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Numerical investigation of dust pollution on a solar photovoltaic (PV) system mounted on an isolated building

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HIGHLIGHTS

- Effects of dust pollution on PV panels mounted on building roofs were investigated by CFD.
- The dust deposition rates first increased and then decreased with the increase of dust size.
- The gravity has different influences on dust deposition rates of large and small dusts.
- The influence of released dust number on dust deposition rate is less than 8%.
- A simple model was developed to estimate the PV efficiency reduction ratio by dust pollution.

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ABSTRACT

Dust deposition on a solar photovoltaic (PV) system mounted on the windward roof of an isolated building was investigated by CFD simulation. The *SST* k-ω turbulence model with UDF inlet profiles and the discrete particle model (DPM) were adopted to simulate the wind flow fields and the dust deposition behavior, respectively. The CFD wind flow velocity profiles around the building were in good agreement with experimental results reported in the literature. The effects of various dust particle sizes, differing quantities of released dust particles, and the force of gravity on the rates of dust deposition upon the PV panels were investigated in detail. It was found that the dust deposition rate first rose and then declined with the increase of dust particle size. The maximum deposition rate was about 0.28% for 10 μm dust, and the minimum deposition rate was about 0.13% for 50 μm dust. Gravity also had a significant effect on the rate of dust deposition for large-particle dust ($d_p > 5$ μm), and the rate could reach 75% for 50 μm dust. However, the effect of gravity on dust deposition was less than 5% for small-particle dust ($d_p < 5$ μm). The effect of releasing differing quantities of dust particles on the dust deposition rate was less than 8%. Moreover, the mechanisms by which dust was deposited on the PV roof were analyzed and discussed. Finally, a simple empirical model was developed to estimate the PV efficiency reduction ratios in relation to exposure time, as based on this study's CFD results and the experimental data reported in the literature.

1. Introduction

Solar photovoltaic (PV) technology is a promising means of generating clean, sustainable energy, and the use of this technology is rapidly developing around the world. The average growth rate for the worldwide solar PV industry was 50% over the past ten years [1]. The global demand for new solar PV modules has reportedly risen to 65 GW as of 2016 [2]. However, previous studies have indicated that the efficiency of PV modules may be reduced to very low values within only a few years after their installation [3–9].

One of the main mechanisms of PV module degradation is pollution from airborne particulates [10–12]. Salim et al. [13] investigated the effects of dust pollution on PV array power output in Saudi Arabia. These researchers found that power output was reduced by 32% due to dust accumulation within eight months. Grassi [14] found a reduction in the power output performance of outdoor PV modules after only a few weeks of operation. Wakim [15] observed a 17% reduction of PV energy efficiency after only six days, due to sand accumulation in Kuwait. Pavan et al. [16] found that the PV efficiency reduction of polycrystalline Si PV modules

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ranges from roughly 1–5% by dust deposition pollution after one year of operation. The losses in efficiency due to dust accumulation are significant in districts with high concentrations of dust. Therefore, the mechanisms of dust deposition and its effects on PV module performance need to be well investigated.

Many outdoor studies on this important issue have been conducted in specific regions over the last few decades. For example, El-Nashar [17] found that monthly reductions in glass transmittance could reach 10% in the summer and 6% in the winter in the United Arab Emirates. The power output performance could be reduced by as much as 70% over the whole year. Elminir et al. [18] studied the effects of various tilt angles for the PV modules on dust deposition and glass transmittance. They found that increased tilt angles reduced the dust deposition density and helped to prevent loss of transmittance. Recently, Vivar et al. [19] investigated the effects of soiling in concentrator PV (CPV) systems in Madrid (Spain) and Canberra (Australia). They found that the energy losses could reach up to 26% after exposure periods of four months. Beattie et al. [20] found that the rate of degradation in PV performance could be described as an exponential decay due to dust accumulation on the free fractional area. Piliougine et al. [21] developed a new anti-soiling self-cleaning coating to prevent dust deposition on PV modules. They found that the anti-soiling surface can reduce the soiling pollution and increase the PV performance. In addition, several experimental studies have been carried out to investigate the relationship between dust deposition density and PV module performance. El-Shobokshy and Hussein [22] studied the effects of the size and density of dust particles on PV performance, and they found that fine dust had a greater effect on PV module performance than coarse dust. Moreover, Goossens and Kerschaever [23] performed air duct experiments to investigate the influence of wind velocity on dust accumulation on PV modules. Their results showed that more energy was lost when the wind velocity rose, due to the greater density of dust deposition on the PV panels. Jiang et al. [24] studied the influence of PV module properties on efficiency degradation due to dust accumulation. They found that the differences between types of cells had no obvious effects on dust-related problems.

