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An experimental study on the characterization of electric charge in electrostatic dust removal

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ABSTRACT

Automatic dust removal using the electrostatic forces of electrodynamic screen (EDS) is an emerging method for mitigation of energy yield losses caused by dust accumulation on solar collectors. Both electric field distribution and dust particles' charge acquired during the removal process play pivotal roles in thorough evaluation of EDS performance. Previous studies have comprehensively analyzed the electric field distribution in EDS. In this paper we have conducted a number of experiments to examine how two EDS design parameters, electrode width and inter-electrode spacing, and two operational parameters, applied voltage and relative humidity, affect dust particles' charge. Sixteen EDS prototypes in two sets were developed and tested in a laboratory environment to study the acquired charge by dust particles via charge-to-mass ratio measurements. It has been shown that the charge-to-mass ratio is directly affected by the electric field intensity on an EDS surface. Furthermore, we have shown the detrimental impact of relative humidity on EDS performance. The results are advantageous in the evaluation of EDS design and its optimization to attain maximum dust removal efficiency.

1. Introduction

Arid and semi-arid areas of the world provide the greatest potential for installation of utility-scale solar energy harvesting plants due to abundant irradiance received in these areas. Despite this significant potential, accumulation of dust particles on the optical surfaces of solar collectors is a performance-limiting factor, causing substantial energy loss in their energy yield due to scattering and absorption of the incident radiation [1–7].

To restore the original output power of the soiled solar collectors, manual cleaning using high-pressure water jets, conducted by a team of technicians, is the most widely-practiced method [8–10]. However, the high volume of water consumption needed for each cleaning cycle, transportation of desalinized water to the solar plant, and labor cost are among the main prohibitive factors in this cleaning method. To cope with shortcomings of the manual cleaning method using water, robotic devices [11–13] and passive surface treatments such as (super)hydrophobic, (super)hydrophilic, and antisoiling coatings [14–18] that modify the surface properties of solar collectors are in developmental stages. Despite the promise of robotic devices, they face challenges such as minimization of water usage, maintenance and operation costs. The durability of anti-soiling coatings, especially in harsh environments, is still of great concern.

As an alternative to the aforementioned cleaning methods, the concept of automatic dust removal using the electrostatic forces of electrodynamic screen (EDS) [19–28] is an emerging method for mitigation of dust accumulation losses in solar collectors. An EDS film consists of rows of transparent, conducting, parallel electrodes sandwiched between two transparent dielectric layers. The EDS film is integrated with a photovoltaic (PV) module or retrofitted on optical surface of solar collectors to maintain high transmission or reflection efficiency without requiring water. To remove dust particles deposited on an EDS film surface, the electrodes are activated by applying three-phase low-frequency high voltage pulses. The

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dust particles are then electrostatically charged and removed by the Coulomb force.

Since the Coulomb force $q\mathbf{E}$ is the predominant force in the EDS dust removal process, both electric charge of the particle q and electric field distribution $\mathbf{E}$ have major importance when evaluating EDS performance. In previous studies [29,30], the analytical models for the electric potential and electric field distribution in an EDS and their numerical verification have been comprehensively discussed. Furthermore, the impacts of different EDS design parameters and the electrical properties of the transparent dielectric layers in the electric field distribution on the EDS surface have been addressed. Since deposited dust particles are exposed to a non-uniform electric field distribution on the EDS surface, they experience dielectrophoretic (DEP) forces [31,32]. The DEP forces contribute significantly in charging dust particles, especially in initial moments of EDS operation when the particles have no net charge or their charge is insignificant [33,34].

Horenstein *et al.* [35] showed that dust particles acquire charge when they are transported by the energized EDS. A control group showed that the electric charge of particles that were in contact with the un-energized EDS was recorded to be almost zero. Hence, Horenstein *et al.* [35] deduced that the electric field distribution generated by the energized three-phase electrodes was the main cause of charging the dust particles.

In this paper, we describe the development of sixteen EDS prototypes with different designs to perform measurements of charge-to-mass ratio, denoted as Q/M, in an environmentally-controlled experimental setup. In addition to studying the impacts of the electrode width and inter-electrode spacing on the acquired charge by dust particles, we present the effects of the applied voltage and relative humidity in the Q/M measurements.

