experiments, the particles in the top layer were levitated after applying the electric field. These particles could gain more excess charges than the particles for which the levitation was governed by the force balance.**

***Index Terms*— charging, electric field, levitation, negative charge cloud, particle, photoemission, UV irradiation.**

NOMENCLATURE

D_p	particle diameter (m)
d_i	irradiation distance (m)
$\boldsymbol{E}_{ex}$	external electric field generated by applied voltage (V/m)
$\boldsymbol{E}_n$	electric field generated by negative charge cloud (V/m)
$\boldsymbol{E}_p$	electric field generated by positively charged particle layers (V/m)
E_{UV}	UV irradiance (W/m^2)
e	elementary charge (= −1.6×10^{-19} C)
$\boldsymbol{F}_d$	drag force (N)
$\boldsymbol{F}_e$	electrostatic force (N)
$\boldsymbol{F}_g$	gravitational force (N)
$F(q_p)$	cumulative distribution of particle charge (–)
$\boldsymbol{g}$	gravitational acceleration (m/s^2)
h	Planck constant (= 6.626×10^{-34} J·s)
h_e	height of photoelectron emission (m)
h_p	height of particle position (m)
I_n	variation of negative charge per unit time caused by the capture of emitted photoelectrons and/or produced negative ions (particles acquire negative charges) (A)
I_p	variation of positive charge per unit time caused by photoemission (particles acquire positive charges) (A)
J	flux of levitated particles (1/(m^2·s))
m_p	mass of primary particle (kg)
n_{photon}	number of photons irradiated on a particle per unit time (1/s)
q_p	particle charge (C)
t	time (s)
t_s	time required to start particle levitation (s)
V_e	potential of photoelectron (V)
$\boldsymbol{v}_p$	particle velocity (m/s)
W	work function (eV)

Greek symbols

η	quantum efficiency (–)
λ	wavelength of UV light (m)
μ	fluid viscosity (Pa·s)
ν	frequency of UV light (Hz)
ρ_p	particle density (kg/m^3)

I. INTRODUCTION

DUST particles on the dayside surface of the moon and on asteroids without atmosphere are exposed to solar radiation. The particles are charged by the photoelectric effect due to ultraviolet (UV) irradiation [1–3] and easily adhere to devices and spacesuits, resulting in damage to equipment and human health. Therefore, dust removal technologies using electric fields, such as electrodynamic dust shields, have been developed [4–6].

In industries such as the electronics, pharmaceutical, and food industries, particle adhesion can lower the quality and productivity of the manufacturing processes [7]. Although gas flow [8–10] and vibration [11–13] can also be used to remove the particles, the use of an electric field has the added

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advantages of the ability to control the motion of the charged particles even in stationary fluids, low-pressure environments, and vacuum in a non-contact manner [14–18]. In addition, UV irradiation of the particles enables photoelectric charging regardless of the presence or absence of gases [19–21]. Therefore, this technique is useful for pre-charging the particles.

When particle layers are irradiated by UV light, photoelectrons are emitted from the surface and the particles are positively charged. The emitted photoelectrons move toward the particles along the electric field; thus, a photoelectron cloud is formed above the particle layers in the equilibrium state [22]. Because the photoelectrons result in air ionization, a negative ion cloud is also formed [23]. The charged particles will be levitated when the electrostatic forces are sufficiently large. The levitated particles can acquire further positive charges due to the UV irradiation as well as negative charges from the photoelectron cloud and/or negative ion cloud. Consequently, the particle charges vary with time and exhibit complicated motions [24].

Furthermore, photoelectrons that are emitted from the particles collide with neighboring particles, which can lead to the emission of secondary electrons and result in further particle charging [25, 26].

In this study, the charging and levitation of particles deposited on an electrical insulating plate are investigated using UV irradiation and an upward electric field. The fluxes and motions of the levitated particles are analyzed in detail from images recorded by a high-speed camera. The charge of each levitated particle is determined by fitting the results calculated using the equation of motion to the experimentally obtained particle motion. The effects of the electric field strength and UV irradiance on the charges and motions of the levitated particles are investigated.

