Particle-Size Sorting System of Lunar Regolith Using Electrostatic Traveling Wave

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***Abstract*—The authors have developed a particle-size sorting system of lunar regolith using an electrostatic force for In Situ Resource Utilization on the moon to extract indispensable resources from the regolith and realize long-term explorations. The regolith is sorted by utilizing a balance between the electrostatic force and the gravitational force, which are determined corresponding to the particle size, in a vacuum condition where no air drag is applied to particles. In the present study, the authors confirmed the effect of particle charges on the particle movement by conducting a model experiment and a numerical calculation based on the distinct element method. In addition, it was experimentally demonstrated that particles less than 20 µm in diameter were efficiently separated from the bulk of a lunar regolith simulant FJS-1 in a vacuum condition (~1.5×10^{-2} [Pa]). The system utilizes only the electrostatic force, and it does not need gas, liquid, or even mechanical moving parts.**

I. Introduction

To realize long-term exploration of the moon, In Situ Resource Utilization (ISRU) is necessary to both manage the risk and reduce the cost of transporting resources from the earth [1]. The ISRU will require processes such as drilling, collection, storage, sorting, and chemical processing of lunar regolith to synthesize oxygen, water, and metals. Those extracted resources can be used as fuels for propelling rockets, life support consumables and building materials for a lunar base. Concentration rates of those resources in the regolith are affected by the particle size. In addition, small lunar regolith particles, smaller than 10 µm in diameter, contain rich nanophase Fe^0 [2]. To succeed in the chemical reaction process corresponding to a mission objective of ISRU, a size sorting system of lunar regolith is indispensable. Moreover, the size sorting system is required to increase fluidization of particle motions and increase the surface area of particles and reaction rate for the improvement of the ISRU performance [1] [3].

Pneumatic, liquid, and mechanical methods of particle size sorting have been conventionally used for industrial applications on the earth, such as cyclone, sedimentary sorting, and sieve systems. However, utilization of a gas or liquid is difficult on the moon and the gravitational force on the moon is 1/6 of that on earth. In addition, the sieve system requires periodic cleaning of accumulated particles on the sieve to prevent clogging, and so the system requires a mechanical cleaning system which will make the system more complex and increase the failure risk because small regolith particles easily enter gaps in the mechanical system [4]. Therefore, a new type of the size sorting system that reliably works in the moon environment is necessary.

As a unique system that is appropriate for operations on the moon, an electrostatic size sorting system has been developed [5]. This system utilizes an electrostatic traveling wave [6] [7] [8] that transports regolith particles by utilizing the Coulomb force and a dielectrophoresis force [9]. The travelling wave was mainly used for the cleaning of regolith particles deposited on surfaces of solar panels and optical lenses [10] [11]. While the particles were being transported using the travelling wave, size sorting of the regolith was conducted by using a balance between the electrostatic and gravitational forces acting on particles, which depends on the particle diameter. The electrostatic system does not require a liquid, gas, or even mechanical parts, which makes the system highly reliable. In a previous study [5], demonstrations of particle size sorting using the electrostatic system were experimentally conducted in a low vacuum environment (=10 [Pa]). Although the system could sort small particles less than 20 μm in diameter from the bulk of the regolith in the vacuum environment, the analysis of the particle dynamics in the electrostatic field was not enough. In particular, the effect of the particle charges, which largely affects the particle motion, was not investigated.

In the present study, the authors measured the charge of each particle, and the effect of those charges on particle movements was investigated by conducting a model experiment and a numerical calculation based on the distinct element method. In addition, it was experimentally demonstrated that particles less than 20 μm in diameter were sorted from the bulk of a lunar regolith simulant under moderate vacuum conditions (~1.5×10^{-2} [Pa]).

