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Electrodynamic dust shield performance under simulated operating conditions for solar energy applications

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ABSTRACT

Electrodynamic dust shield (EDS) uses traveling-wave or standing-wave electrodynamic effects to repel dust particles from a surface, and has been proposed as a potential anti-dust solution for mitigating soiling loss in solar energy applications. In this study, a standing-wave EDS technique was tested in a cyclic manner at field-relevant dust loading levels using dust deposited by aerosol deposition, in order to assess the EDS' dust removal efficiency under simulated real-world operating conditions. Tests using sieve deposition and the single-operation mode were also carried out for comparison. Each single-operation test only used freshly-deposited dust with a single activation of the EDS, and the results showed that the dust removal efficiency with aerosol deposition to be moderately lower than that with sieve deposition. In contrast, a cyclic-operation test consisted of many consecutive cycles, which began with the first cycle using freshly-deposited dust, and each additional cycle having new dust added on top of the persistent dust from the previous cycle. The cyclic-operation dust removal efficiency was found to be strongly dependent on the dust deposition method. Using aerosol deposition, the cyclic-operation efficiency continually decreased as the number of cycles increased; with sieve deposition, the cyclic-operation EDS efficiency fluctuated and had a much higher average value than with aerosol deposition. The different behaviors of the cyclic-operation EDS efficiency can be modeled with two hypothetical scenarios, based on how the persistent dust from a previous cycle reacts to EDS activation. However, the physical mechanisms behind the different behaviors are not well understood. The results from this study suggest that further research is critically needed for evaluating the effectiveness of electrodynamic anti-dust solutions for solar energy applications in dusty environments.

1. Introduction

In dry and dusty regions, dust accumulated on critical surfaces of solar devices can block solar irradiation and cause significant loss in energy output, also known as soiling loss [1]. In dusty environments, a photovoltaic (PV) module can accumulate 80 mg m^{-2}–300 mg m^{-2} of dust per day, and every 100 mg m^{-2} of dust accumulation can cause an additional output loss of 0.4–0.7% [2,3]. Such high levels of soiling calls for active cleaning to maximize the economic return of a solar power generation project. Development of various PV cleaning technologies has been active, and there is a need for standardized laboratory test methods for evaluating these technologies, so that their technical merits can be assessed under comparable conditions.

Electrodynamic dust shield (EDS) has been proposed as a candidate for anti-dust solutions for solar power generation in recent years [4,5]. Initially developed for space applications, EDS is also known as electrodynamic screen, electric curtain, or electrostatic cleaning system [6–8]. As shown in Fig. 1, the basic EDS design involves fabricating electrodes on a substrate. The electrodes are either transparent or made very thin so as to minimize any shading effects, and they may be formed into straight lines or other more complex patterns [4,5]. Over the electrodes, a transparent dielectric cover is needed to isolate the electrodes from air. The dielectric cover becomes the outer most layer that requires soiling mitigation. When operating in the field, dust deposition occurs on the outside (air side) of the dielectric cover, but activation of the EDS can repel the deposited dust, taking advantage of the electrostatic charges carried by the dust particles [9]. The dielectric cover is a thin sheet that is bonded to the electrodes/substrate through an adhesive, or applied as a coating [4,5]. Activating, or "energizing" the EDS, involves applying an alternating high voltage to the electrodes, which leads to an alternating electric field. Electrically charged dust that deposited on the air side of the dielectric cover can then be repelled from the EDS due to the alternating electric field. The EDS can either be a standalone thin structure that covers the front surface of a solar

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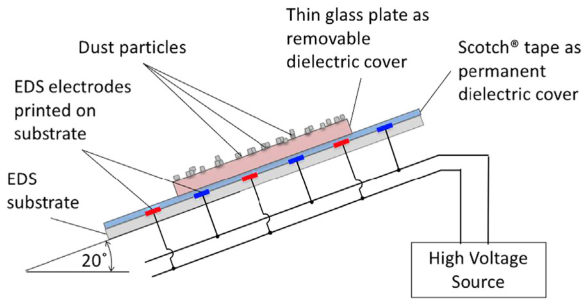

Fig. 1. A schematic drawing of the experimental setup for EDS efficiency measurement with the EDS device shown in plan view (not to scale).

module, or a component that is integrated into a solar module [10]. By periodically energizing the EDS, dust accumulated on the front side of the solar module can be repelled, to fall on the ground or be blown away by wind. As energizing the EDS only consumes a small amount of power [4,11,12] and the operation is expected to be periodic, it is technically possible for EDS to bring net economic benefits to solar power generation by reducing soiling loss. The EDS can be designed to have either traveling-wave [5] or standing-wave [4] alternating electric field. The traveling-wave design involves more complex electrical circuits and more complex high voltage sources. Kawamoto and Shibata suggested that the standing-wave design may be better suited for utility-scale solar power generation [4]. Material properties, most notably surface energies of the particles and the EDS dielectric cover, play important roles in particle-EDS and particle-particle interactions and thus affect the dust removal efficiency [13,14].