II. Experimental Method

The experimental setup is presented in Fig. 1. A stainless-steel wire mesh electrode (external dimensions: 60 × 60 mm, wire diameter: 0.60 mm, opening: 3.63 mm) was used as the upper electrode and placed at a distance of 10 mm from the lower plate electrode (external dimensions: 60 × 60 mm). Particles were deposited on an electrical insulating plate (a 2 mm-thick glass plate), which was attached to the lower electrode. The thickness of the particle layers was 1 mm. A DC voltage was applied to the lower electrode using a power supply (610D, Trek Inc.) and the upper electrode was grounded to generate an upward electric field between the two electrodes. The applied voltage was $V = 2$ kV.

UV light from a mercury-xenon lamp with wavelengths in the range of λ = 240 to 400 nm (L9588-02A, Hamamatsu Photonics K.K.) was irradiated on the particles through a condenser lens (E5147-04, Hamamatsu Photonics K.K.) placed close to the upper electrode. This is the standard configuration of the system.

Although UV light (3.1–5.0 eV) cannot ionize the air molecules (ionization energy: 12–16 eV), it can charge the particle surfaces positively through photoemission. Glass beads with a mass median diameter of 61 μm (particle density: ρ_p = 2300 kg/m^3, work function: W = 4.7 eV) were used for the experiments. Here, it is worth noting that the work function is smaller than the maximum light energy. Therefore, these particles can be charged and levitated along the electric field.

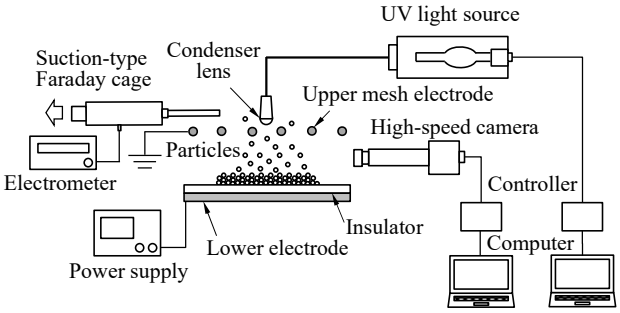

Fig. 1. Experimental setup.

A series of particle motions was recorded using a high-speed camera (5000 fps, 1280 ×1000 pixels, FASTCAM Mini UX100, Photron Ltd.) with a high-magnification zoom lens (VSZ–10100, VS Technology Corporation). In addition, a suction-type Faraday cup (IF-02, IMP., Co. Ltd.) and an electrometer (8252, ADC Corporation) were used to measure the specific charge, i.e., the charge-to-mass ratio of the particles.

The particles were dried at 120 °C for 12 h and cooled to room temperature in a desiccator before use. All experiments were carried out under room conditions (temperature: 22 ± 2 °C and relative humidity: 55 ± 5%).

III. Motion Analysis of the Levitated Particles

The charge of each levitated particle is determined by two processes, namely, photoemission by UV irradiation and the capture of emitted photoelectrons and/or produced negative ions. The former can charge the particles positively, and the latter can charge them negatively. The time differential of the particle charge $\mathrm{d}q_p/\mathrm{d}t$ is given by

$$\frac{\mathrm{d}q_p}{\mathrm{d}t} = I_p + I_n , \tag{1}$$

where I_p is the variation of the positive charge per unit time and I_n is the variation of negative charge per unit time. I_p can be expressed as

$$I_p = e\, n_{photon} \eta , \tag{2}$$

in which

$$n_{photon} = \frac{E_{UV}}{h\nu} \frac{\pi D_p^2}{4} , \tag{3}$$

where e is the elementary charge, n_{photon} is the number of photons irradiated on the particle per unit time assuming the irradiated cross section of the particle is $\pi D_p^2/4$, η is the quantum efficiency defined as the ratio of the number of emitted electrons to the number of incident photons [27, 28], E_{UV} is the UV irradiance, h is the Planck constant, ν is the frequency of the UV light, and D_p is the particle diameter.

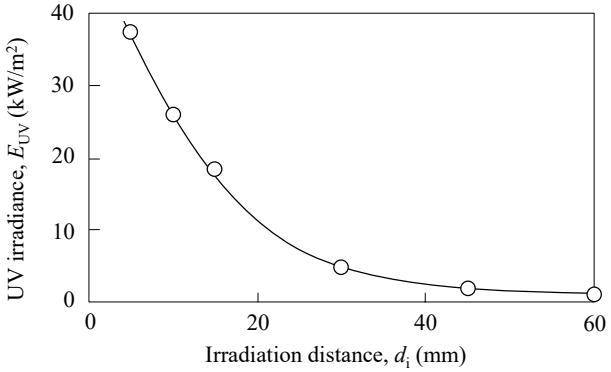

Fig. 2. Relationship between UV irradiance and irradiation distance from condenser lens.

