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Electrostatic Cleaning System Integrated with Thunderon Brush for Lunar Dust Mitigation

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***Abstract*—**Detrimental effects of lunar dust on space hardware, spacesuits, and astronauts' health have been already identified during Apollo missions. Developing effective dust mitigation technologies is critically important for successful space exploration and related missions in NASA applications. In this study, an electrostatic cleaning system (ECS) integrated with a negatively ionized Thunderon brush was developed to mitigate small-sized lunar dust particles with diameters ranging from 0.04 µm to 35 µm, and the mean and median size of 7 µm and 5 µm, respectively. It was found that the frequency pulses of the negative ion generator caused particles to stick to the Thunderon bristles and repel between the pulses. The brush was used manually to ensure that particles were removed from areas where the ECS failed to mitigate the lunar simulant. The acquired data demonstrated that the developed system removed over 91-96% of the lunar dust particles. The present study was performed as a proof-of-concept to enhance the cleaning performance of ECSs by integrating a brushing process. Suggestions were made to further improve the performance of the developed technology through future research.

***Keywords*—**Lunar dust mitigation, electrostatic cleaning system, brushing, Thunderon brush, cleaning rate.

I. Introduction

THE lunar surface is covered with a layer of micrometer-sized dust particles that are electrostatically charged and tend to adhere to surfaces, e.g., spacesuits, optical devices, and mechanical components [1]-[3]. Lunar dust can cause serious problems such as vision obscuration, damage to mechanical parts of equipment, abrasion on spacesuits, deposition on optical surfaces, and harmful effects on astronauts such as respiratory and cardiovascular diseases [4]-[10]. Particularly, spacesuits are an essential part of space exploration because they protect the astronauts from the harsh extra-terrestrial conditions and provide several resources to assist astronauts during extravehicular activities [10]. As a result, developing effective dust mitigation technologies has been a priority for the US National Aeronautics and Space Administration (NASA) for successful future lunar and Mars missions as well as preventing the detrimental impact of lunar dust on the lifetime and functionality of spacesuits [11], [12].

Brushing has been already identified as an effective lunar dust mitigation technique. In the NASA Glenn Research Center, the effectiveness of Thunderon brushes to remove dust from the thermal control surfaces was demonstrated [13]. As another effective lunar dust mitigation technique, ECSs have been demonstrated high cleaning efficiency/rate of exceeding 80% [14]. An ECS is a technology to repel particles by an electrostatic force that generates through a single- or multiple-phase AC voltage supply to the electrodes that are embedded into a flexible substrate (e.g., spacesuit) [15], [16]. However, despite high cleaning performances of ECSs, complete cleaning is usually difficult to achieve due to remaining trapped small particles, particularly those with diameters of less than 10 µm, between the fibers of spacesuit fabric [14]. To overcome the challenges of removing remaining small particles, ECSs are integrated with other technologies. For example, [17] used a mechanical vibration technique; however, it failed to mitigate particles smaller than 10 µm.

Under a NASA-funded project, the present study was performed as a proof-of-concept to develop an effective dust mitigation technology by integrating an ECS with a negatively ionized Thunderon brush to mitigate small dust particles. The justification for developing this technology was to remove the majority of large particles by the ECS and then the remaining particles by brushing. Specifically, brushing can be helpful to remove small particles from the areas where the ECS fails to mitigate dust such as between micrometer-sized fibers. Since Thunderon bristles are fine and soft, they reach into small areas and do not cause abrasion on spacesuits. This is an advantage of a Thunderon brush because abrasion is a significant concern in spacesuits.

II. Experiment

A. Sample Preparation

In the present experiments, Kevlar fabric was used to represent spacesuit fabric. Two insulated copper wires with a diameter of 100 µm were embedded in parallel into the fabric to form the electrodes. The distance between two parallel electrodes is an important design parameter because the generated electrostatic force and, in turn, the cleaning performance highly depend on this distance [14], [17]. The present experiments were conducted at three different electrode distances of 3 cm, 4 cm, and 5 cm.

The capability of the developed dust mitigation technology was evaluated by using sufficiently small-sized particles. LHS-1D (Exolith Lab) was used as the lunar dust simulant. The particle size was ranged from 0.04 µm to 35 µm, with the mean and median size of 7 µm and 5 µm, respectively. Since large particles have high weight compared to their number, they are usually removed prior conducting the experiments to

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avoid an overestimated cleaning performance [16]. However, because the particles in this study were sufficiently small, the experiments were conducted without elimination of larger sized particles. Fig. 1 illustrates the fabric, electrodes, and lunar dust simulant.

