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Characterization of Particle Electrostatic Charging in Vibration and Electric Field

Megumi Mizutani, Masatoshi Yasuda, Shuji Matsusaka*

Department of Chemical Engineering, Kyoto University, Nishikyo-ku, Kyoto, 615-8510 Japan
matsu@cheme.kyoto-u.ac.jp

A novel system for characterizing particle charging as a function of the distance traveled has been designed and manufactured on the basis of the particle charging induced by repeated contacts with a wall. A vibration of several hundred hertz is applied for effective contact of the particles with the wall. In addition, an electric field is applied to change and control the charge on the particles. Using this system, sample particles with diameters of less than a hundred micrometers are studied under varying conditions of particle material and electric field strength. It is verified that the particles repeatedly contact the wall through the observation of the behavior of the particles on the vibrating wall using a high-speed camera with a zoom lens. Furthermore, it is confirmed that the system has an excellent performance to characterize particle charging from the theoretical and experimental analyses of the particle charge accumulation.

1. Introduction

In general, materials have inherent work functions. When two different materials are brought into contact and separated, contact charging occurs, where an electric charge is transferred from one material to the other. This phenomenon is often called contact electrification, contact charging, triboelectric charging, or simply tribocharging (Matsusaka et al., 2010). Owing to their high specific surface areas, particles are often charged during powder handling operations; this can cause adverse phenomena such as deposition, adhesion (Adhiwidjaja et al., 2000), and electrostatic discharge (Nifukuku and Katoh, 2003). As charged particles are used in many industrial applications, including electrophotography (Schein, 1996), dry powder coating (Bailey, 1998), and electrostatic separation (Gupta et al., 1993), particle electrostatic characterization and charge control (Matsusaka et al., 2007) are required to reduce the adversities during the handling processes and to improve the performance in industrial applications.

Various techniques have been proposed to characterize the tribocharging of particles. For instance, Oguchi and Tamatani (1993) proposed a cascade method. They fed particles from the top of a reference plate that is held at a certain angle. Tribocharging occurs when the particles cascade down the slope. Higashiyama *et al.* (1997) proposed another useful characterization method. Their device consists of a vibrating feeder and a charging plate. The particles contact the plate and are charged while moving from one end toward the other.

We apply vibration for the effective movement of fine particles. In addition, an applied electric field enables to control the charge transfer. The test section consists of two plates. The first plate controls the flow rate and charge on the particles using the vibration and electric field. The second plate is used for the characterization of the contact charging of the particles. In this study, we propose a novel system for characterizing contact charging.

2. Mechanism of particle charging

2.1 Theoretical model

The contact region between a particle and the wall can be considered as a capacitor. When a particle impacts and rebounds on the wall, the contact time is short; however, it is still long enough for charge

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transfer; thus, the transferred charge Δq induced by the impact can be represented by the condenser model (Matsusaka et al., 2000), that is,

$$\Delta q = k_c C V \tag{1}$$

where k_c is the charging efficiency, C is the capacitance, and V is the total potential difference. Capacitance C is expressed as

$$C = \frac{\varepsilon_0 S}{z_0} \tag{2}$$

where ε_0 is the absolute permittivity of gas, S is the contact area, and z_0 is the critical gap including the geometrical factors between the contact bodies. The total potential difference V at the contact gap is expressed as

$$V = V_c - V_e - V_b + V_{ex} \tag{3}$$

where V_c is the potential difference obtained on the basis of the surface work functions, V_e is the potential difference arising from the image charge, which is expressed as

$$V_e = k_e q \tag{4}$$

where q is the particle charge held on the particle before contact. V_b is the potential difference arising from the space charge induced by the surrounding charged particles, which is negligible under a dilute condition.

V_{ex} is the potential difference arising from other electric fields. For instance, when an external electric field is applied to the system, the contact potential difference can be easily changed. Figure 1 shows the concept of the particle charge control on the basis of the contact potential difference. For $V < 0$, the particles are negatively charged, and for $V > 0$, they are positively charged; that is, the amount of charge on the particles can be controlled by varying the external electric field (Matsusaka, 2011).

2.2 Repeated impacts of single particle

The transferred charge induced by an impact decreases with the number of impacts. The accumulated charge approaches a limiting value (Matsusaka, 2000).