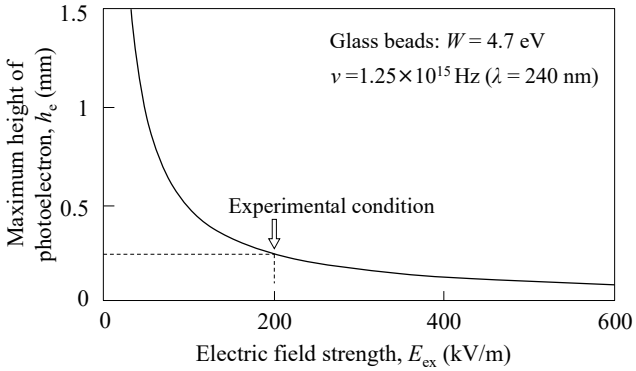

Fig. 3. Maximum height of emitted photoelectrons from particle layers.

To determine the charge of each levitated particle, the particle motion needs to be analyzed. A particle moving in the electric field experiences the drag force $\boldsymbol{F}_d$, gravitational force $\boldsymbol{F}_g$, and electrostatic force $\boldsymbol{F}_e$. The equation of motion of the particle is

$$m_p \frac{d\boldsymbol{v}_p}{dt} = \boldsymbol{F}_d + \boldsymbol{F}_g + \boldsymbol{F}_e , \tag{4}$$

where m_p, $\mathbf{v}_p$, and t are the particle mass, the velocity of the particle, and the time, respectively. For a stationary fluid, $\boldsymbol{F}_d$ is

$$\boldsymbol{F}_d = 3\pi \mu D_p \boldsymbol{v}_p , \tag{5}$$

where μ is the fluid viscosity. $\boldsymbol{F}_g$ is given by

$$\boldsymbol{F}_g = \frac{\pi D_p^3 \rho_p}{6} \boldsymbol{g} , \tag{6}$$

where ρ_p and $\boldsymbol{g}$ are the particle density and the gravitational acceleration, respectively. $\boldsymbol{F}_e$ consists of the Coulomb forces related to the external electric field $\boldsymbol{E}_{ex}$ generated by the applied voltage, the electric field $\boldsymbol{E}_p$ generated by the positively charged particle layers that result from photoemission, and the electric field $\boldsymbol{E}_n$ generated by the negative charge cloud that results from the emitted photoelectrons, i.e.,

$$\boldsymbol{F}_e = q_p \left(\boldsymbol{E}_{ex} + \boldsymbol{E}_p + \boldsymbol{E}_n \right) . \tag{7}$$

where q_p is the particle charge. In this study, $\boldsymbol{E}_{ex}$ reached as high as 200 kV/m; thus, the particle motion was calculated assuming that $|\boldsymbol{E}_p + \boldsymbol{E}_n| << |\boldsymbol{E}_{ex}|$. The value of q_p was determined by fitting the result calculated using the equation of motion to the experimentally obtained particle motion.

IV. Results and Discussion

Fig. 2 shows the relationship between the UV irradiance E_{UV} measured with a UV meter (UIT-250, Ushio Inc.) and the irradiation distance d_i. The value of E_{UV} decreases with an increase in d_i. When d_i is 10 mm, which is the distance in the experimental geometry, E_{UV} is 26 kW/m^2.

The photoelectrons emitted from the particles experience a downward Coulomb force in the electric field. The maximum

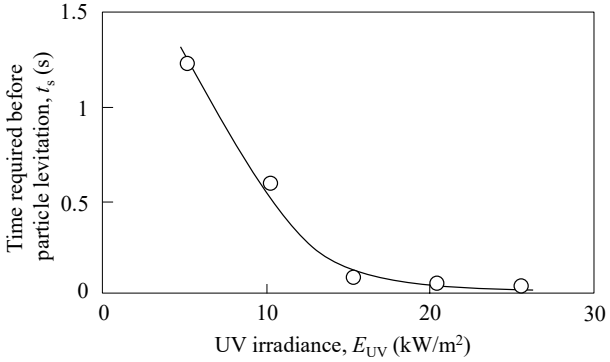

Fig. 4. Relationship between the time required before particle levitation and UV irradiance.

height of the photoelectron emission h_e, at which the kinetic energy is zero, is given by

$$h_e = \frac{V_e}{E_{ex}} = \frac{h\nu - W}{e E_{ex}} , \tag{8}$$

where V_e is the potential of the photoelectron.