Fig. 1 Components of the fabric: (1) Electrodes; (2) Kevlar fabric; (3) Lunar dust simulant

The Thunderon brush (Gordon Brush Mfg. Co., Inc.), made of an extremely soft fiber (~ 38 µm in diameter), was used for the brushing. Fig. 2 illustrates the Thunderon brush and different components that were installed on that.

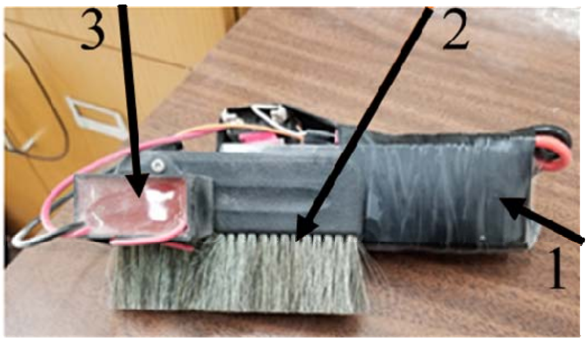

Fig. 2 Components of the Thunderon brush: (1) Power supply; (2) Thunderon brush; (3) Ion generator

The Thunderon brush can be used in a wide variety of electrical dusting and cleaning applications and dissipate a charge on any electrically charged surface. Preventing abrasion to spacesuits due to extremely soft fiber of Thunderon is another merit of using a Thunderon brush. The innovation of the present study was to use an ion generator, which allowed the brush to be activated and electrostatically discharge the dust particles in addition to applying the frictional forces (manual brushing).

B. Experimental Procedure

Lunar dust simulant particles were rubbed uniformly onto the area between two parallel electrodes, as shown in Fig. 1. For obtaining the weight of added particles, the weight of individual sample was measured before and after the simulant was added using an accurate digital weight scale with a capability of measuring grams up to four decimal places. We used an outlet with an output voltage of 110 V that was stepped down and converted to 12 V DC using a conventional adapter. Then, the voltage was transferred to a pulse frequency signal generator. The voltage was then emitted at 20% of the input (20% of 12 V) and 10 Hz toward a power module (i.e., high voltage pulse transformer arc generator). Then, the power module emitted a high single phase AC voltage to the electrodes. Because the fabric was insulative, the applied voltage between the parallel electrodes resulted in a large electrostatic field [17]. The frequency of the applied voltage at the present experiments was set at 10 Hz because it was identified as an optimal frequency in several studies such as [8] and [18].

The electrical power was applied for four 30 s periods with 5 s of rest in between. Then, the negative ion generator activated the brush, and fabric was swept manually. The entire brushing process took for 30 s corresponding to 15 brushing cycles, which each cycles represented 1 s sweeping in one direction and 1 s rest. At the end of cleaning process, the weight of an individual fabric was measured to obtain the weight of removed particles. For minimizing the effects of environment on the experiments, the experimental setup was located inside a glass enclosure as shown in Fig. 3.

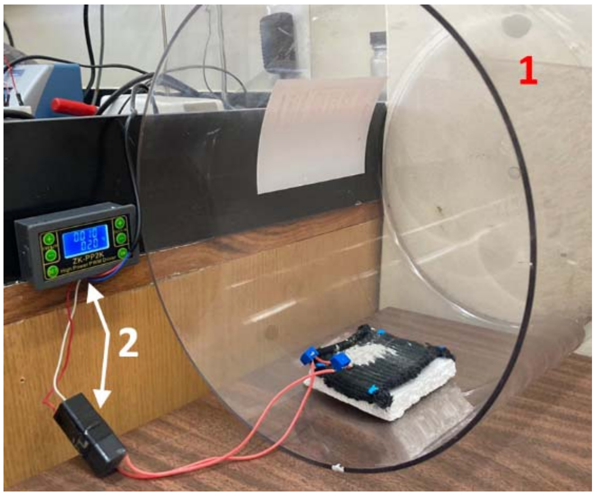

Fig. 3 Experimental setup: (1) Glass enclosure; (2) Signal generator and voltage converter

III. Results

Results included a combination of quantitative and qualitative data. The performance of the developed dust mitigation technology was characterized by the cleaning rate, which corresponded to the ratio between the weight of removed particles and the initial weight of particles [17]. The cleaning rates at different electrode distances are illustrated in Fig. 4. The developed technology achieved high cleaning rates of 91-96%. It was very difficult to identify the range of size of particles that remained on the fabrics. However, the lunar simulant in the present study consisted of particles with a mean diameter size of 7 µm, which is less than the size of lunar dust of interest (i.e., 10 µm); therefore, it can be concluded that the most of mass removal in the present experiments was not due to the large particles. As a result, the high cleaning rates achieved in this study with sufficiently small particles indicate the developed technology as a promising dust mitigation technique for future missions in NASA.