II. Experimental Set Up

The size sorting system, shown in Figure 1, consists of three parts. One is a power supply that generates four-phase rectangular voltages by using four function generators, four amplifiers, and an additional function generator for controlling the delays of each phase. Second is a particle conveyer in which parallel copper electrodes (thickness: 18 μm, width: 0.3 mm, pitch: 1.3 mm) are printed on a flexible polyimide substrate (thickness: 0.1 mm, width: 128 mm, length: 490 mm). The surface of the conveyer is covered with an insulating film made of a polyimide (thickness: 12.5 μm) to prevent electrical breakdown near the electrodes. The last part is a collection box located at the upper-right end of the conveyer. When a voltage is applied to the parallel electrode, an electrostatic travelling wave is created on the surface of the conveyer [8], and particles on the conveyer follow the wave propagating toward the right direction. Because the gravitational force significantly affects large particles, they cannot float at a higher position than small particles in a vacuum, and they pass underneath the collection box. On the other hand, the collection box samples small particles that float and reach the collection box. This system utilizes only the electrostatic force, and it does not require a gas or liquid. Moreover, the power consumption of the system is very small, and it does not require periodic cleaning of the conveyer surface, so it could be operated reliably on the moon. As the experimental materials, the lunar regolith simulant FJS-1[12], which is almost identical to the popular simulant JSC-1A reproducing lunar regolith particles [13], was used. Before the experiments, the simulant was sorted, as its maximum diameter was less than approximately 106 μm, by using a mechanical sieve. The SEM photograph and size distribution of the simulant are shown in Figure 2.

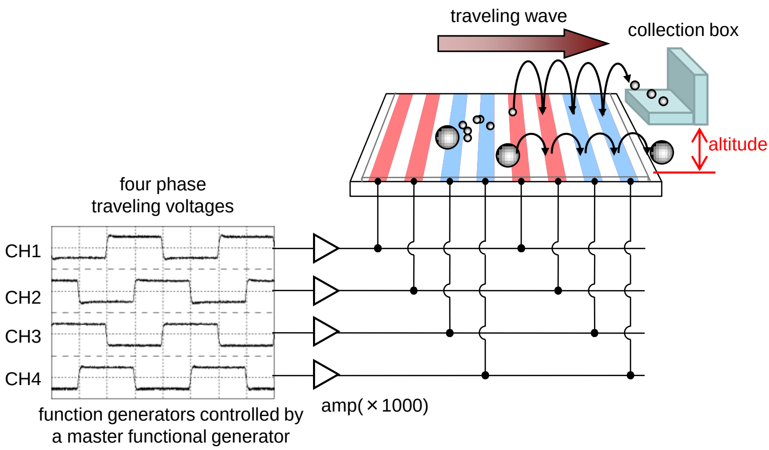

Fig. 1. Schematic diagram of size sorting system using electrostatic force.

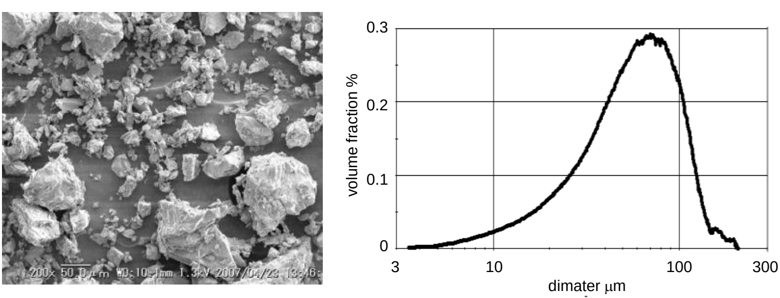

Fig. 2. SEM photograph of lunar regolith simulant FJS-1 (left) and its size distribution (right).