Fig. 3 shows the maximum height h_e of the photoelectrons emitted from the particle layers of glass beads as a function of the electric field strength E_{ex}. The value of h_e decreases with an increase in E_{ex}. At E_{ex} = 200 kV/m, which is the field strength in the experiment, h_e is 0.24 mm. This implies that the photoelectron cloud is formed at the vicinity of the particle layers.

A. Observations

When UV light was irradiated on the particle layers in the external electric field, the particles in the top layer were levitated.

Fig. 4 shows the relationship between the time required before particle levitation began after the UV irradiation, t_s, and the UV irradiance, E_{UV}. The strength of E_{UV} was controlled by the opening of the shutter installed in the optical path. The value of t_s decreased with an increase in E_{UV}. Here, it is worth noting

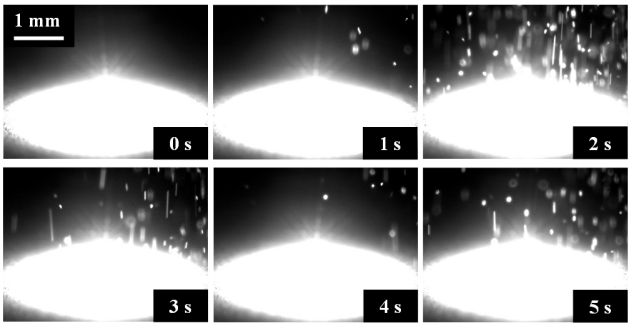

Fig. 5. Particles levitated from top layer.

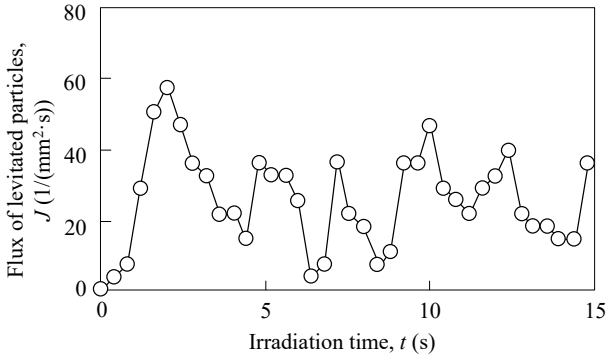

Fig. 6. Flux of levitated particles as a function of elapsed time.

that the particle levitation started immediately after UV irradiation, i.e., in less than 1 s at $E_{UV} \geq 10$ kW/m^2.

Fig. 5 presents a time series of images of the top layer, at which the UV irradiation started at $t = 0$. The areas of UV irradiation and the levitated particles appear bright. The particles were levitated immediately after UV irradiation, and the flux of levitated particles was maximized at approximately 2 s. The flux was not constant, i.e., it was smaller at 4 s and larger at 5 s. This phenomenon can be explained by the fact that initially, only the particles in the top layer were charged by UV irradiation and levitated. Subsequently, the non-charged particles in the second layer were also charged and levitated.

Fig. 6 shows the flux of the levitated particles as a function of the elapsed time. This result was obtained by digital processing (PFV4, Photron, Ltd.; Dipp-Motion V/2D, DITECT Co. Ltd.) of the images recorded by the high-speed camera (see Fig. 5). The peak fluxes were observed at intervals of a few seconds. The maximum value was approximately 60 per square millimeter per second.

Approximately 60% of the levitated particles passed through the camera frame, while the other particles fell down immediately after levitation. Fig. 7 shows the two typical motions, namely, an upward motion, and an upward and downward motion. The circles and lines represent the experimental and calculated particle positions, respectively. The values calculated with the fitting parameter, i.e., the particle charge, accurately reproduced the experimental ones.

