Mitigation Strategies for Lunar Dust: Challenges and Innovations

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Abstract

This study presents a hybrid dust mitigation technique that combines passive and active methods to remove silica dust from solar cell surfaces under vacuum conditions. The proposed system integrates three key components: a Polydimethylsiloxane (PDMS) surface coating to reduce adhesion forces, a pulsed electron beam to electrostatically charge dust particles, and a DC-biased grid to generate an electric field that lifts and removes the charged particles. The hybrid configuration achieved approximately 90% cleaning efficiency and power recovery, significantly outperforming the active technique alone. However, minor challenges were observed, including partial shading from the PDMS and grid alignment effects. Proposed improvements include the development of a deployable grid and optimization of PDMS thickness to reduce optical losses. Overall, the hybrid approach demonstrates a promising mitigating dust accumulation on solar cells.

Keywords: Lunar dust charge- Mitigation technique- Electron beam irradiation.

1. Introduction

Lunar dust presents a significant challenge to the performance and longevity of equipment on the Moon, particularly solar cells, which are vital for powering long-term lunar exploration missions [1]. The lunar dust, known as lunar regolith, can degrade the efficiency of solar cells by accumulating on their surfaces, blocking sunlight, and creating barriers for charge carriers. Lunar dust caused numerous operational challenges during the Apollo missions, most notably the reduced efficiency of solar panels. For instance, experimental and analysis results of Apollo mission showed that dust accumulation on solar cells reduced their power output by 50% at dust levels of 3 mg/cm² [2]. Additionally, smaller dust particles further degrade the efficiency of solar cells. These effects underscore the critical need for effective dust mitigation strategies to preserve the functionality of solar cells in future lunar missions [3,4].

To overcome this problem, mitigating lunar dust contamination is critical for sustaining long-term lunar operations and ensuring the efficiency of technological infrastructure. Dust mitigation strategies are broadly categorized into two main types: active and passive, The Active method involves external energy input to remove or repel dust; However, Passive methods focus on preventing dust adhesion using surface coatings and material properties rely on inherent properties of materials or coatings that allow for self-cleaning or resistance to dust accumulation without the need for external power [5-7].

In this experimental work, we are trying to restore the solar cell electrical performance inside the vacuum chamber after the contamination of the dust on its surface. The dust removal technique combines high-energy electron beams and electrostatic charging to clean the contaminated solar cell exposed to lunar dust. Using an electron beam to remove dust particles from sample surfaces has been investigated as an active dust mitigation technique. The method has shown effective results when applied to optical lenses and spacesuit fabrics; however, it exhibited notable limitations when used on solar cell surfaces, as reported by Farr [8,9]. In those studies, electron beam exposure alone achieved only about 40% cleanliness, while introducing sample rotation improved the efficiency to roughly 50%, indicating only a marginal enhancement. These findings highlight the intrinsic challenges of applying electron beam cleaning to solar cells, where surface conductivity, multilayer coatings, and uneven charge accumulation hinder effective dust removal compared with smoother dielectric surfaces.

To overcome that, the used solar cell coated with Polydimethylsiloxane (PDMS). PDMS is a flexible, optically transparent, and chemically inert material, showing promise in mitigating dust accumulation on solar cells due to their low surface energy and adhesive properties. Its flexibility allows it to conform to irregular surfaces, ensuring effective dust capture without significantly impacting solar efficiency, given its transparency in the visible spectrum [10,11].

To further enhance the cleaning efficiency, a positively biased grid (+500 V) was positioned above the solar cell surface in addition to the electron beam exposure. The high-energy electron beam (300 eV) charges the dust particles negatively, after which the positively biased grid electrostatically attracts and dislodges the charged particles from the surface. Meanwhile, the PDMS coating reduces the adhesion forces between the particles and the solar cell surface, enabling more efficient removal. The effectiveness of this hybrid cleaning approach was evaluated using image analysis in MATLAB, comparing the brightness of the solar cell surface before and after cleaning to quantify dust removal. The experimental results demonstrated promising performance, achieving approximately 90% reduction in dust coverage.

