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Particle-size sorting system of lunar regolith using electrostatic traveling wave ☆

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A B S T R A C T

A particle-size sorting system of lunar regolith using an electrostatic traveling wave is developed for In-Situ Resource Utilization on the Moon to extract indispensable resources from the regolith and realize long-term exploration. The regolith is sorted by utilizing a balance between the electrostatic and gravitational forces, which are determined depending on particle size, in vacuum conditions where the particles are not subjected to air drag. In this study, the effect of particle charge on the particle motion is confirmed by conducting model experiments and numerical calculations based on the distinct element method. In addition, it was experimentally demonstrated that particles less than approximately 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), and the performance of the size sorting system on the Moon was predicted by the numerical calculations. The system utilizes only the electrostatic force, and it does not require any gas, liquid, or mechanical moving parts.

1. Introduction

To reduce the launch mass, cost, and mission risks for the purpose of advanced future lunar exploration, as well as colonizing the space beyond the Earth, In-Situ Resource Utilization (ISRU) has been proposed. It will harness both the natural and discarded resources at exploration sites to make propellant fuels and life support consumables for the astronauts and prepare repair tools and parts for the robotic equipment in situ [1–3]. The Moon is entirely covered with regolith particles [4,5] and the ISRU on the Moon would require processes such as drilling, collection, storage, sorting, and chemical processing of the lunar regolith to synthesize oxygen, water, and metals. A particle-size sorting system will play an important role in those processes. Particles in a particular size range have to be supplied continuously to improve the efficiency of the chemical processing in ISRU and stabilize the performance [3]. The required particle size depends on the objective of exploration missions because the components and properties of the lunar regolith change with diameter [6]. Although the size sorting of particles in any range is necessary, that of small particles is significant for ISRU because the surface area of the particle is large compared to the mass, and the reaction rate of the chemical processing is high.

Pneumatic, liquid, and mechanical methods of particle-size sorting have been conventionally used for industrial applications on the Earth and considered for space applications [7–9], such as cyclone sorting, sedimentary sorting, and sieve systems. However, the utilization of a gas or liquid is difficult on the Moon. In addition, the sieve system requires the periodic cleaning of accumulated particles on the sieve to prevent clogging, and the system requires a mechanical cleaning system, which would make the system more complex and increase the risk of failure because small lunar dust particles easily enter gaps in the mechanical system [10,11]. Therefore, it is necessary to develop a new type of size sorting system that reliably works in the harsh Moon environment, such as the dust contamination of equipment, a limited power source, and the non-existence of a gas or liquid.

Toward this end, a unique size sorting system that utilizes the electrostatic traveling wave was developed to extract particles smaller than approximately 10 μm in this study. Use of an electrostatic force to mitigate the lunar dust degradation effects was proposed by Tatom and his colleagues [12]. The electrostatic travelling wave was invented by Masuda's group [13]. The system has

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been developed in the industrial field of electrophotography [14,15] and in the space application [16,17], and a new function of size sorting was added to the technology [18–20]. While the particles were transported using the electrostatic traveling wave, the size sorting of particles was conducted by using a balance between the electrostatic and gravitational forces acting on the particles, which depends on the particle diameter. The electrostatic system does not require liquid, gas, or even mechanical parts, which makes the system highly reliable. In previous studies, the effects of electrostatic traveling wave frequency and particle diameter on the transport direction of a carrier particle used for electrophotography were confirmed in air and 1-G environments [18], and the size sorting of the carrier particles was performed in the Earth environment [19]. A size sorting of lunar regolith simulant by using the electrostatic traveling wave was demonstrated in a low vacuum environment of 10 Pa [20]. Although the system could sort small particles less than approximately 20 μm in diameter from the bulk of the simulant particles in the low vacuum [20], the analysis of the particle dynamics in the electrostatic field and space environment was not sufficient. In particular, the effects of particle charge, vacuum, and low-gravity were not investigated, although these largely affect the particle motion. In this study, the authors measured the charge of each particle and the effect of those charges on the size sorting performance in air and vacuum conditions. It was investigated by conducting model experiments and numerical calculations based on the distinct element method (DEM). Moreover, it was experimentally demonstrated that small particles were sorted from the bulk of lunar regolith simulant under moderate vacuum conditions (~1.5×10^{-2} Pa), and the performance in the Moon environment was predicted by the numerical calculations.

