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Design of an electrostatic lunar dust repeller for mitigating dust deposition and evaluation of its removal efficiency

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ABSTRACT

The dusty environment of the moon and the deposition of charged particles were troublesome in previous NASA explorations. In this study, an electrostatic lunar dust repeller (ELDR) was developed to mitigate the dust deposition problem. The ELDR consists of an arrangement of thin, needle-shaped electrodes in front of the protected surface to repel approaching, like-charged lunar dust. A discrete element method (DEM) was applied to track particle trajectories for determining the removal efficiency. Simulation results for single electrodes ($L=5$ cm, $D=1$ mm and $L=10$ cm, $D=1$ mm) both protecting a 5-cm × 5-cm surface indicated that 4 kV and 1.5 kV were the respective-applied voltages required to achieve 100% protection from falling 20-μm lunar dust particles. The electrical particle–particle interaction was identified to be a beneficial factor. Finite element analysis concluded that an x-shaped pattern was the most effective arrangement of the ensemble electrodes to protect a 30-cm × 30-cm surface. Modeling results showed that 2.2 kV and 1.4 kV were the minimum voltages applied to electrodes of length $L=5$ and 10 cm, respectively, on each electrode of the ensemble model to achieve complete removal of 20-μm-sized particles. The ensemble-electrode ELDR required lower applied voltage than the single-electrode ELDR, and in the most conservative scenario, it consumed only 9 times more electric power to protect an area 36 times larger.

1. Introduction

Observations from the Apollo missions revealed that the hard vacuum lunar environment is suffused with electrically charged fine particles, with high affinity to stick to the nearby surfaces. The minimal atmosphere of the moon leaves the lunar surface unprotected from intense solar radiation. Photoemission of highly energetic electrons caused by UV and X-rays on the lunar dayside and interaction of less-energetic electrons due to solar winds on lunar nightside make the lunar particles electrostatically charged (Abbas et al., 2007; Stubbs et al., 2006). Based on the results inferred from the measurements during the Apollo program, accumulation of positive and negative charges on lunar grains causes repulsive forces between the like-charged particles, opposing gravitational and cohesive forces on particles. Once fine particles attain an adequate charge, they accelerate upward and lift off from the surface. Micron- and submicron-sized particles leave the

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sheath region with an initial velocity but eventually fall back toward the lunar surface due to gravity (Stubbs et al., 2006; Colwell et al., 2009). The consequent deposition of the falling lunar dust on the exposed components deteriorates performance of solar panels (Sims et al., 2003), obscures optical surfaces (Calle et al., 2011), degrades thermal radiators (Gaier et al., 2011), creates false responses from the measuring devices, and interferes with the operation of Extra-Vehicular Activity (EVA) systems (Gaier, 2005). Therefore, the National Aeronautics and Space Administration (NASA) has prioritized dust mitigation programs to develop appropriate lunar and Martian dust control technologies for future exploratory space missions.

Inspired from terrestrial applications, a wide variety of passive and active methods have been proposed to mitigate the effects of lunar dust. Implementation of any gas, liquid, foam or gel spray in the hard-vacuum lunar environment is inapplicable due to the impracticality of directing the materials toward the contaminated surfaces (Wood, 1991). Mechanical methods such as the application of a dust wiper proposed by Fernández et al. (2007) and brushes proposed by Gaier et al. (2011) were efficient and light but abrasive and appropriate only for small surface areas (less than 30 cm^2). Additionally, the methods require complex robotic technology and frequent brush cleaning.

He et al. (2011) reviewed a number of suggested self-cleaning methods for the solar panels and concluded that electrodynamic-based approaches are the best strategies for dust removal. The best-characterized technology on this category is the electrodynamic dust shield (EDS), introduced by researchers at NASA Kennedy Space Center (KSC) (Sims et al., 2003; Calle et al., 2008) using the electric curtain concept developed by Tatom et al. (1967) at NASA and Masuda and Matsumoto (1973) at the University of Tokyo in the 1970s. The EDS, consisting of a series of electrodes connected to an AC source inside a transparent insulator film installed on the solar cell surfaces, lifts and transports deposited particles with generated standing and traveling waves (Calle et al., 2011). Although the EDS' high efficiency for surface cleaning has been reported in various studies (Calle et al., 2004, 2011; Liu & Marshall, 2010; Atten et al., 2009), operation of an EDS may expend energy significantly faster than the energy capture rate of the solar panel (Qian et al., 2012).

Clark et al. (2010) introduced another electrostatic-based tool called Space Plasma Alleviation of Regolith Concentrations in the Lunar Environment (SPARCLE). The SPARCLE consists of an electron gun and a surrounding collection circular plate to charge particles to deposit on an assumed surface. After adequate bombardment of the dust layer with a low-energy beam of electrons, repelling Coulomb forces between the particles overcome gravitational force and surface forces over the particles, lifting the particles up for collection on the oppositely charged surfaces around the device. Although SAPRCLE is portable and operates at low power, it requires either robotic arms or an astronaut's involvement, and its application to clean large surfaces is cumbersome.

An electrostatic lunar dust collector (ELDC) was suggested by Afshar-Mohajer et al. (2011a, 2011b, 2012) as a feasible lunar dust mitigation technology requiring the least electrical power. The ELDC applies a grid layer of thin, parallel, conducting, transparent and squared plates in front of the protected surfaces. Since ELDC plates are alternatively connected to the positive and negative terminals of a DC power supply, each pair of plates forms an electrical capacitor to attract the falling charged particles toward the collection plate with opposite electrical polarity before deposition on the protected surface. The ELDC concept requires much less electrical energy than the EDS. However, the weight of the plates, partial blockage of the solar radiation and the need for occasional cleaning are concerning factors for wide application of this mitigation technology.

In this study, an electrostatic lunar dust repeller (ELDR) was developed to address the abovementioned concerns. The ELDR consists of an array of needle-shaped thin electrodes, all connected in parallel to the same terminal of the DC power supply. As the other terminal of the power supply is grounded, charges accumulate on the electrodes' surface, and an electrostatic field forms around the group of electrodes to direct falling particles away from the protected surface. Because the levitated lunar particles are ideally like-charged on each side of the moon, the electrostatic field created by the electrode array will repel the falling lunar dust away before it approaches the protected surfaces. Although the ELDR has the abovementioned advantages over the ELDC, its electrical power requirement and optimum arrangement of electrodes are unknown. This study is aimed to address these issues.

2. Methods

Evaluating the removal efficiency of the ELDR involves calculation of non-uniform charge distribution on the electrodes surface, individual follow-up of the particle trajectories, and determination of electric field vectors and electric potential distributions for the system of electrodes, all around the protected area. Removal efficiency of a single-electrode ELDR was studied initially with sensitivity analyses on the applied voltage and electrode length. The results give insight into proposing an electrode-ensemble ELDR operating not only more efficiently but also at a lower voltage. Estimating the lunar dust properties using the related literature was the first step of this study. To fulfill each of the abovementioned modeling tasks, an appropriate numerical modeling scheme was implemented as explained below.

2.1. Lunar dust properties

The lunar dust characterization used for the discrete element model (DEM) was the same as our previous studies on ELDC (Afshar-Mohajer et al., 2012). All particles falling toward the ELDR were assumed to be identical in shape, density,