The next section presents the experimental procedure, followed by Section 3, which discusses the results and analysis of the obtained findings. Section 4 provides a detailed discussion of the results in comparison with previous studies, and finally, the conclusion section summarizes the key outcomes and highlights the overall effectiveness of the proposed dust mitigation approach.

2. Experimental Work and Test Setup

The experimental work was carried out in a vacuum chamber to investigate the removal of silica dust from the surface of a solar cell using a hybrid dust mitigation technique. Silica dust was selected with a layer thickness of approximately 100 µm and uniformly deposited on the solar cell surface. The tested sample was a triple-junction solar cell with an area of 8 × 4 cm². Under standard illumination, the initial electrical parameters of the clean solar cell were 0.445 W and 0.225 A for maximum power and short-circuit current, respectively. After adding PDMS coating layer to the cell surface, a slight reduction in electrical performance was observed, with P_{max} 0.400 W and I_{sc} 0.200 A, due to the optical shading introduced by the coating.

In the hybrid cleaning process, the solar cell was first coated with PDMS to reduce the adhesion between dust particles and the surface. The PDMS play a role of passive mitigation technique due to its physical characterization mentioned previously. The contaminated surface with the silica dust was then exposed to a pulsed electron beam with an energy of 300 eV and a current density of 3.7×10^{-4} A/m², applied in 10-second on/off cycles for a total duration of 1 minute. This step charged the dust particles, enhancing their response to the subsequent electrostatic force. After charging, a +500 V DC potential was applied to a copper grid placed above the solar cell surface, also in pulsed mode (10-second on/off cycles for 1 minute). The combination of the electron beam and the electric field generated by the grid produced sufficient electrostatic force to overcome the gravitational and adhesive forces acting on the dust particles. The charged dust particles by the electron beam were attracted toward the grid and subsequently swept away from the solar cell surface.

Inside the vacuum chamber, there is a xenon lamp used to measure the solar cell's electrical parameters during the different stages of the experiment (clean, contaminated, and after cleaning process) to evaluate the cleaning effectiveness based on the solar cell electrical performance. A HSC (High-Speed Camera) placed outside the vacuum chamber recorded high-resolution images through the vacuum access window for the solar cell surface. The captured images were analyzed using MATLAB to compare the dust coverage before and after cleaning, quantifying the removal efficiency based on pixel intensity (black pixels representing clean areas and white pixels representing dust-covered areas). The diagram for the experimental setup is shown in Figure 1.

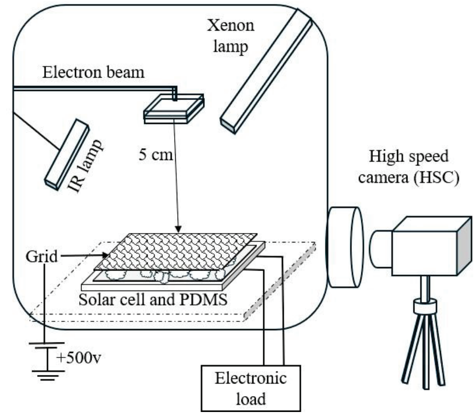

Fig. 1. Experimental setup of the silica dust ejecta inside the vacuum chamber.

3. Results and Discussion

The sequence of images presented in Figure 2 illustrates the effectiveness of the hybrid dust mitigation technique over the course of the experiment. In image (A), a uniform layer of silica dust can be observed on the PDMS-coated solar cell surface. Image (B) shows the grid positioned on top of the surface prior to initiating the cleaning process, enabling the application of an external electric field before starting the cleaning process. Image (C) is shown the solar cell surface after the cleaning process demonstrates a significant reduction in dust coverage.

