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# A novel model to estimate the cleaning frequency for dirty solar photovoltaic (PV) modules in desert environment

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ABSTRACT

Accumulated dust on solar photovoltaic (PV) modules can significantly decrease their energy output in desert environment. Therefore, cleaning the deposited dust on the PV module surface is crucial in engineering applications to maintain the high power output of solar power plants, especially in desert areas. Nevertheless, it is difficult to predict the reasonable cleaning frequency for PV modules by traditional methods. In this paper, a novel model to simply estimate the cleaning frequency was developed for dirty PV modules in desert areas based on the dust deposition velocity and the relationship between deposited dust density and PV module power performance. The studied parameters are the installation tilt angles, the dust concentration in the ambient air and the representative average particle diameter. Based on this model, module cleaning frequency for desert regions is approximately 20 days when the power output reduction and particle concentration equal to 5% and 100 $\mu g/m^3$, respectively. In addition, the effects of accumulation density, average particle diameter, tilt angles and wind velocity on the cleaning frequency are discussed and analyzed respectively.



## 1. Introduction

In recent decades, solar energy has been widely applied because it's a kind of clean, environmental friendly energy. Solar photovoltaic (PV) module, directly converting solar irradiation into utilized electrical energy for consumers based on the photovoltaic effect of semi-conductor materials, is one of the most common and effective way to use solar energy. In general, the performance of PV modules in energy conversion can be influenced by different environmental parameters, such as solar irradiance, tilt angles and wind speed (Hasan et al., 2010; Ma et al., 2014; Cabrera-Tobar et al., 2016; Gökmen et al., 2016). Recently, it was found that the accumulated dust on the module glass cover may lead to a significant reduction in the energy output of PV modules. More than 5% degradation in PV panel output was found just after exposure outdoor for one month in Saudi Arabia (Rehman and El-Amin, 2012). Similarly, 13% of the maximum output power was reduced for PV system after one month of operation outdoor in Abu Dhabi, UAE (Al Hanai et al., 2011). Furthermore, it was found that the output of PV modules was declined at least 5.8% in only 20 days in Hermosillo, Mexico (Cabanillas and Munguía, 2011). These findings strongly verified that the accumulated dusts on PV modules would significantly decrease the PV efficiency performance, especially in the desert or polluted regions. Consequently, the cleaning process of dust accumulating on PV module surface is crucial and necessary for keeping the high level of operating efficiency in desert environment.

There are a large number of studies conducted on the dust deposition process on PV modules. It was found that the installation tilt angle of PV modules has a strong influence on accumulated dust density (Hegazy, 2001; Elminir et al., 2006; Hee et al., 2012). Moreover, the relationship between wavelength loss and accumulated density have also been studied (Al-Hasan, 1998; Qasem et al., 2014). In addition, the effect of dust size and composition has been comprehensively investigated (El-Shobokshy and Hussein, 1993; Goossens and Offer, 1995; Sanusi, 2012). Considering the importance of cleaning the dirty or polluted PV module covers, it is obvious that cleaning issues in desert environment where water resource is scarce requires to minimize the cleaning cycles at a reasonable level for maintaining the system performance (Khonkar et al., 2014). However, research on cleaning frequency of dusts on the PV modules has been very limited. Therefore, this paper aims to propose a theoretical model based on the dust deposition velocity calculation to recommend the frequency for cleaning dirty PV modules in desert environment.

In this paper, a novel method was developed to calculate the accumulated velocity of dust on PV modules and to estimate the

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module cleaning frequency for the desert environment. This work may help the engineers to predict the velocity of dust accumulation based on just two or three parameters, and to determine the frequency for preparing the cleaning equipment for the dirty PV modules. Therefore, it can make the operation of PV modules more efficient, and can help to avoid the meaningless waste of cleaning water and manpower.

## 2. Research methodology

### 2.1. Particle deposition velocity model

In general, commercial PV modules are composed of three parts, i.e. glass top covers for protection of core solar cell, crystalline silicon solar cells for generation of electricity by absorbing solar radiation and other electronic accessories for transportation of converted electricity. Airborne dust particles can deposited on the top glass covers, and the PV module efficiency performance will be decreased because of the reduction of the transmittance of glass covers accordingly. The relationship between the deposited dust density and PV module efficiency performance was experimentally investigated by our research group (Jiang et al., 2011). Therefore, this paper was focused on developing the theoretical model to estimate the cleaning frequency based on the particle deposition velocity model and the relationship between dust density and PV performance. In addition to crystalline silicon solar cells, other innovative materials, such as thin-film amorphous silicon solar cells, organic solar cells and perovskite solar cells, have attracted much attention due to their potential of high conversion efficiency and low costs. The accumulated dust particles on solar cells would block and absorb solar incident but would not change the spectrum of solar incident. Therefore, the model developed in this paper can be applied not only for crystalline silicon solar cells but also for other kinds of solar cells.