It is possible to formulate the particle charge generated by repeated impacts. The condenser model is applied to the formulation. For obtaining charge q as a function of the number of collisions n, a continuous quantity dq/dn is used, that is,

$$\frac{\mathrm{d}q}{\mathrm{d}n} = k_c C V \tag{5}$$

From equations (2)–(5), the charge transfer under a dilute condition is derived as

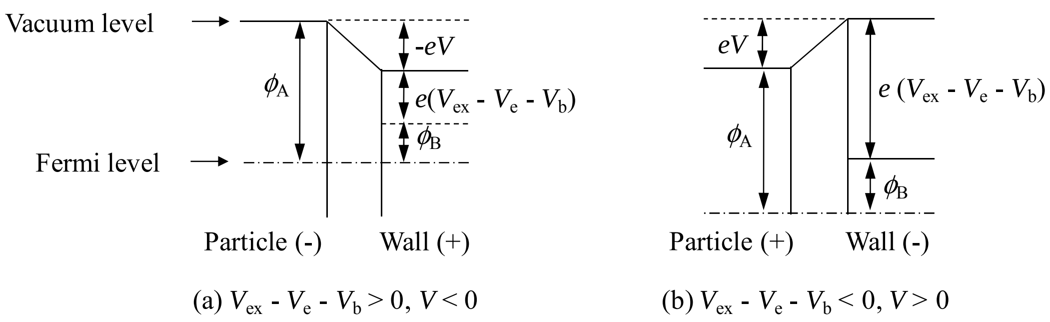


Figure 1: Conceptual model of particle charge control on the basis of contact potential difference (see equation (3)).

$$\frac{dq}{dn} = -\frac{k_c k_e \varepsilon_0 S}{z_0} q + \frac{k_c \varepsilon_0 S (V_c + V_{ex})}{z_0} \tag{6}$$

Solving equation (6) with the initial condition, $q = q_0$ at $n = 0$, we obtain the following exponential equation:

$$q(n) = q_0 \exp\left(-\frac{n}{n_0}\right) + q_\infty \left\{1 - \exp\left(-\frac{n}{n_0}\right)\right\} \tag{7}$$

where

$$n_0 = \frac{1}{\frac{k_c k_e \varepsilon_0 S}{z_0}} \tag{8}$$

and

$$q_\infty = \frac{V_c}{k_e} + \frac{z_0}{k_e} E_{ex} \tag{9}$$

The exponential equation represented by equation (9) can be used for almost all the repeated impacts of a single particle. The effect of the differences in the experimental conditions should be considered for two terms, that is, n_0 and q_∞.

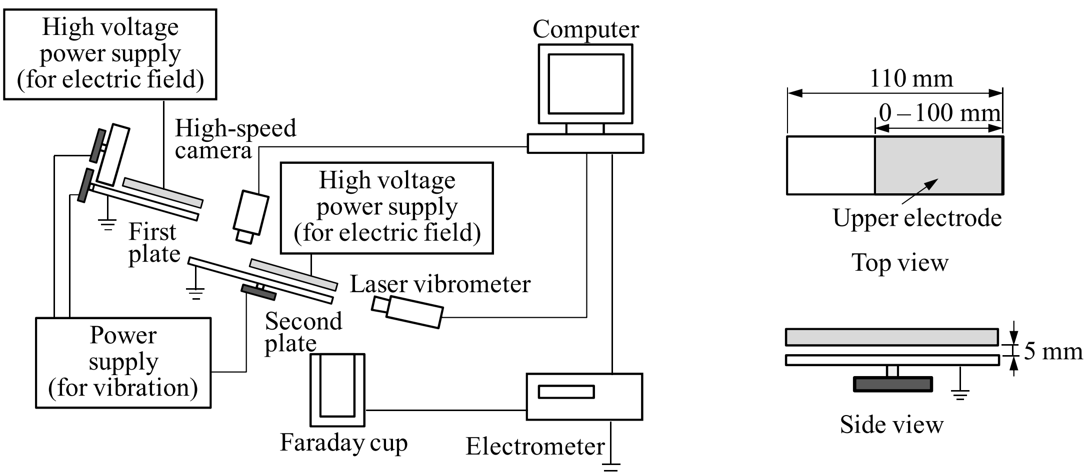
When the particles are traveling on a plate, it can be assumed that the frequency of the particle-wall impacts per unit plate length is constant and that the number of impacts n is proportional to the plate length L; thus, equation (7) is rewritten as

$$q(L) = q_0 \exp\left(-\frac{L}{L_0}\right) + q_\infty \left\{1 - \exp\left(-\frac{L}{L_0}\right)\right\} \tag{10}$$

where L_0 is the characteristic length of the particle charging.

