Journal of Electrostatics 84 (2016) 42–47

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Electrostatic transport of regolith particles for sample return mission from asteroids

H. Kawamoto*, M. Kato, M. Adachi

Department of Applied Mechanics and Aerospace Engineering, Waseda University, 3-4-1, Okubo, Shinjuku, Tokyo 169-8555, Japan

ARTICLE INFO

Article history:
Received 4 July 2016
Received in revised form
15 September 2016
Accepted 16 September 2016

This work was presented at 2016 Electrostatic Joint Conference, Purdue University, June 2016.

Keywords:
Aerospace engineering
Asteroid
Regolith particles
Space exploration
Sample return

ABSTRACT

To achieve reliable and autonomous regolith sampling from asteroids in space, the authors have developed a new sampling system that utilizes electrostatic force. This system consists of electrostatic capture and transport subsystems. Regolith particles on an asteroid are captured through parallel screen electrodes activated by the application of an alternating high voltage. The captured particles are then transported to a collection capsule from side to side basically along the electric flux lines in a zigzag path where an alternating electrostatic field is applied. It has been demonstrated that glass and sand particles can be transported in the horizontal direction that imitates micro-gravity on asteroids. The transport rate was increased by applying a high voltage of appropriate frequency. The demonstrated transport rate was approximately 3 g/min. The configuration of the path was improved to increase the transport performance. Numerical calculation using the discrete element method predicted that the transport of particles is successful if the gravity is less than 0.02-G. The process of sampling particles on asteroids will be easier than that on the Earth, because gravity is extremely low on small asteroids, particles are assumed to be highly charged because of cosmic rays, no air drag is exerted on the particles, and high voltage can be applied in vacuum where no gas discharge occurs.

1. Introduction

Sample return missions that are intended to bring back regolith samples from asteroids to the Earth are attracting remarkable attention because the analysis of substances collected from asteroids could provide critical information on the history of the solar system and the origin of life. The first sample return mission from an asteroid was completed successfully by the Japan Aerospace Exploration Agency's (JAXA) spacecraft Hayabusa (MUSES-C) in 2010 [1]. Hayabusa brought back more than 1000 small regolith particles from a small asteroid called Itokawa. The returned samples are now being studied [2,3]. Followed by the Hayabusa mission, JAXA launched a new spacecraft in 2015 for another sample return mission, the Hayabusa-2, to investigate the C-type asteroid, Ryugu [4]. The regolith of C-type asteroids is considered to contain organic matter and water. Other sample return missions planned by space agencies worldwide are the National Aeronautics and Space Administration's (NASA) OSIRIS-Rex [5] and European Space Agency's (ESA) MarcoPolo-R [6].

Hayabusa employed a bullet-firing sampling system that consisted of a series of operations: landing on the asteroid, firing the bullet, crushing the asteroid surface by the bullet, introducing the flung-up regolith particles into a collection capsule through a horn, and closing a shutter of the capsule. However, because of an error in the autonomous operation system, the bullet was not fired, and large samples were not captured; only some small floating particles were collected. The sampling system employed on Hayabusa-2 is similar to that of Hayabusa. Hayabusa-2 will use explosives to fire a copper impactor into the asteroid to carve an artificial crater, exposing underground pristine rocks for the probe to pick up during a touch-and-go maneuver. On the other hand, OSIRIS-Rex will use a robotic arm to pluck the samples flung up by injecting nitrogen gas to the surface of an asteroid.

The sampling technique used in Hayabusa-2 is very challenging owing to the complicated firing system and operational scheme that needs to be operated autonomously to compensate for a long communication delay. The sampling technique used in OSIRIS-Rex is also challenging because it needs delicate mechanisms, such as a gas injection system and a robotic arm. A simple sampling system that uses electrostatic force has been developed to aid the existing

* Corresponding author.
E-mail address: kawa@waseda.jp (H. Kawamoto).

http://dx.doi.org/10.1016/j.elstat.2016.09.002
0304-3886/

systems [7–9]. High ac voltage is applied between parallel screen electrodes mounted at the end of the collection tube. During the touch-down operation, particles on the surface are agitated by an alternating electrostatic field, and some particles that are flung up are captured in the collection capsule after passing through the openings in the upper screen electrode. It was demonstrated that approximately 900 mg of lunar regolith simulant FJS-1 was successfully captured in a micro-gravity environment reproduced by the parabolic flight of an aircraft with a 1-s operation time that simulated the touch-down sampling adopted for Hayabusa. In addition to the lunar regolith simulant whose diameter is 1–500 μm, it was demonstrated that large rocks (approximately 4 mm in diameter) and glass beads (2 mm in diameter) were captured in the micro-gravity environment. The system would be suitable as an optional or additional sampler because it could automatically capture floating particles with a simple operation, even when the other sampling system does not work. The merits of this system are that it is very simple and compact, that there is no need for any mechanical drive and precision control, no contamination of impurities, very little need for power, and that it does not disturb the spacecraft's motion.