A. Measurement of particle charge distributions

Particle dynamics in an electrostatic field is largely affected by the particle charge. Therefore, charge quantities of each particle were measured by utilizing the free-fall system [7]. The measurement set up is shown in Figure 3. The parallel plate electrodes were placed as the centerline of the free-fall system was 20 mm from the right side of the conveyer. The particles that were initially settled 150 mm from the right side of the conveyer were transported and supplied to the free-fall system. To reduce the scattering of the particles, two layers of slits were used at the inlet of the free-fall system. When the DC voltage was applied to the parallel plates, the supplied particles fell, moving right or left from the centerline owing to an electrostatic force. To prevent the effect of air flow in the space between the plate electrodes, a wind shelter was equipped around the free-fall system. The distances between the centerline and touch-down positions of fallen particles on a glass plate were measured using a particle image analyzer (Morphologi G3/G3S, Malvern). As the particle fell, the motion equation of the ***i***-th particle is given by equation (1):

$$m_i \ddot{\boldsymbol{x}}_i = -6\pi\eta \boldsymbol{R}\dot{\boldsymbol{x}}_i + \boldsymbol{F}_{Coulomb} + \boldsymbol{F}_{dielectro} + \boldsymbol{F}_g \qquad (1)$$

where $\boldsymbol{x}$: the displacement vector, = (x, y, z), η: the viscosity of air (=1.8×10^{-5} [Pa·s] at 1 atm), m: the particle mass, R: the particle radius. The particle is affected by Coulomb, dielectrophoresis, and gravitational forces, which are represented by equations (2), (3) [9], and (4), respectively:

$$\boldsymbol{F}_{Coulomb} = q_i \boldsymbol{E} \qquad (2)$$

$$\boldsymbol{F}_{dielectro} = 2\pi\pi_0 \frac{\varepsilon_r - \varepsilon_0}{\varepsilon_r + 2\varepsilon_0} R_i^3 \nabla \boldsymbol{E}^2 \qquad (3)$$

$$\boldsymbol{F}_g = m_i \boldsymbol{g} \qquad (4)$$

where q: the particle charge, $\boldsymbol{E}$: the electrostatic field, ε_r: the relative permittivity (1.0 for air, 2.5 for particle), ε_0: the permittivity of free space (8.8×10^{-12} [F/m]), $\boldsymbol{g}$: the gravitational acceleration. The external electrostatic field $\boldsymbol{E}$ is calculated using a three-dimensional finite difference method. All parameters without the particle charge in those equations are known, so the charge can be calculated by using the distance from the centerline and those equations.

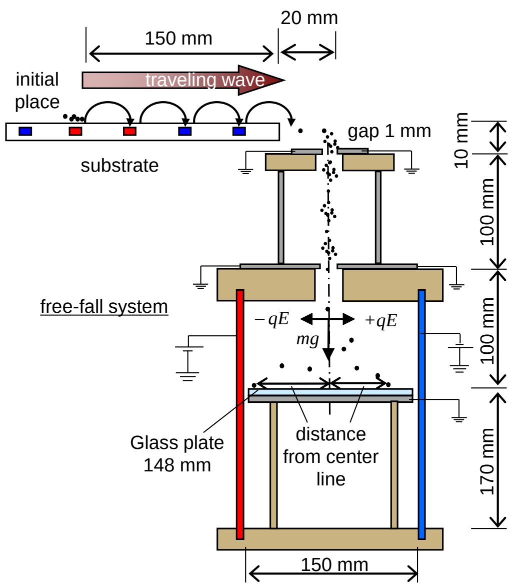

Fig. 3. The experimental set up for measuring the particle charges utilizing the free-fall method.