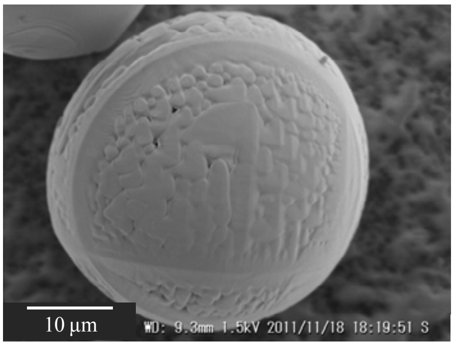
3. Experimental setup and procedure

Figure 2 shows the schematic diagram of the experimental setup. The test section consists of two inclined plates. All the inclination angles are adjustable. The particles fed at the top of the first plate (80 mm (L)×15 mm (W)) travel on the surface and drop on the second plate (110 mm (L)×30 mm (W)); that is, the first plate plays the role of a particle feeder for the second plate. The particle flow rate is controlled by the amplitude of the tangential vibration, which is generated by a piezoelectric vibrator attached to the first plate. The charge on the particles is controlled by contact with the surface under an applied electric field.

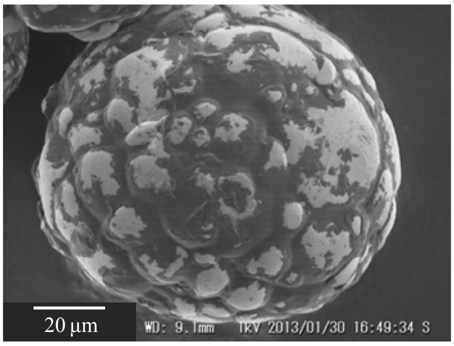


(a) Particle charging system (b) Test section (second plate)

Figure 2: Experimental setup



(a) Alumina particle



(b) Manganese ferrite particle coated with polymer

Figure 3: SEM images of particles.

By changing the particle feed point on the second plate, the travel distance of the particles is changed. For an effective contact charging with the surface under an applied electric field, a vibration is applied to the second plate in the normal direction. The total charge on the particles is measured with a Faraday cup at the ends of the first and second plates. The charge transfer on the second plate is obtained from the difference between these measurements.

The maximum electric field strength is ±0.16 MV/m. The two plates are grounded and the upper electrodes are connected to high voltage power supplies. The frequency and amplitude of vibration are 300 Hz and 10 µm, respectively. Two types of particles are used: alumina particles with a count median diameter (CMD) of 50 µm and a particle density of 4000 kg/m^3 and manganese ferrite particles coated with a polymer (CMD: 90 µm; particle density: 3500 kg/m^3). As shown in Figure 3, the images of these particles indicate that both the types of particles are round in shape, although the surface roughness is determined. In addition, it is determined that the manganese ferrite particles are partially coated with a polymer. Experiments are carried out under room conditions (temperature: 17~22 °C, relative humidity: 20~40 %).

4. Results and discussion

4.1 First plate

Figure 4 shows the total charge of the particles measured with a Faraday cup at the end of the first plate. The charge increases positively or negatively with time at a constant rate. This is because the particle charge and particle flow rate are constant in all the experiments. The increasing rate depends on the electric field strength. These results demonstrate that the first plate has an excellent performance with respect to the stability of the particle feed rate and particle charging.

Figure 5 shows the linear relationship between the charge-to-mass ratio, that is, specific charge q_m, and

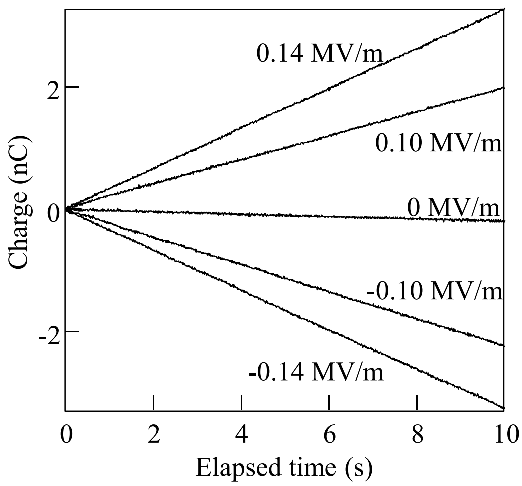


Figure 4: Accumulated charge in Faraday cup (alumina particles).