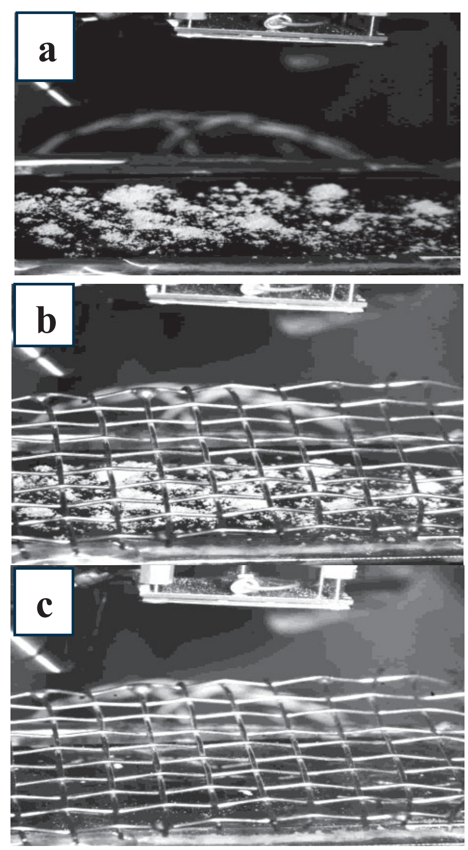

Fig. 2. Sequential images illustrating the condition of the solar cell surface at different stages of the experiment: (A) before cleaning, (B) during preparation with the grid in place, and (C) after the cleaning process.

The results in Figure 3 provide a quantitative evaluation of the dust removal process. In the clean state, nearly the entire surface is represented by black pixels, indicating minimal dust coverage. After deposition, the number of white pixels increases significantly, reflecting extensive dust accumulation on the solar cell surface with the silica dust. Following the cleaning process, the pixel distribution shifts back toward the initial clean condition, with a clear reduction in white pixels and a corresponding increase in black pixels indicating that after following the cleaning process, most of the dust particles removed.

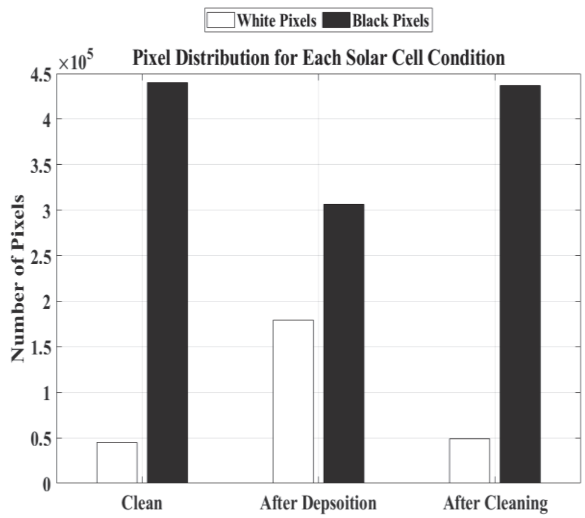

Fig. 3. Pixel distribution for the solar cell under three conditions: clean, after dust deposition, and after cleaning. Black pixels correspond to clean surface areas, while white pixels represent regions covered by dust particles.

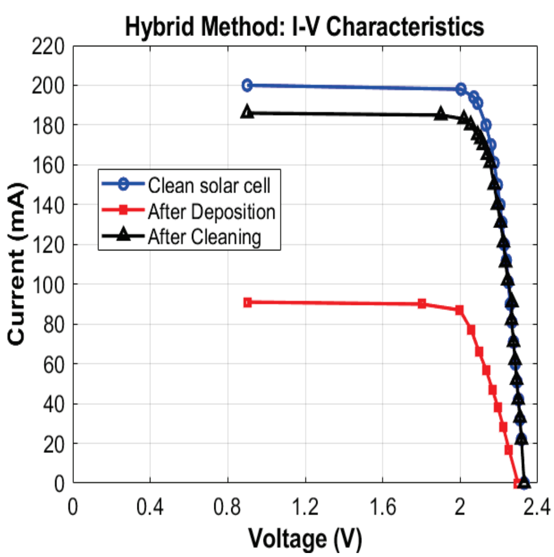

Fig. 4. I–V characteristics of the solar cell under three surface conditions: clean, after dust deposition, and after cleaning using the hybrid dust mitigation method. The results show the effect of dust accumulation and removal on the electrical performance of the solar cell.

