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Electrostatic force distribution on an electrodynamic screen

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ABSTRACT

The enormous potential of solar energy harvesting plants to provide clean energy is severely limited by dust accumulation on their optical surfaces. In lieu of the most commonly-practiced manual cleaning method of using high-pressure water jets, electrodynamic screen (EDS) technology offers an attractive solution for removing dust particles from optical surfaces using electrostatic forces. In this paper, the impacts of different EDS design parameters in the electric field distribution on an EDS have been studied. Furthermore, based on electric field expressions, closed-form solutions for multipolar dielectrophoretic (DEP) forces in the EDS application are provided. Detailed evaluation of the EDS performance necessitates investigation of different forces involved in the dust removal process. Different comparisons are made between repelling and attracting forces exerted on dust particles deposited on an EDS surface. These comparisons elucidate EDS performance in the removal of a given size range of dust particles. The significant detrimental impact of relative humidity upon the dust removal process is quantitatively addressed. It is shown how just a 10 percent increase in relative humidity can make the repelling force ineffective in the dust removal process.

1. Introduction

The enormous potential of solar energy harvesting plants, to provide clean energy with a minimal carbon footprint, is impeded by dust accumulation on optical surfaces: the so-called “soiling” effect. This severe performance-limiting factor decreases solar collector efficiency by the absorption and scattering of incident light [1–3]. The performance drop could happen gradually in the course of exposure time, because of the accumulation of atmospheric dust; or abruptly due to a dust storm, in which the efficiency loss can reach 60 percent in less than 6 h [4].

The mitigation of soiling losses in solar collectors, using high-pressure water jets, often mixed with detergents, is the most commonly-practiced method in large-scale solar plants [5–7]. Scarcity of water resources, large amounts of water usage, deionization expenses, and labor cost are the main prohibitive factors associated with water-based cleaning methods. Efficiency in large scale solar plants may also be restored by robotic devices, currently under developement [8–10]. Although significant endeavors have been pursued in improving the performance of robotic devices, they are still facing some challenges such as scalability, minimization of water usage, and maintenance costs. Alternatively, electrodynamic screen (EDS) technology enables automatic dust removal using electrostatic forces, and is nearing commercialization [11–20]. The EDS consists of a set of parallel electrodes, either transparent or opaque, deposited on a glass substrate and embedded by a thin transparent dielectric film. When three-phase, low frequency (5–10 Hz), high- voltage pulses are applied to the electrodes, accumulated dust particles on the EDS surface are charged electrostatically and repelled by electrostatic forces.

In dust particle removal by the EDS, Coulomb force $q\mathbf{E}$ predominates among the repelling forces. Therefore, having a detailed model of the electrostatic force distribution on an EDS is of utmost importance in evaluating its performance, examining influential parameters, and maximizing dust removal efficiency. In this paper, we provide analytical solutions for the electric field distribution in an EDS configuration with one layer of dielectric coating. Furthermore, we present a thorough study of the impacts of influential parameters, viz., electrode width, inter-electrode spacing, thickness and relative permittivity of the dielectric coating in the electric field distribution.

Since the electric field distribution generated by the EDS is non-uniform, the accumulated dust particles, whether charged or neutral, experience dielectrophoretic (DEP) forces [21].

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Dielectrophoresis applications in biological research, as well as in microfluidic devices for particle separation and manipulation, have been studied in depth [22–25]. This phenomenon, however, has not been studied thoroughly with regard to the EDS technology. It is strongly speculated that the dust particles are charged electrostatically through triboelectrification caused by the DEP forces, especially in initial moments of EDS operation when the particles have no net charge or their charge is insignificant [26]. In this study, the analytical expressions for the multipolar DEP forces up to the third-order are derived, based upon the closed-form solutions of the electric field distribution. Our analytical expressions for the multipolar DEP forces enable the study of the impact of EDS design parameters on these forces. The analytical expressions for the DEP forces presented herein can be usedin the equation of motion for particle trajectory modeling, something that seemed a formidable task previously [27].

The ultimate goal of the EDS activation is to ensure at each given point over the EDS surface, the summation of repelling forces is greater than the attracting ones in the balance of forces exerted on the particle. In other words, for a particle to levitate from the EDS surface, the exerted Coulomb force must dominate all the attracting forces that push the particle toward the surface. The attracting forces include the van der Waals force and the capillary force. For a preliminary comparison of these two forces to the other forces, we consider idealized models for them, in which a spherical dust particle is in contact with a surface, both being perfectly smooth with no surface asperities. It is shown that these idealized models not only result in overestimation of these two forces, but also are unsubstantiated by our experimental observations. For this reason, we have inserted terms for surface asperities of the top EDS surface into our idealized models for calculating these two forces. Furthermore, we address the significant role of relative humidity in the increase of the capillary force and consequently inferior performance of the EDS in the dust removal process. Furthermore, we address the significant role of relative humidity in the increase of the capillary force, which compromises the EDS dust removal.