However, in the experiment for electrostatic capture in the micro-gravity environment, we observed that some rocks and glass beads adhered to the inner surface of the sampling tube, probably owing to the electrostatic adhesion force, and some of them were not captured in the collection capsule. Because nobody knows how much the regolith is charged in space, a method is necessary to unfailingly transport the captured regolith particles into the capsule, even if the particles are highly charged and extremely high adhesion force is applied to the particles.

To overcome this issue and to assure the electrostatic sampling of asteroid regolith in space, the authors have developed a unique regolith transport system that consists of a zigzag path where the alternating electrostatic field is applied and is compatible with the electrostatic capture system. This study investigates the configuration and performance of the transport system that is expected to increase the reliability of the sampling system.

2. System configuration

Fig. 1 shows a schematic illustration of the system and photographs of the zigzag path for transporting regolith particles. The system has two primary functions: capture and transport of particles. When a rectangular two-phase high voltage is applied between the parallel screen electrodes attached to the lower end of a sampler, the resultant Coulomb force and electrophoresis force [10] act on particles near the electrodes, and some agitated particles pass through the openings of the upper screen electrodes [7–9]. The captured particles are introduced into the zigzag path where an alternating electrostatic field is created by the application of ac voltage to the plate electrodes placed along the zigzag path. Particles are transported from side to side basically along the electric flux lines, designated by arrows in Fig. 1. Both positively and negatively charged particles are transported by the Coulomb force because an alternating electric field is applied. The regolith is generally assumed to be electrostatically charged by photoelectric emissions caused by radiation or by electron/ion collisions via sticking or secondary electron emissions in space, and the particles are not discharged in vacuum [11,12]. Although electrostatic adhesion force by image force is large for a highly charged particle, the Coulomb force by the externally applied electric field is also high for the highly charged particle. Therefore, electrostatic transport is possible for the highly charged particle. Actually, we demonstrated that particles charged by a corona device in both positive and negative can be transported by the Coulomb force [13]. The dielectrophoresis force is also applied to particles but it is small compared to the Coulomb force in the path, because the electrostatic field is not highly concentrated in the zig-zag path [10].

In the micro-gravity environment, captured particles would be transported to a collection capsule attached at the upper end of the zigzag path without dropping down. A two-phase rectangular voltage was generated with a set of positive and negative amplifiers switched by semiconductor relays controlled by a microcomputer [14].

In the experiment, we used two kinds of small transporting paths as shown in the right-hand side of Fig. 1; one is a narrow path (10 mm pitch) and the other is a relatively wide path (15 mm pitch). Plate electrodes, made of aluminum, are arrayed in frames made of epoxy resin. The total path length is 125 mm.

Because the characteristics of the particles present on an asteroid surface are unknown, the following four kinds of particles were used in the experiments. The scanning electron microscopy (SEM) images and particle size distributions are shown in Fig. 2.

(1) Glass beads: Spherical, 100 μm in diameter, insulator.
(2) Lunar regolith simulant: FJS-1 (Shimizu Corp.,Tokyo) [15], wide range of sizes, highly irregular shaped, insulator.

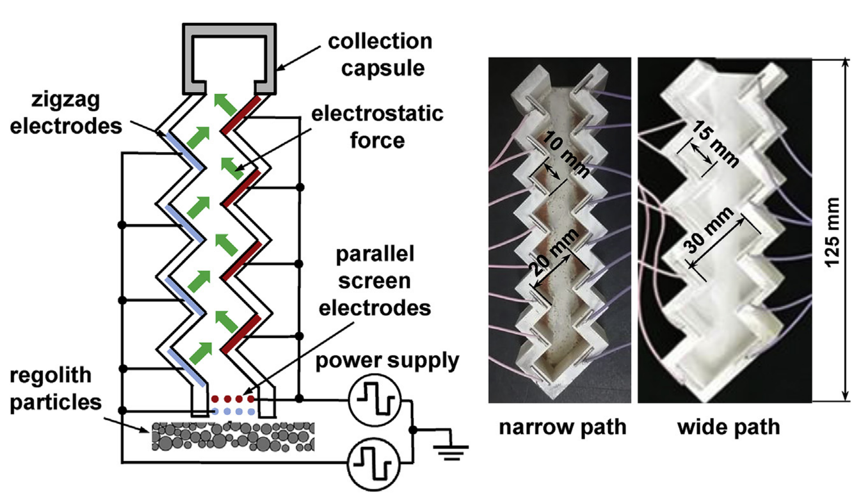

Fig. 1. Schematic illustration of the sampling system (left) and photographs of the zigzag path for transporting regolith particles (right).