Confirming the image analysis results, the I–V characteristics in Figure 4 clearly demonstrate the impact of dust accumulation and subsequent cleaning on the solar cell's electrical performance. The figure demonstrates a clear improvement in electrical performance after the cleaning process. Before cleaning, the short-circuit current (I_{sc}) dropped significantly due to dust coverage, with a measured value of approximately 100 mA, resulting in a notable reduction in power output. After cleaning, I_{sc} recovered to around 180 mA, which corresponds to roughly 90% of the initial clean state. Similarly, the maximum power (P_{max}) increased from 0.19 W before cleaning to 0.38 W after cleaning.

4. Discussion

The presented results highlight the innovation of combining passive and active techniques to remove silica dust from the solar cell surface under vacuum conditions. The hybrid dust mitigation technique integrates three main components: (1) PDMS surface coating to reduce adhesion forces as a passive technique, (2) pulsed electron beam exposure to electrostatically charge the dust particles, and (3) a DC-biased grid to generate an electric field that lifts and removes the charged particles. Both electron beam and the grid considered active mitigation techniques. This integrated approach demonstrated a significant improvement in cleaning efficiency and power recovery compared with the active method alone. After cleaning, the solar cell recovered up to 90% of its initial electrical output, and image analysis confirmed a comparable ~90% dust removal, showing strong agreement between optical and electrical measurements.

The PDMS coating plays a key role in enhancing the efficiency of the cleaning process. By coating the surface of the solar cell, it reduces the adhesive forces that normally hold dust particles to the surface. This means that the same exposure parameters 300 eV pulsed electron beam (10 s on/off cycles for 1 min) and +500 V grid voltage become sufficient to detach and remove the dust. The pulsed operation also minimizes power consumption and allows efficient charge accumulation on the particles without excessive heating or damage to the surface.

Despite its advantages, the hybrid technique also presents specific challenges. First, the PDMS coating introduces a minor shading effect, reducing the solar cell output by approximately 8% even before dust deposition. Second, the copper grid casts a shadow during operation, limiting the power measurement during the cleaning phase. Additionally, maintaining good alignment between the grid and the solar cell surface is essential for stable and uniform cleaning performance.

To address these challenges, practical solutions are proposed for future work. A deployable or retractable grid could be implemented, allowing the grid to be activated only during the cleaning phase and stowed afterward, thereby eliminating its shadowing effect during power generation. Optimization of the PDMS layer thickness and optical properties could further minimize shading while maintaining low surface adhesion. Finally, refining the grid geometry and positioning would enhance field uniformity and allow more consistent dust removal across the entire solar cell area.

In summary, the hybrid dust mitigation method demonstrates a promising and innovative solution to one of the key challenges facing long-duration lunar surface operations. By combining PDMS coating with pulsed electron beam exposure and a DC-biased grid, this approach achieves high cleaning efficiency and power recovery with relatively simple hardware. Addressing the identified limitations through engineering improvements will enhance the system's readiness for practical deployment on future lunar missions.

5. Conclusion

This study demonstrated an effective hybrid dust mitigation method for solar cells under vacuum conditions by integrating PDMS coating, pulsed electron beam exposure, and a DC-biased grid. The approach achieved high cleaning efficiency and significant power recovery, confirming its potential for future lunar surface applications. Addressing shading and grid limitations through optimized design will further enhance system performance and reliability for long-duration missions.

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