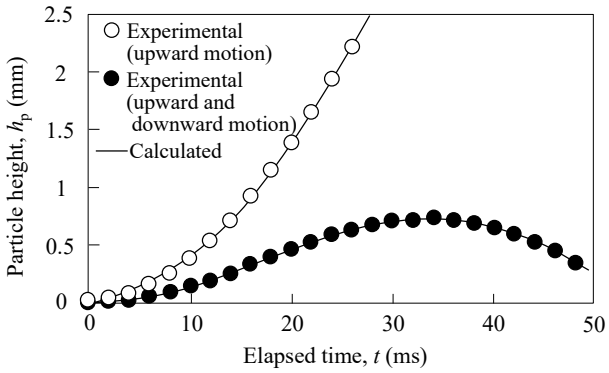

Fig. 7. Particle height as a function of elapsed time.

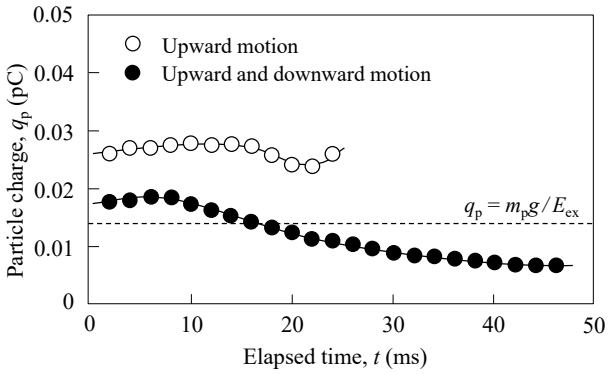

Fig. 8. Particle charge as a function of elapsed time.

A particle moves upward when the charge on it is constant or increases. In contrast, when the particle charge decreases and the upward Coulomb force is also smaller than the gravitational force, the particle moves downward.

B. Particle Charges

Fig. 8 shows the particle charge determined by the above fitting procedure (see Fig. 7). The charge of the particle with the upward motion was almost constant, i.e., $q_p = 0.026 \pm 0.002$ pC; however, the charge of the particle with the upward and downward motion was less than 0.02 pC, and the particle charge began to decrease at 6 ms. When $t \geq 18$ ms, the upward electrostatic force $q_p E_{ex}$ was smaller than the downward gravitational force $m_p g$.

The decrease in the particle charge can be explained as follows: When the particle layers are irradiated by UV light, photoelectrons are emitted from the particles. Consequently, a photoelectron cloud is formed above the particle layers in the equilibrium state [22]. A negative ion cloud is also formed by air ionization [23]. The acquisition of these negative charges by the levitated particles causes the initial positive charge on the particles to decrease. However, the levitated particles can still be charged positively through photoemission under UV irradiation. As shown in (1), the particle charge is determined by the kinetics of the two factors, I_p and I_n.

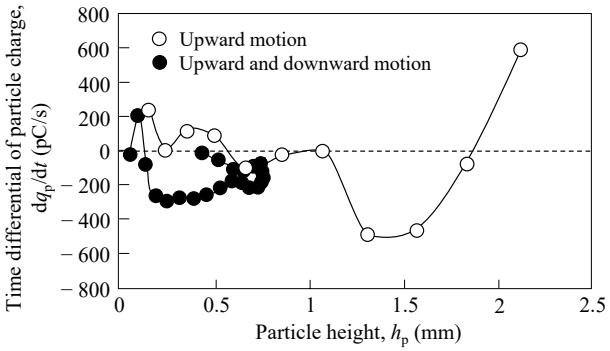

Fig. 9. Time differential of the particle charge as a function of particle height.

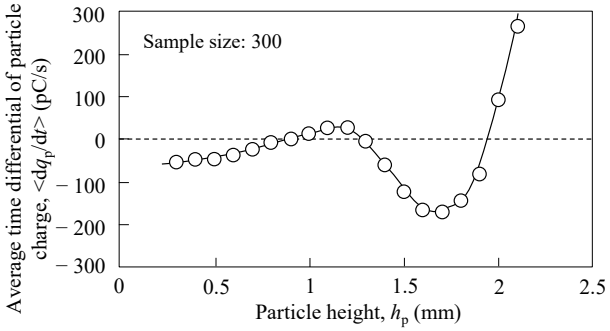

Fig. 10. Time differential of average particle charge as a function of particle height.

