Sand and Dust Accumulation on Photovoltaic Modules in Dry Regions

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Abstract

The accumulation of sand particles on a horizontal glass surface is found to exponentially reduce the available area for transmission of incident photons. This experimental result is confirmed by numerical and analytical modelling which provides insight relating to the clustering of sand particles on the glass. The results can be used to qualitatively explain photovoltaic field performance data beyond existing theoretical treatments and are the basis of an engineering tool to assist building designers engaged in photovoltaic projects in dry climates.

Introduction

The Middle East is a strong candidate region for electricity generation from photovoltaics (PV) as a result of high sunlight levels and the availability of land. Furthermore, recent growth in construction projects in places such as the United Arab Emirates (UAE), Saudi Arabia, Qatar and Kuwait also raises the prospect of building integrated PV (BIPV) systems. Sustainability in these projects is increasingly important as engineering companies' clients demand internationally recognised green building accreditation [1]. While both PV and BIPV can contribute to this objective, their ultimate inclusion in new buildings is currently limited by a lack of readily available performance data. This information is particularly important because of the relatively demanding field conditions found in such dry regions. (Throughout this paper the word "dry" refers to any location in Group B of the Köppen climate classification scheme.)

Two factors are expected to dominate PV performance in dry regions: extreme temperatures (e.g. average August daily maximum of ~ 40 ºC in Kuwait [2]) and reduced light transmittance due to wind-driven sand (~60-2000 µm diameter) and dust (silt ~4-60 µm diameter and clay <4 µm diameter). While the effects of elevated temperature on PV performance are well understood, there is only a limited understanding of the effect of sand and dust. Sand and dust degrades PV performance either by increasing the component of diffuse irradiance (due to atmospheric scattering) or by accumulating on the glass surfaces of PV modules. This latter phenomenon has also been observed on other surfaces of the building envelope including vertically orientated glazing [3].

Although sand and dust accumulation on PV modules has been the subject of several field [4] and laboratory investigations [5,6], no adequate theoretical treatment has been presented since existing treatments are limited to low dust levels [7]. There is a need therefore to provide building designers and engineers engaged in PV/BIPV projects in dry regions with a modelling tool which characterises the problem quantitatively.

In this work we present the results of a laboratory investigation designed to simulate the accumulation of sand and dust particles on the surface of a PV module. We then demonstrate how the experimental data can be described over a wide range by an exponential decay and explain the underlying physical processes. Our analysis is supported by numerical simulations, our own experimental results and data from a previous field experiment. The results of this work can be used to support the design of cleaning systems and provides the basis of a tool for PV designers considering potential PV installations in dry regions.

Experimental details

Simulation of sand accumulation on PV modules was performed in a laboratory environment under controlled conditions. Although this is not an accurate representation of field conditions, it permits investigation of the fundamental processes leading to a reduction in the incident sunlight levels.

SiO_2 particles from Sigma Aldrich (50-70 mesh) were uniformly deposited on a glass slide of dimensions 76×26×1 mm and mass 4.70804 g by a sieving process from a height of approximately 10 cm. The deposited particles measured an average equivalent radius of 170±20 µm. During deposition the slide was located in a stable horizontal position above a computer-controlled Veho VMS-004D optical microscope. This arrangement enabled acquisition of digital images for analysis and also allowed observation of sand accumulation in real-time.

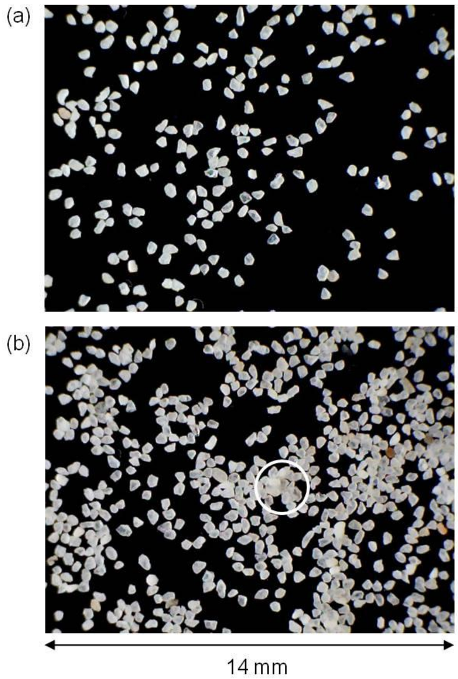

Fig. 1: Accumulation of sand particles on a glass substrate. The circled area in (b) is an example of clustering in which particles in the first layer are able to support further particles in upper layers.