The anti-dust performance of EDS and the effects of material properties eventually need to be assessed through field tests, as anti-dust coatings have been in previous studies [15–17]. In conjunction with tests conducted in the field, it is typical to conduct laboratory tests that mimic the real-world conditions. In the real world, airborne dust continuously deposits onto solar panels, and any anti-soiling mechanism needs to be acting continuously (in the case of coatings) or activated continually (in the case of EDS), i.e., in a cyclic manner. Since the dust removal efficiency is usually less than 100%, there will be some remaining dust (the persistent dust) after each EDS activation. The persistent dust and the new dust added over the activation interval together are to be repelled during the next EDS activation. As the cycle of dust-accumulation-EDS-dust-removal goes on, the dust loading on the EDS surface over a period of time should be what concerns us. Ideally, EDS should be able to keep the cyclic dust loading low, so that soiling loss is maintained at an acceptable level. Earlier EDS studies have mostly assessed the dust removal efficiency of EDS in the single-operation mode, in which the EDS is cleaned by wiping or washing, loaded with dust, energized, and cleaned by wiping or washing again before running another measurement [4,18]. In other words, most experimental studies have only used dust that is freshly loaded onto the EDS surface (no “persistent” dust from any previous EDS energization). Mazumder et al. carried out a traveling-wave EDS study in a cyclic manner, but the per-cycle additional dust loading was too high to be considered relevant for real-world applications [5].

Additionally, accumulated dust can undergo cementation and caking when night-time temperature/humidity conditions are conducive to dew formation, which has been simulated in laboratory experiments [19]. The cementation effect should be considered in future EDS research, but it is beyond the scope of this study.

To obtain meaningful results from cyclic laboratory experiments, the dust loading added to the test surface per cycle should be consistent with the simulated real-world operation interval. For example, to simulate real-world EDS activation once every 24 h, in a lab cyclic-operation experiment we should add 80 $mg\,m^{-2}\,d^{-1}$–300 $mg\,m^{-2}\,d^{-1}$ in every cycle (see real-world dust accumulation rate in [2]). This is important because the EDS efficiency is a strong function of dust loading, when the dust loading levels are relatively low [18]. Therefore, the cyclic-operation results should be dependent on the per-cycle dust loading level. In the study by Mazumder et al. [5], dust loading in each experimental run was mostly greater than 10 $g\,m^{-2}$, which would be acceptable for simulating real-world soiling cycles or one months or more, based on the dust accumulation rate found in the field [2]. This further shows that when running laboratory experiments, we should use appropriate dust loading levels so as to obtain meaningful results. This principle should apply to PV soiling lab studies in general. For example, when studying dust cementation or caking due to diurnal temperature/humidity variations, the dust loading applied on a test surface should be comparable to one day's dust accumulation in the field.

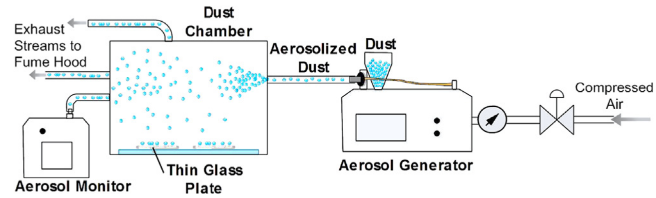

Fig. 2. Schematic of setup for aerosol deposition.

Real-world dust deposition on solar panels normally occurs as a result of aerosol deposition of aeolian dust [20]. Airborne dust particles deposit onto solar panels due to gravitational settling and turbulent deposition [21], some of which are removed due to rebound and resuspension, while some dust particle remain leading to dust accumulation [22]. To mimic aerosol deposition in the lab, it would typically require an aerosol generation apparatus, such as a powder disperser (see Fig. 2) to cause the dust particles to be suspended in air flow over some horizontal distance before depositing on the test surface. A more involved laboratory study can utilize a dust wind tunnel, in which dust is suspended in air flow with a well-defined velocity profile and dust concentration [23]. However, earlier EDS studies mostly use sieve deposition, in which a mesh sieve containing dust is shaken or vibrated directly above the EDS, and dust particles fall through the mesh openings onto the EDS surface without significant horizontal movement [4,5]. One could argue that the dust falling out of a mesh sieve might also be called an aerosol, but herein we use the terms “sieve deposition” and “aerosol deposition” to operationally distinguish the two different methods of dust deposition in laboratory experiments. Particles deposited with sieve deposition are much more agglomerated compare to those with aerosol deposition, leading to very different morphology and apparently particle size distribution, as we have previously reported [18] and as we shall see in the results of this study.

Towards the development of an EDS technology that is relevant to real-world applications, it was our hypothesis that both the mode of operation (cyclic-operation vs. single-operation) and the method of dust deposition (sieve vs. aerosol) should have an impact on the dust removal efficiency of EDS. The objective of this study was to determine that impact, so as to gain further insight into EDS as a potential anti-dust solution for solar energy applications. Herein we describe the methods and the results of this study.

2. Methods

2.1. Dust removal efficiency measurement

Fig. 1 shows a schematic drawing of the experimental setup used in this study. A removable dielectric cover method utilizing a thin soda lime glass plate placed over an EDS base tilted at 20° was used to measure the dust removal efficiency. In each experiment, we gravimetrically determined the dust removal efficiency from the surface of the removable dielectric cover. The high voltage source consisted of two Trek 10/10B-HS high voltage amplifiers (Trek Inc., Lockport, NY,