B. *Procedure of size sorting experiments in vacuum environment*

To confirm the performance of the electrostatic size sorting system in a vacuum environment, we conducted experiments in a vacuum chamber of the JAXA Chofu Aerospace Center. The vacuum chamber and the experimental set up for size sorting in the chamber are shown in Figure 4. After the air was evacuated for approximately 1 h, the vacuum reached below 1.5×10^{-2} Pa in the chamber. In the vacuum conditions, particles were fed from the left side of the conveyer by using a vibration supplier. The supplier consists of a mechanical sieve (mesh size: 0.5 mm) and a DC vibration motor (FA-130RA, Mabuchi Motor). (1) Lunar regolith simulant FJS-1 of 5 g was initially set on the sieve before evacuating the air. (2) When the DC voltage of 2.0 V was applied to the motor for 10 s, the sieve was vibrated, and some of particles were fed to the conveyer passing thorough the openings of the sieve. (3) The applied voltage was turned off for 50 s, and the fed particles were transported by the electrostatic travelling wave. (4) Processes (1) and (2) were repeated for 15 min. (5) Air was ejected into the chamber. After the vacuum rate restored the atmospheric pressure, the collected particles in collection box were sampled and analyzed using a particle image analyzer (Morphologi G3/G3S, Malvern). Four collections boxes were settled at heights of 100, 150, 200, and 250 mm.

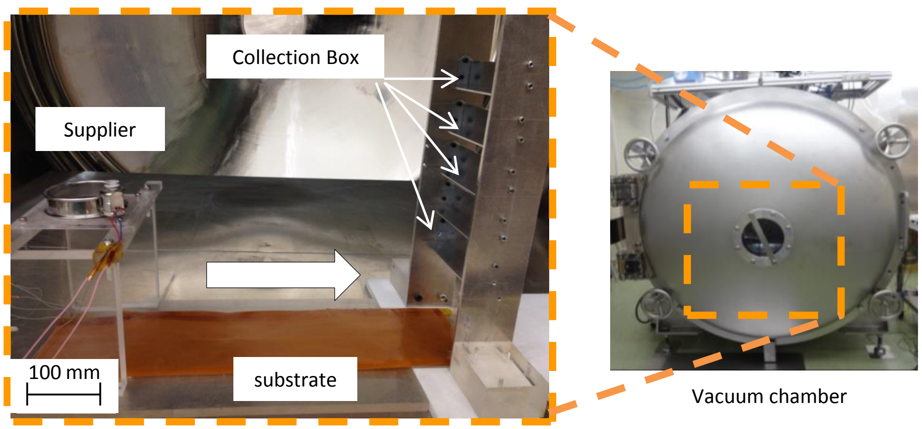

Fig. 4. Vacuum chamber used for size-sorting experiments (right) and the experimental set up in the chamber (left).

III. NUMERICAL CALCULATION

Numerical calculations using the hard sphere model of the three-dimensional distinct element method were conducted to analyze the particle motion in detail [14] [15]. The equations of motion for particle *i*-th are given by equation (5):

$$m_i \ddot{\boldsymbol{x}}_i = -6\pi\eta \boldsymbol{R} \dot{\boldsymbol{x}}_i + \boldsymbol{F}_{Coulomb} + \boldsymbol{F}_{dielectro} + \boldsymbol{F}_g + \boldsymbol{F}_{adhesion} \qquad (5)$$

An adhesion force, represented by equation (6), is added to equation (1). In addition, the torque acting on the particle is assumed to be zero:

$$\boldsymbol{F}_{Adhesion} = -\alpha\left(\frac{R_i R_k}{R_i + R_k}\right)\boldsymbol{n} \tag{6}$$

where α: the correction coefficient of the adhesion force (0.00027). The particle was assumed to be the lunar regolith simulant FJS-1, and its mass was estimated according to the specific gravity of FJS-1 (= 2700 kg/m^3). The coefficient of the adhesion force α was obtained from the literature [15]. When equation (5) is solved repeatedly using the Runge-Kutta method at each short time step (=0.00001 s), the velocity and position of moving particles can be calculated. The velocities and angular velocities of particles after particle-particle and particle-object collisions were calculated by using the modified hard sphere model based on the conservation law of momentum [14]. The air drag is neglected in the vacuum condition. The size distribution and charge distribution of the particles are reproduced for the actual measured values. Twenty thousand particles were randomly placed on the substrates, and their motions in the electrostatic field were followed for 5.0 s. To reduce the calculation load of the DEM, the length of the substrate was set to 5.2 mm, and periodic boundary conditions were applied to both ends of the substrate.