After the desired sand coverage had been applied and images, such as those shown in Figure 1, recorded the slide was weighed using a Sartorius MC-210S precision balance. This instrument was located immediately next to the microscope and care was taken not disturb the particles during this step. The slide was then carefully returned to the microscope stage and gently tapped. The introduction of a small amount of energy served to induce settling in the sand piles. The subsequent sand distribution was recorded using the microscope and the weight again measured.

The slide was then cleaned and returned to its initial position above the microscope before a subsequent cycle of sand deposition. Measurements were also performed without cleaning the slide between depositions and had no effect on the results.

Results and Discussion

Images of sand accumulation on the glass slide were obtained for different amounts of sand. Figure 1 shows digital images acquired for two different quantities of particles deposited on the surface. The masses of the deposited particles were (a) 0.04005 g and (b) 0.20051 g. Nearly all the particles in Figure 1a rest directly on the glass surface. In Figure 1b however, particle clustering is observed as a result of the increased quantity of sand on the glass. It is evident that these clusters can support further particles thereby allowing subsequent layers of particles, which are not in direct contact with the glass.

A grain threshold algorithm in the software Gwyddion, was used to determine the fractional area of the glass covered by the particles. Figure 2 shows that the available free area on the glass slide decreases with increasing amounts of sand both before and after a gentle disturbance caused the sand structures to settle. The rearrangement effect becomes more pronounced with increasing sand accumulation, as a result of clustering and the formation of upper layers of particles.

We now qualitatively explain the dependence of free surface area against mass shown in Figure 2. The addition of a sand particle to the first layer reduces the available surface area of the glass slide by approximately the sand particles cross sectional area and the decrease in free area is linear. Initially all sand particles are distant from each other and subsequent particles landing on them cannot be supported and fall onto the glass. In this regime the free surface area decreases linearly with sand mass. As more particles arrive on the surface, clusters are gradually formed and there is an increasing probability that subsequent particles will land on a cluster rather than on the glass. This causes the evolution of the free surface area to deviate from the linear behaviour described in previous work [7]. The relaxation of particles into a lower energy state following vibration destroys the clusters and recovers the linear behaviour in free surface with mass, as captured in Figure 2.

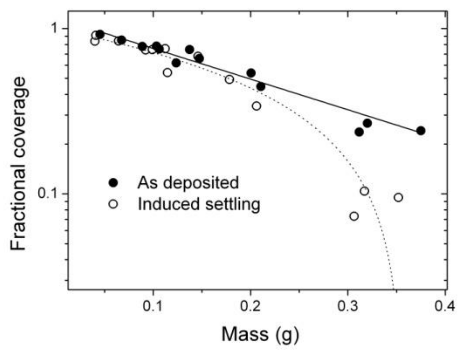

Fig. 2: Reduction in the available free surface area of a glass slide with increasing quantities of sand. Filled circles show the as-deposited coverage while open circles show coverage after application of gentle vibration to the glass slide. The solid and dotted lines are exponential and linear fits to the data respectively.

The exponential behaviour of the as-deposited data in Figure 2 can be captured qualitatively using a simple analytical expression and illustrated using a Monte-Carlo simulation in which circular dots were randomly distributed over a square area, approximating the accumulation of sand particles on the glass slide. The resulting images were once again analysed to determine the evolution of the available free surface area as a function of the number of particles. To model this process, consider adding particles of an arbitrary shape to a slide. The total area of particles deposited as a fraction of the total area of the slide is N, and is directly proportional to their mass. However, the free fractional area A is not simply 1-N as particles overlap. The behaviour can be captured mathematically by noting that, for small particles, the probability of a particle landing on free glass area is 1-A, such that

$$\frac{\mathrm{d}A}{\mathrm{dN}} = 1 - A \quad \Rightarrow \quad A = 1 - e^{-N} \qquad (1)$$

The computer simulation demonstrates precisely this behaviour, as shown in Figure 3.