The average charge of particles levitated above the upper electrode was measured using the suction-type Faraday cup. The measured value was found to be 0.023±0.002 pC, which is in rough agreement with the value in Fig. 8.

Fig. 9 shows the time differential of the particle charge dq_p/dt as a function of particle height h_p. These values were obtained from the results in Fig. 8. The filled circles correspond to the upward and downward motion. The particle position was restricted to a limited range ($h_p < 0.8$ mm) where the dq_p/dt value was almost completely negative. This is because the particle charge was controlled by the negative charge cloud formed at the vicinity of the particle layers (see Fig. 3). The unfilled circles correspond to the upward motion. The particle had a rather large positive charge (see Fig. 8) and quickly passed through the negative charge cloud; thus, the variation of the dq_p/dt value was small at $h_p \leq 1$ mm. However, the dq_p/dt value decreased at $1.3 \leq h_p \leq 1.8$ mm. This implies that the particle captured negative charges at these heights. There were many particles with upward and downward motion. The high concentration of the levitated particles below 1 mm resulted in the formation of a second negative charge cloud at these heights. At $h_p \geq 2$ mm, the dq_p/dt value became large because of the photoemission by the particle under UV irradiation.

To ensure the consistency of the above experimental results, the variation of 300 dq_p/dt values was analyzed. Fig. 10 shows the average value $<dq_p/dt>$ as a function of the particle height.

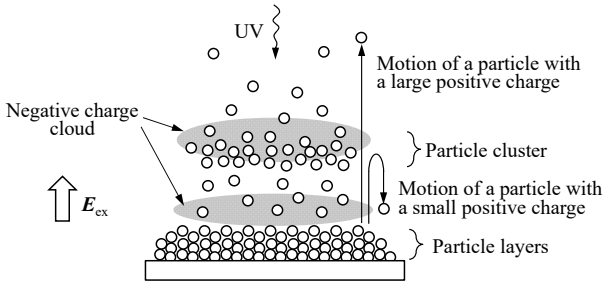

Fig. 11. Mechanism of particle motion and the variation of particle charge.

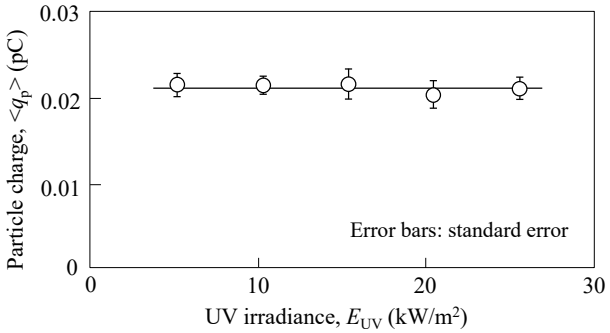

Fig. 12. Effect of UV irradiance on particle charge.

The $<dq_p/dt>$ values are negative at $h_p < 0.8$ mm and $1.3 \leq h_p \leq 1.8$ mm, and positive at $h_p \geq 2$ mm.

Fig. 11 illustrates the mechanism of the particle motion and the variation of particle charge. A particle with a large positive charge continues to move upward after levitation, whereas a particle with a small positive charge falls down immediately. The latter case, in which the particles are levitated to a height of less than 1 mm (see Fig. 7), accounts for approximately 40 % of all the levitated particles. Consequently, the particle concentration becomes high, and a particle cluster is formed. Photoelectrons are emitted from the particle cluster as well as from the surface of the particle layers under UV irradiation, and two negative charge clouds are formed. Therefore, although the particles can be charged positively by their own photoemission, the particle charges can also be decreased by the two negative charge clouds.

Fig. 12 shows the relationship between the average charge of the levitated particles $<q_p>$ and the UV irradiance E_{UV}. The $<q_p>$ value is constant regardless of E_{UV}; i.e., E_{UV} does not affect $<q_p>$ even though the number of photoelectrons emitted from the particles per unit time varies with E_{UV} (see Eqs. (2) and (3)). This result can be explained by the balance between the upward and downward forces in the particle levitation. The former comprises the Coulomb force, and the latter consists of the gravitational force and adhesion force. When the downward force is constant, the charge of the levitated particles is also constant. However, the charging time required for particle levitation depends on E_{UV}, as shown in Fig. 4.