In this paper, the airborne dust was assumed as spherical particle. The theoretical model to estimate spherical particle deposition velocity onto inclined surfaces was based on the three layer model (You et al., 2012). The deposition particle flux in the model can be described as follows (Zhao and Wu, 2006):

$$J = -(\varepsilon_p + D)\frac{\partial C}{\partial y} - i\upsilon_s C + V_t\, C \quad (1)$$

where $\varepsilon_p$ is the particle eddy diffusivity in the boundary near the surface, D is the particle Brownian diffusivity, $\upsilon_s$ is the settling velocity due to gravity, i is the parameter for surface orientation, $V_t$ is the turbophoretic velocity, C is the particle concentration and y is the distance between particles and the surface. By considering the effect of the Brownian diffusion, the turbulent diffusion, the gravitational settling and the turbophoresis on particle deposition process, this model can accurately estimate the particle deposition velocity on a plate surface.

The theoretical model used in this study includes four parts in term of particle diameter, and they are called "Fine zone", "Coarse zone", "Zero zone", and "Transition zone", respectively. The equation for each zone consists of two parts: the equation itself and the corresponding applied range. In the "Fine zone", where particles have small diameters, the inclined angles have no effect on particle deposition velocity. The "Coarse zone" is for particles with large diameters and for surfaces with the inclination angle smaller than 90°. In this zone, particle deposition velocities are proportional with the cosine function of the inclination angle of the surface. The 'Zero zone' is for surfaces with the inclination angle larger than 90°, so it is not used in this study because the angle of installed PV panels is less than 90°. The 'Transition zone' is for the remaining data. The errors for these four parts are 1.53%, 1.50%, within 10% and 21.93%. So, this empirical model can be used in the calculation process for particle deposition velocity on PV modules, although the error is relatively large in the transition zone because this zone has no certain regulation and not significant in the actual calculation process.

The first parameter which needs to be estimated in the theoretical model is the friction velocity $u^*$. Friction velocity represents the friction stress magnitude of the air flow on the surface and the general expressions for deposition velocity are the function of surface friction velocity. The formula is given as below:

$$u^* = \sqrt{\frac{\tau_w}{\rho}} \quad (2)$$

where $\tau_w$ means the wall shear stress and $\rho$ is the air velocity.

Wall shear stress, $\tau_w$, can be estimated by:

$$\tau_w = \frac{1}{2} C_f \rho U_\infty^2 \quad (3)$$

where $C_f$ is the skin friction parameter and $U_\infty$ is the free stream velocity and equals to the local wind velocity.

The wall shear stress can be estimated by (Schlichting, 1979):

$$C_f = 0.0592 Re_x^{-1/5} \quad (4)$$

where $Re_x$ is the Reynolds number of the local air.

Then, the particle deposition velocity can be estimated by the following equations based on the calculated friction velocity from Eqs. (2)–(4) (You et al., 2012):

$$V_{di} = \begin{cases} (5.15 \times 10^{-8}\ u^* - 5.63^{-11}) d_p^{-1.263} & d_p < 0.0512(\ u^*)^{0.4227} \\ 3.7 \times 10^{-5} d_p^{1.9143} (\cos\theta) & d_p > 0.3577(\cos\theta)^{-0.41},\ \cos\theta > 0 \\ 0 & d_p > g(u^*,\ \cos\theta),\ \cos\theta \leqslant 0 \\ f(u^*,\ \cos\theta,\ d_p) & \text{for others} \end{cases} \quad (5)$$

Because the tilt angle of installed PV modules is less than 90 degrees, the third term of this equation, the zero zone, can be negligible in this study.

### 2.2. Cleaning frequency calculation for PV modules

Generally, mechanical cleaning and preventative coating are two main methods to mitigate the dust pollution on PV modules. The most common mechanical cleaning is to wash away the accumulated dusts from the PV module surfaces by water. The other way for preventing dust pollution is to cover self-cleaning coating on PV module surface, and then the dusts on the PV modules would be easily cleaned by rainwater. However, this coasting way is not suitable for desert region where the rainfall is quite rare. Besides, air flow and vibration are also accessible approaches for cleaning the dirty PV surface (Sarver et al., 2013). For solar PV power plants located in the desert, washing by water cannon is the most usual way for effectively cleaning dirty PV modules and maintaining the high energy conversion efficiency. However, it's always challenging to determine the cleaning frequency in different regions, as the dust properties, size distribution and wind conditions are quite different. Therefore, this study tried to develop a simplified model to estimate the cleaning frequency for engineering application."

Based on the obtained particle deposition velocity from Eq. (5), the cleaning time then can be estimated by:

$$T = M_d \times\ A\ \div (A \times\ C_d \times V_d) = \frac{M_d}{C_d \times V_d} \quad (6)$$

where $M_d$ is the particle accumulation density for a specific power loss; A is the area for PV modules; $V_d$ is the particle deposition velocity obtained from formula (5) with a representative average diameter; and, $C_d$ is the particle mass concentration in the ambient air.