2. Analytical solutions

2.1. Electric field distribution

Fig. 1 shows the cross section of an EDS configuration with one transparent dielectric coating on top of the electrodes. In Fig. 1, the thickness of the dielectric layer and its relative permittivity are denoted as δ and ε_d, respectively. Also, the width of the electrodes and inter-electrode spacing are denoted as w and g, respectively. It is assumed that the height of the electrodes is negligible compared to the thickness of the dielectric layer. For a three-phase activated EDS, the fundamental spatial period denoted as T_s is written as:

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

Since we assume there is no net charge in the space above the dielectric layer in Fig. 1, i.e. the deposited dust particles do not have a net electric charge initially, we can write Laplace's equation for the electric potential on the EDS surface $\phi(x,y)$ in Cartesian coordinates as:

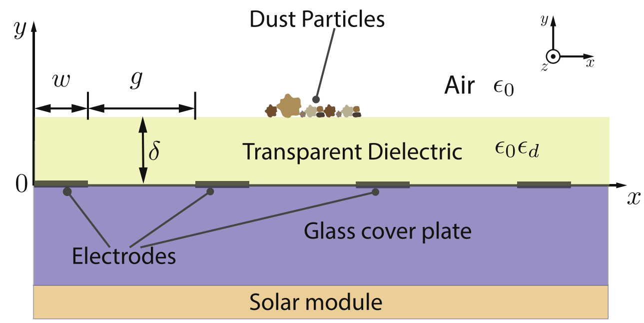

Fig. 1. Cross section of the EDS configuration with one layer of transparent dielectric coating on top of the electrodes with thickness δ and relative permittivity of ε_d. The problem is assumed to be infinite in the z direction (normal to the page). The solar module represents a photovoltaic (PV) cell or a reflecting mirror in a concentrated solar power (CSP) system.

$$\frac{\partial\phi^2(x,y)}{\partial x^2} + \frac{\partial\phi^2(x,y)}{\partial y^2} = 0, \quad 0 \le x \le T_s, \quad \delta \le y < \infty \tag{2}$$

Since the electrodes are placed periodically in x direction with fundamental spatial period T_s, the electric potential at $y=0$ can be expressed in terms of a Fourier series as

$$\phi(x,0) = \sum_{k=0}^{\infty} a_k\cos(\Omega_0 kx) + b_k\sin(\Omega_0 kx). \tag{3}$$

Sayyah et al. [28] have provided the comprehensive analytical expressions for electric field distributions in an EDS with two stacked layers of dielectric coatings. Following the same approach, we obtain the closed-form solutions for the electric field distributions in the dielectric layer and on the EDS surface of Fig. 1. By denoting unit vectors in x and y directions as $\mathbf{a}_x$ and $\mathbf{a}_y$, respectively, the electric field in the dielectric layer $\mathbf{E}_d$ and in the air (i.e. $y \ge \delta$) $\mathbf{E}_a$ are written as:

$$\begin{aligned}\mathbf{E}_d(x,y) = \Omega_0\Bigg\{\sum_k \frac{\sinh[k\Omega_0(y-\delta)]}{\sinh(k\Omega_0\delta)}[-ka_k\sin(\Omega_0 kx)+kb_k\cos(\Omega_0 kx)] + \sum_k \frac{\sinh(k\Omega_0 y)}{\sinh(k\Omega_0\delta)}[kg_k\sin(\Omega_0 kx)-kh_k\cos(\Omega_0 kx)]\Bigg\}\mathbf{a}_x \\ + \Omega_0\Bigg\{\sum_k \frac{\cosh[k\Omega_0(y-\delta)]}{\sinh(k\Omega_0\delta)}[ka_k\cos(\Omega_0 kx)+kb_k\sin(\Omega_0 kx)] - \sum_k \frac{\cosh(k\Omega_0 y)}{\sinh(k\Omega_0\delta)}[kg_k\cos(\Omega_0 kx)+kh_k\sin(\Omega_0 kx)]\Bigg\}\mathbf{a}_y,\end{aligned} \tag{4}$$

and

$$\begin{aligned}\mathbf{E}_a(x,y) = \Bigg\{\Omega_0\sum_k e^{-\Omega_0 k(y-\delta)}[kg_k\sin(\Omega_0 kx)-kh_k\cos(\Omega_0 kx)]\Bigg\}\mathbf{a}_x \\ + \Bigg\{\Omega_0\sum_k e^{-\Omega_0 k(y-\delta)}[kg_k\cos(\Omega_0 kx)+kh_k\sin(\Omega_0 kx)]\Bigg\}\mathbf{a}_y,\end{aligned} \tag{5}$$

in which the Fourier coefficients g_k and h_k are obtained from Eqs. (6) and (7), respectively, assuming the Fourier coefficients a_k and b_k are