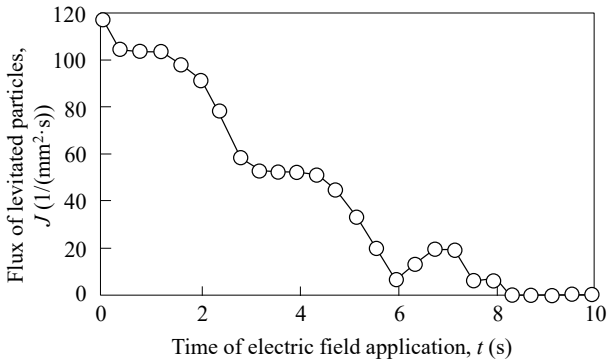

Fig. 13. Flux of levitated particles as a function of time that electric field was applied after UV irradiation.

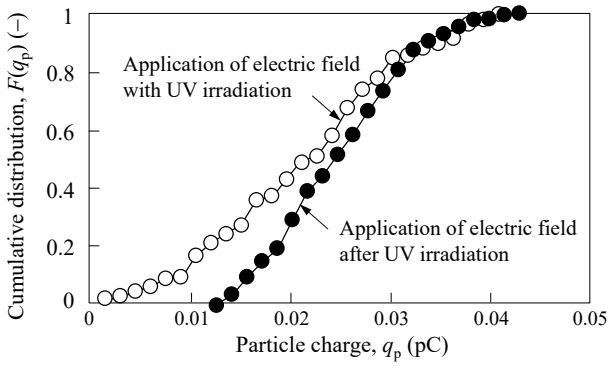

Fig. 14. Cumulative distributions of particle charge obtained by different procedures.

C. Alternative Procedure for Particle Levitation

In a separate set of experiments, the particle layers were irradiated by UV light without the external electric field; subsequently, an upward electric field (E_{ex} = 200 kV/m) was applied without UV irradiation. The particles in the top layer began to be levitated immediately after applying the electric field and passed through the camera frame, i.e., downward motions were not observed.

Fig. 13 shows the flux J of levitated particles as a function of elapsed time under the applied electric field. At the beginning, the value of J was higher than those in Fig. 6 but decreased with time and became almost zero after 8 s. This is because the particles in the top layer were charged positively through photoemission to a sufficient extent and subsequently experienced Coulomb forces due to the applied electric field; however, the particles below the top layer were not charged. Consequently, the particle levitation could not continue.

Fig. 14 shows the two particle charge distributions obtained by the different procedures, i.e., application of electric field after UV irradiation and application of electric field with UV irradiation. The particles in the former (filled circles) have larger charges than those in the latter (unfilled circles). As in Fig. 8, a charge larger than 0.013 pC is required for the particles to be levitated, however, the latter includes charges smaller than the critical value. This implies that the levitated particles acquired negative charges.

V. Conclusion

UV light with wavelengths ranging from 240 to 400 nm was irradiated on the surface of the particle layers in an upward electric field. The results obtained can be summarized as follows:

1) The particles in the top layer are charged by photoemission and levitated by electrostatic forces. The irradiation time required for the particle levitation decreases with an increase in the UV irradiance. The flux of the levitated particles fluctuates at intervals of a few seconds. The fluctuation can be explained as follows: After the levitation of the particles in the first layer, uncharged particles appear on the surface and become charged. Subsequently, the particles in the second layer are levitated. This process occurs repeatedly.

2) Approximately 40% of the levitated particles fall down immediately after levitation because the positive charge of the particles decreases with time. This decrease is caused by the negative charge clouds formed by photoemission from both the particle layers and the levitated particles.

3) The charge of the particles beginning to be levitated is determined by the balance between the upward and downward forces and thus is not affected by the UV irradiance. That is, particle levitation occurs when the particle charge exceeds a critical value.

In a second set of experiments, an upward electric field was applied after UV irradiation. The results obtained can be summarized as follows: The particles in the top layer begin to be levitated immediately after applying the electric field. The particles are charged more excessively than those in the first set of experiments in which the charging is governed by the force balance.

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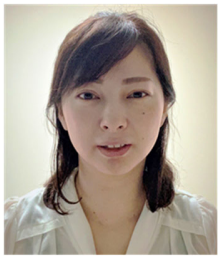

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