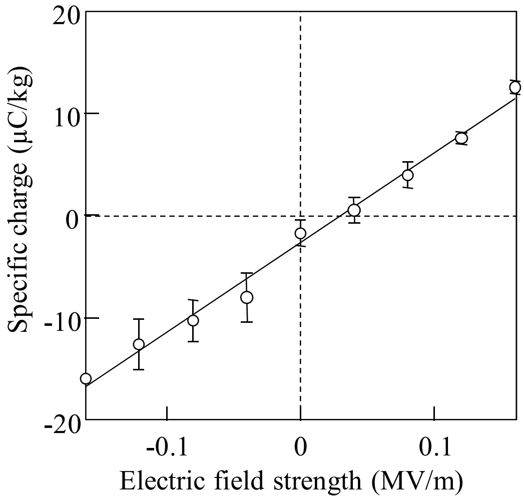


Figure 5: Initial charge (alumina particles).

the electric field strength. Therefore, the specific charge of the particles can be easily controlled by the electric field. In addition, a similar relationship holds for manganese ferrite particles coated with a polymer.

4.2 Second plate

Figure 6 shows the specific charge as a function of the distance traveled on the second plate. The specific charge at the end of the first plate is controlled such that it tends to zero, that is, the initial charge of the particles on the second plate is zero. The electric field strength on the second plate is set at ±0.04, ±0.1, and ±0.16 MV/m. The parameters denoted by the solid lines shown in Figure 6 are calculated by using a theoretical model, where two constants, that is, L_0 and $q_{m\infty}$, are determined from the multiple regression analyses of the experimental results. Consequently, the experimental results are verified to be in good agreement with the calculated ones. The average value and standard deviation of L_0 for the manganese ferrite particles coated with a polymer are 16 mm and 9.3 mm, respectively. For the alumina particles, the average value and standard deviation are 50 mm and 13 mm, respectively. The value of L_0 for the alumina particles is greater than that for manganese ferrite particles coated with a polymer. This is probably because of the low electric conductivity of the alumina particles.

Figure 7 shows the relationship between $q_{m\infty}$ and the electric field. This linear relationship can be explained by equation (9).

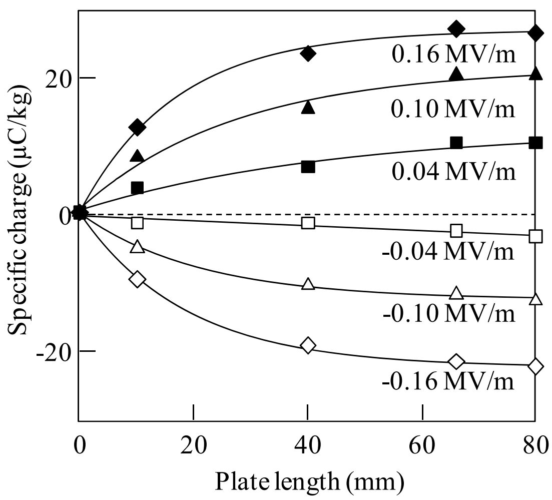


Figure 6 Relationship between specific charge of particles and plate length (manganese ferrite particles coated with polymer).

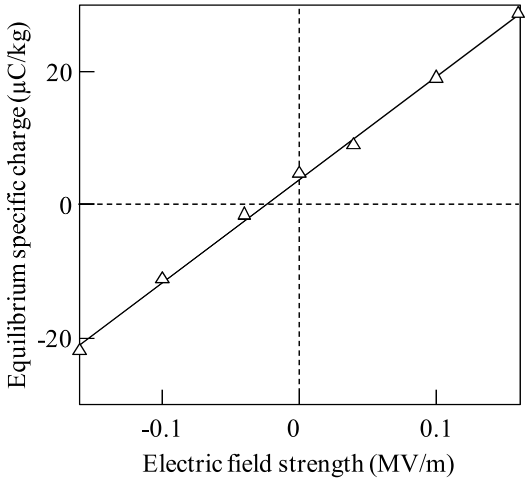


Figure 7: Relationship between specific charge of particles and electric field strength (manganese ferrite particles coated with polymer).

5. Conclusions

A novel system for characterizing particle charging as a function of the distance traveled has been designed and manufactured on the basis of particle charging induced by repeated contacts with a wall, and the following conclusions are drawn.

(1) The flow rate and specific charge of the particles can be controlled by the electric field and vibration.

(2) A linear relationship between the specific charge and the electric field is determined using this system.

(3) Particle charging as a function of the distance traveled can be explained by a theoretical model with two constants, that is, the characteristic length of the particle charging and the equivalent specific charge.

(4) This system has the advantage of easily determining these two characteristic values.

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