IV. Results and Discussion

Figure 5 (a) shows the measured charge distribution of initial particles that were not electrostatically treated at all before being directly supplied to the free-fall system, and Figure 5 (b) shows those of particles after being transported on the polyimide substrate and charged by the tribocharging caused by the friction with the polyimide. Moreover, the standard deviations of the charge distributions are shown in Figure 6. Because the balance between the electrostatic force and the gravitational force is important to conduct size sorting of particles, the measured charges are shown as a charge density in Figure 5 and 6.

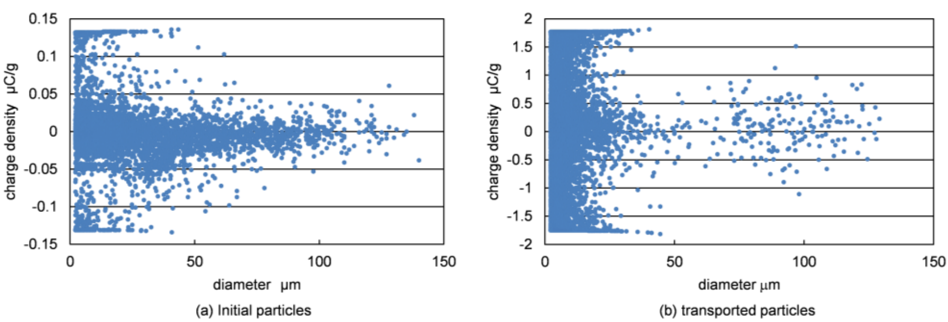

Fig. 5 Measured charge distribution of (a) initial FJS-1 particles that are not electrostatically treated and (b) those particles after transported on the surface of the substrate.

As shown in Figure 5 (a) and (b), the charges of the particles of the same diameter were not equal, and they were randomly charged in negative and positive polarities. Because FJS-1 has wide varieties of the compositions, it affected the charge quantities and polarities. Moreover, the particles interacted with each other mechanically, and an exchange of the charge occurred within particles during those collisions. In addition, the particles that were transported for 150 mm on the polyimide were charged larger than initial particles because of the tribocharging with the polyimide. As shown in Figure 6, the charge density of transported particles increased with decreasing particle diameter, so it is expected that small particles move more than large particles, and size sorting of those small particles using the balance between the electrostatic and gravitational forces can be successful. On the other hand, the charge densities of particles in each diameter were similar for the initial regolith particles, so size sorting of particles that are not charged intentionally will be difficult. The charging process in which particles are transported on the polyimide substrate is indispensable for successful size sorting in this system.

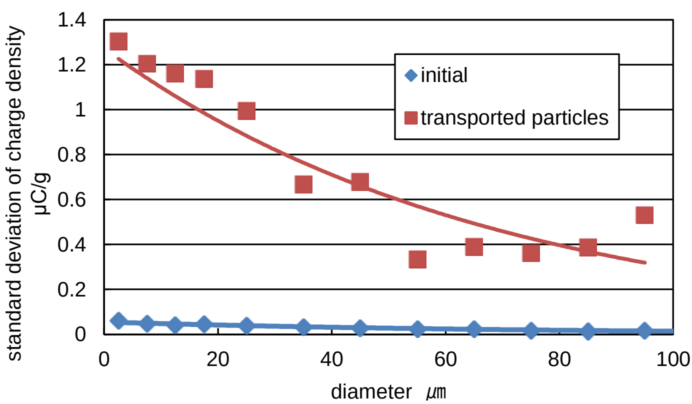

Fig. 6. Standard deviations of measured particle charges in each diameter.