2. Experimental arrangement

2.1. Electrodynamic screen prototypes

Fig. 1 (a) shows the general schematic of the EDS prototypes used in this study, developed on either an opaque or a transparent substrate. In Fig. 1(a), the electrode width and inter-electrode spacing are denoted as w and g, respectively. Two transparent dielectric coatings, an optically clear adhesive (OCA) [36] and a thin borosilicate glass layer, are placed sequentially on the electrodes. For a three-phase activated EDS, the fundamental spatial period T_s is defined as:

$$T_s = 3(w + g). \tag{1}$$

For the experiments pursued in this study, we used two types of EDS prototypes: (1) printed circuit board (PCB)-EDS prototypes (see Fig. 1(b)), in which the electrodes are developed on an opaque non-conductive substrate; and (2) transparent EDS prototypes (see Fig. 1(c)), in which the electrodes are printed on a transparent borosolicate glass substrate with 2 mm thickness.

Table 1 provides the dimensions of the eight PCB-EDS prototypes used in this study. As listed in Table 1, the 8 PCB-EDS prototypes have the same electrode width of 80 μm but differ in inter-electrode spacing. It should be noted that although the PCB-EDS prototypes have no practical application due to opacity of the substrate, the results in this study are applicable to EDS prototypes with a transparent substrate. Durability, ease of manufacturing, and robustness of the interconnections of three phases are the main reasons why PCB-EDS prototypes are used in the experiments.

In addition to the PCB-EDS prototypes, we fabricated laboratory-scale transparent EDS prototypes using a photolithography process. We first performed the design for a three-phase configuration using CAD software, then we loaded it into a mask writer in a cleanroom environment. Subsequently, the mask writer wrote the design onto a chrome-film coated borosilicate glass substrate with an overcoat of a photoresist film. Next, we developed and etched the EDS prototype, with interconnection of its three phases using silver epoxy, oven treated for 15 min at 75 °C. Afterward, we placed

Table 1
The electrode width w and inter-electrode spacing g of the 8 PCB-EDS prototypes used in this study.

PCB-EDS Prototype Identification Number	Electrode Width w [μm]	Inter-electrode Spacing g [μm]
1	80	400
2	80	500
3	80	550
4	80	600
5	80	650
6	80	700
7	80	750
8	80	800

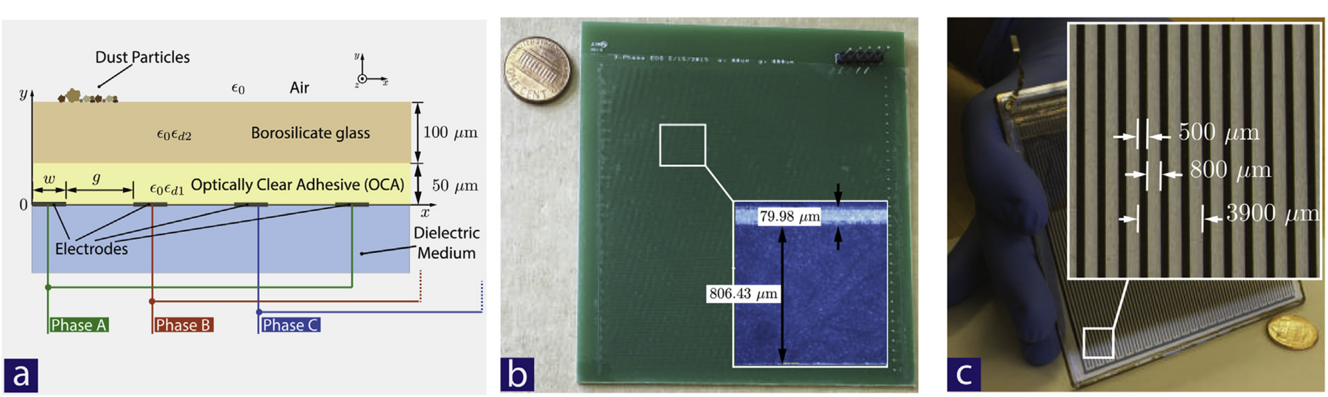

Fig. 1. (a) Cross section of the EDS configuration with two stacked layers of transparent dielectric coatings. The relative permittivity of the optically clear adhesive (OCA) film and thin borosilicate glass layers are $\varepsilon_{d1} = 5.14$ and $\varepsilon_{d2} = 5.5$, respectively. The thickness of the OCA and thin borosilicate glass layer are 50 μm and 100 μm, respectively. In practical EDS applications where the dielectric medium is transparent, a solar collector, either a PV module or a mirror film, is placed underneath the transparent dielectric substrate. The electrodes are connected to a three-phase power supply that generates rectangular pulses. (b) One of the PCB-EDS prototypes with nominal electrode width and inter-electrode spacing of 80 μm and 800 μm, respectively. The parallel three-phase electrodes have left-right direction and the magnified picture shows the measured values for electrode width and inter-electrode spacing under the microscope. (c) One of the transparent EDS prototypes with nominal electrode width and inter-electrode spacing of 500 μm and 800 μm, respectively.