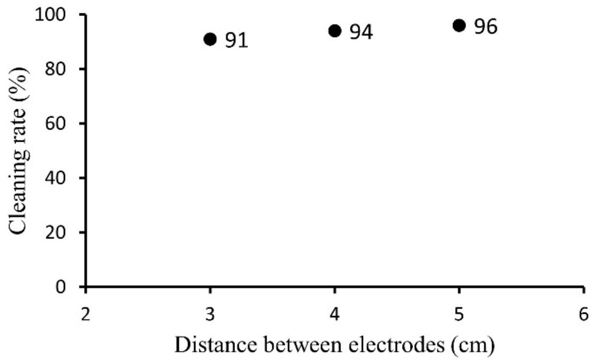

Fig. 4 Cleaning rates at different electrode distances

Figs. 5-7 illustrate the dust mitigation at different cleaning steps for the sample with the largest electrode distance (i.e., 5 cm). The substantial enhancement in the cleaning process due to utilizing the Thunderon brush is obvious by comparison between Figs. 6 and 7. It was observed that simulant particles near the Thunderon bristles were attracted and rapidly flicked in the opposite direction during the bristles discharge as they self-discharge in cycles. This observation indicates the high performance of an ionized Thunderon brush to enhance the cleaning process.

Fig. 5 Lunar dust simulant on the fabric for the electrode distance of 5 cm, prior generating the electrostatic force

Since the purpose of this study was to demonstrate the performance of the ECS integrated with brushing, experiments were not conducted using the ECS and brushing, separately. Therefore, it is not possible to specify the contribution of individual technique on the cleaning performance. However, based on the available data in the literature, the cleaning rates of over 80% was achieved by ECSs similar to the ECS in this study [14]. Thus, it can be concluded that the integrated brushing significantly enhanced the cleaning performance of the ECS in this study.

Fig. 6 Lunar dust simulant on the fabric with an electrode distance of 5 cm after applying the ECS but prior to brushing

Fig. 7 Lunar dust simulant on the fabric with an electrode distance of 5 cm, after the brushing (end of dust removal process)

Although the preliminary results demonstrated that the developed technique in this study can be a promising lunar dust mitigation technology, further research is required to address the challenges of the present technology for future space exploration and related missions in NASA applications. Suggestions for future research are provided as follows:

(1) The present technology requires a high voltage to establish the electrostatic field, which is a safety concern for astronauts. Although we were not successful to measure the high voltage during the experiments, the applied voltage at the frequency of 10 Hz for generating the electrostatic field was reported in the order of KV in the previous studies in [8], [14], [16], and [17]. Because

spacesuits are made of multi-layered insulations [19], the hypothesis is that the spacesuit by itself can provide adequate protection to astronauts from high voltages applied to the outer layer of spacesuit. However, further research is required to prove this hypothesis.

(2) Since the spacesuit is subject to geometrical changes with astronaut's movements, insertion of electrodes into the fabric should be performed through accurate insertion techniques such that an astronaut's movement does not cause uneven distances between parallel electrodes. Uneven electrode distances result in different electricity resistant paths and, in turn, uneven electrostatic fields, which reduce the efficiency of an ECS to remove particles.

(3) The performance of the developed system needs to be analyzed in the cryogenic temperatures, which are the operating temperatures on the lunar surface.

(4) The cleaning performance of the proposed technology should be investigated by using the brushing prior to the ECS. This configuration may decrease cleaning times as enormous sums of soil may be initially removed by brushing and the ECS remove smaller particles when the brushing is terminated.

IV. Conclusion

The present study was performed as a proof-of-concept to demonstrate the cleaning performance of an ECS integrated with brushing to remove small-sized lunar dust particles from spacesuits. By utilizing an electrostatic field generated on the surface of the fabrics along with using a negatively ionized Thunderon brush, cleaning rates of 91-96% were achieved. Further research is required to address the potential challenges arising from using the proposed lunar dust mitigation technology. Suggestions for future research were provided. Special attention must be paid to astronauts' safety to ensure that using high voltages is feasible.

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