Figure 7 shows the calculated maximum heights of transported particles in air and vacuum environments. In those calculations, measured charge distribution is reproduced. Figure 7 (a) shows that the small particles do not float higher than the large particles in air because a relatively large air drag acts on the small particles. On the other hand, because there is no air drag in vacuum, small particles reach higher positions than large particles, as shown in Figure 7 (b), corresponding to the tendency of the measured charge density shown in Figure 5. Considering the results of Figure 7, size sorting of those particles can be expected only in vacuum environment. In addition, the collection box set at the higher position can collect smaller particles.

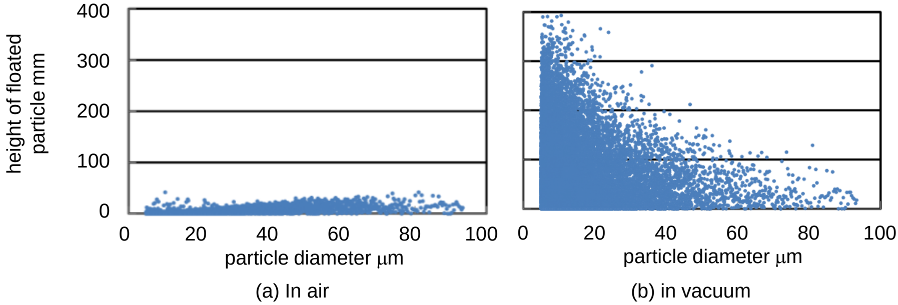

Fig. 7 Calculated maximum heights of transported particles in (a) air and (b) vacuum.

Because the size sorting of the regolith in air is impossible, assumed by the numerical calculations, we experimentally conducted size sorting in vacuum (~1.5×10^{-2} Pa). Figure 8 (a) and (b) shows the calculated and measured size distributions of the sorted particles in each collection box. As shown in Figure 9 (a) and (b), the size sorting of regolith particles were successful in vacuum. This system could collect particles smaller than 20 µm effectively. Moreover, the collection box set at the higher position could collect smaller particles. In the experiments, the collection box at 250 mm could collect particles with small diameters less than approximately 20 µm; however, the amount of those collected particles in the box was extremely small, and the image analyzer could not detect those particles. If we use a large amount of regolith particles (> 5 g) for the experiments, the number of collected particles in the box at 250 mm increases, and the image analyzer can detect those small particles. In addition, comparing the results of the experiments and calculations, numerical calculations can reproduce the experimental results fairly well.

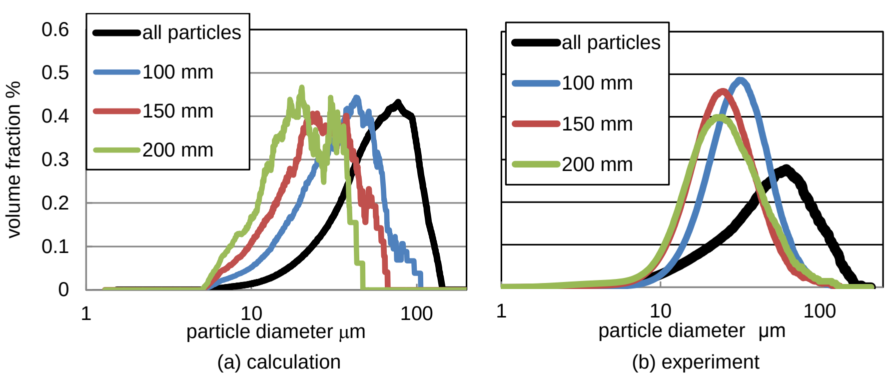

Fig. 8 (a) Calculated and (b) measured size distribution of collected particles in each collection box in a vacuum environment.

V. Conclusion

The authors have developed an electrostatic size sorting system of lunar regolith and investigated the effect of the particle charge to the particle motion. Transported particles on the polyimide surface were largely charged. In addition, small particles had large charges compare with large particles. This size sorting system could sort particles smaller than 20 μm in diameter effectively. In addition, numerical calculations using the distinct element method can reproduce the experimental results very well, and the prediction of the system performance in the moon environment by using the methods will be conducted in the future.

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