However, most studies in this area have been focused on the effects of dust pollution for large-scale PV arrays that are mounted on the ground [25–29]. Few studies have investigated dust accumulation on PV panels that are installed on building roofs. In densely built urban areas such as Hong Kong, a large number of PV modules are mounted on building roofs [30,31]. Therefore, the influence of dust deposition on these rooftop PV systems needs to be well studied. Numerical simulation based on computational fluid dynamics (CFD) has become a powerful tool that has been used in various energy and environment engineering applications in recent years [32–38]. Tominaga et al. [39] studied the air flows around an isolated building with different roof pitches, using both experimental measurements and CFD simulations. These researchers concluded that the steady RANS model could predict the air flow velocity and the turbulent kinetic energy (TKE) very well. Karava et al. [40] investigated the convective heat transfers around the windward roof of an isolated building. The results showed that the *SST k-ω* turbulence model performed better than the *realizable k-ε* model. However, dust deposition on PV panels mounted on building roofs and the effects of such deposition on PV performance have seldom been investigated. Although a large number of researches were conducted on the effects of dust on PV performance, but the PV systems were almost installed on the ground. Moreover, the previous researches emphasized on the relationships of dust pollution density and PV efficiency performance or the mechanisms of PV efficiency reduction by the dust pollution, even when the PV system was mounted on the roof. This work tries to investigate dust deposition process and behaviors on the PV panels, which is seldom considered in the past studies. Moreover, the effects of dust deposition on PV performance mounted on the building roofs remain unclear. This study aims to investigate the dust accumulation processes and characteristics on PV modules that are mounted on the building roofs. Moreover, the influence of dust deposition on PV efficiency was also evaluated, based on the empirical formula obtained by Jiang et al. [24].

2. Numerical models and solution methods

The simplified physical model used for our study is shown in Fig. 1. The wind boundary layer flowed over an isolated building, and the PV system was mounted on the building's windward roof. Dust particles were released from the wind inlet and deposited on the PV system, as shown in Fig. 1. A 1:10 scaled model of a real building previously described by Tominaga et al. [39] was adopted for testing, and the results were compared with those of the Tominaga et al. study's wind tunnel experiments. The height of the building eaves, H_e, was 0.6 m, and the width of the building, W, was 0.66 m in this study. The slope angle of the building roof was 26.6°, as shown in Fig. 1. The computational domain was designed as 21 H_e long and 9 H_e high, which was also made consistent with Tominaga et al. [39] to allow direct comparison. The distance between the wind inlet and the building was 5 H_e, and a distance of 14.9 H_e was allowed for the wake flow redevelopment. The wind velocity at the building eave U_{He}, was 2.6 m/s. These conditions reproduced those applied in Tominaga's wind experiment. The Reynolds number, based on the H_e and U_{He}, was 104,000. The wind flow over the building was simulated by an *SST k-ω* turbulence model with UDF inlet conditions.

After the wind flow fields reached the calculated convergence, typical spherical dust particles were released with a uniform distribution from the inlet. The initial velocities of the particles were equal to the wind velocity at the building eave. The movements of the dust particles were modeled by the discrete particle model (DPM). The density ratio of particles to fluid S was 2250. Goossens and Kerschaever [23] experimentally investigated the effects of dust deposition on solar PV performance. The dust particle sizes in their experiments were 0–63 μm. Nevertheless, their study emphasized on the relationship of dust density and PV efficiency but not the deposition behaviors and processes on PV system. Therefore, the present study chose 1–50 μm as the size range of dust particle, which corresponds closely to the literatures [23]. Six sizes of dust particles (1, 3, 5, 10, 30 and 50 μm) and two quantities of released dust particles (10,000 and 20,000) were studied in the simulation. The property of the dust type is an important parameter to influence the deposition behaviors and further affect the PV performance. However, the composition of dust is quiet complicated and would be very different from different regions. This important research issue can be much better investigated by experimental measurement rather than CFD simulation. Therefore, the dust was simply assumed as calcium carbonate particle in this study.

2.1. Wind flow and dust motion models

The mass and momentum conservation-governing equations used for calculating the wind flow over the building can be described as follows [41]:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{u}_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right), \tag{2}$$