2. Experiment

2.1. Experimental set-up

The electrostatic size sorting system consists mainly of three parts, as illustrated in Fig. 1 [21]. One is the power supply that generates the four-phase rectangular voltage, of which the phases are shifted to 90° using a microcomputer. The second part is the particle conveyor 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), as shown in Fig. 2. The surface of the conveyor is covered with an insulating polyimide film (thickness: 12.5 μm with adhesive) to prevent the electrical breakdown between electrodes. The last part is the collection box located above the conveyor. When a voltage is applied to the parallel electrodes, an electrostatic traveling wave is created on the surface of the conveyor, and particles on the conveyor follow the wave propagating in the right direction. Because the gravitational force significantly affects the motion of large particles, the large particles cannot float at a higher altitude than the small particles in a vacuum; thus, the large particles pass underneath the collection box. Conversely, the small particles that float and reach the collection box are collected. Four collection boxes are installed at heights of 100, 150, 200, and 250 mm above the conveyor. The electrostatic size sorting system does not require a large electric current, and the power consumption is small. Moreover, a periodic cleaning of the conveyor surface is not necessary. The scaling-up of this system is possible when the width of the conveyor is widened and the collection boxes are installed parallelly in the direction of transporting particles. In addition, an optimization of the collection-box shape will improve the size sorting performance. The lunar regolith simulant FJS-1 was used for the experiment [22], as displayed in Fig. 3. The simulant was sorted before the experiments by using a mechanical sieve as its maximum diameter was less than approximately 106 μm.

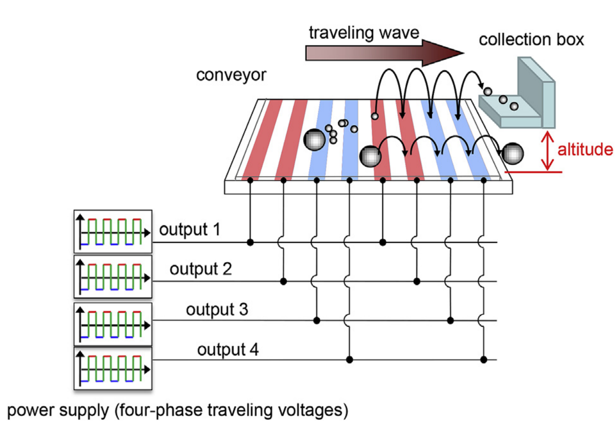

Fig. 1. Configuration of electrostatic size sorting system using electrostatic traveling wave.

2.2. Measurement of particle charge

The particle dynamics in an electrostatic field is affected by the particle charge, and the particle charge variation during transport on the conveyor was investigated. The charge quantities of each particle were measured by utilizing the free-fall system [15]. The measurement setup is illustrated in Fig. 4. The conveyor with parallel plate electrodes was placed above the free-fall system. The particles that initially settled on the conveyor at 30 mm, 100 mm, and 150 mm from an edge of the conveyor were transported toward the edge, and the transported particles were supplied to the free-fall system. To reduce the scattering of particles, two layers of slits were used at the inlet of the free-fall system. After the DC voltage was applied to the parallel plates, the supplied particles fell, moving right or left from the centerline due to the electrostatic force. To prevent the effect of airflow in the space between the plate electrodes, a wind shelter was equipped around the system. After supplying particles, the distances between the centerline and fallen particles on the glass plate were measured using a particle image analyzer (Morphologi G3/G3S, Malvern) which can detect particles on a 1-μm scale. For the particle falling, the motion of the i-th particle is described by Equation (1).

$$m_i\ddot{\boldsymbol{x}}_i = -6\pi\eta R_i\dot{\boldsymbol{x}}_i + \boldsymbol{F}_{Coulomb,i} + \boldsymbol{F}_{dielectrophoresis,i} + \boldsymbol{F}_{G,i} \tag{1}$$

where m, $\boldsymbol{x}$, η, and R are the particle mass, positional coordinate (x, y, z), viscosity of air (1.8×10^{-5} Pa s at 1 atm), and particle radius, respectively. The particle is affected by Coulomb, dielectrophoresis, and gravitational forces, which are represented by Equations (2) and (3) [23,24], and (4), respectively:

$$\boldsymbol{F}_{Coulomb,i} = q_i\boldsymbol{E} \tag{2}$$

$$\boldsymbol{F}_{dielectrophoresis,i} = 2\pi\varepsilon_0\frac{\varepsilon_r - \varepsilon_0}{\varepsilon_r + 2\varepsilon_0}R_i^3\nabla\boldsymbol{E}^2 \tag{3}$$

$$\boldsymbol{F}_{G,i} = m_i\boldsymbol{g} \tag{4}$$

where q, $\boldsymbol{E}$, ε_r, ε_0, and $\boldsymbol{g}$ are the particle charge, electrostatic field, relative permittivity (1.0 for air, 3.0 for particle), permittivity of free space (8.9×10^{-12} F/m), and gravitational acceleration (9.8 m/s^2 on the Earth, 1.6 m/s^2 on the Moon). The external electrostatic field $\boldsymbol{E}$ is numerically calculated using the two-dimensional finite difference method. Because all parameters except for the particle charge are