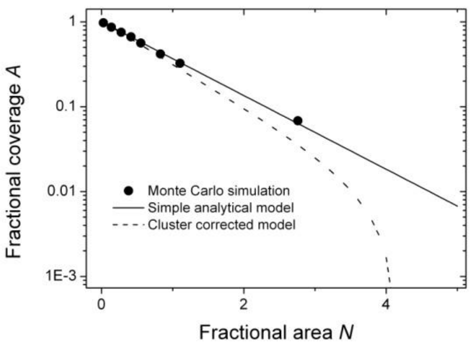

Fig. 3: Numerical (dots) and analytical (lines) simulations of particle accumulation on an arbitrary surface. The dashed line accounts for the formation of clusters which can support particles in upper layers.

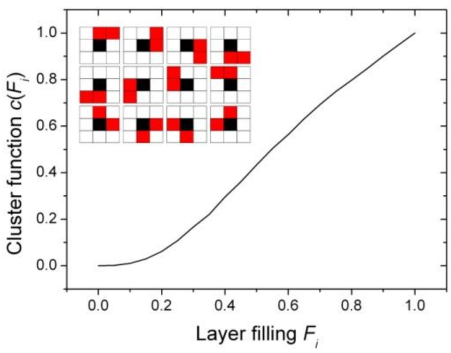

Fig. 4: Fraction of particles within a square lattice that form part of nearest neighbour triangles and are thus able to support a second layer of particles. Inset shows all possible geometric combinations.

There are important differences however between this simple model and reality. In particular, it is clear that there is a limit to how closely grains can pack together and that some, but not all sand grains can support a second grain. To capture this behaviour we introduce the two dimensional random close packing fraction α ~ 0.8 [8], and the fractional filling level of a given layer i, F_i, such that the most a layer of filling F_i can contribute to obscuring the surface is αF_i. Only clusters can support particles in a layer above. We introduce the cluster function $c(F_i)$, describing the fraction of sand grains that sit within a cluster. For illustration, we have evaluated the cluster fraction using a square lattice and the condition that a filled site must, with its neighbours, be part of a triangle to determine that it is part supporting cluster i.e. that all particles in a cluster are part of a triangle. The algorithm and resulting functions are shown in Figure 4. It should be noted this is intended to approximate the experimental system, capturing its behaviour qualitatively rather than precisely. Differences arise in the continuous nature of the sand positions and the fact that in practice sand particles bounce on the glass surface before coming to rest, delaying the onset of cluster formation.

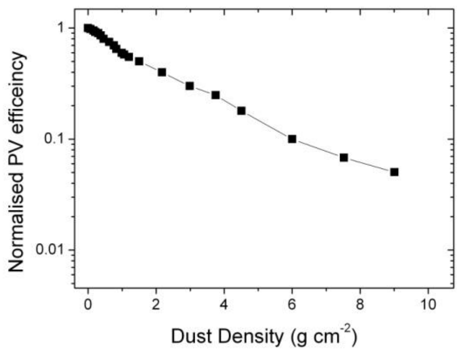

Fig. 5: Experimental data from Al-Hasan [4]. Modulated exponential decay may be associated with the formation of supporting clusters.

Recalling that the close packing factor α must be used to connect particle area N and filling fractions F_1 and F_2, the evolution of the layers is described by:

$$\begin{aligned} \alpha \frac{\mathrm{d}F_1}{\mathrm{d}N} &= 1 - c(F_1) \\ \alpha \frac{\mathrm{d}F_2}{\mathrm{d}N} &= c(F_1)[1 - c(F_2)] \end{aligned} \qquad (3)$$

while the total exposed area is given by,

$$A = 1 - \alpha F_1 - (1-\alpha)F_2 \quad (4)$$

and shown in Figure 3. Note that the behaviour is again exponential over several orders of magnitude of transmission, but decays more quickly than equation (1) as only a subset of particles are able to support a second layer. It is possible that the slight modulation of the exponential behaviour seen in high precision field experiments, as shown in Figure 5 [4], originates in a clustering process through the non-linearity of $c(F_i)$.

Tilt angle is a critical parameter in a field PV installation and was only qualitatively studied here. Increasing the tilt angle to ~ 45° resulted in almost all particles sliding off the glass surface. The apparent difference between this observation and empirical evidence [3,9] and is likely to be a consequence of atmospherically present moisture. The presence of moisture in our experiments resulted in much more rapid cluster formation due to damped particle motion on the glass slide. Moisture also caused particles to stick to the glass slide at a 45° tilt angle.

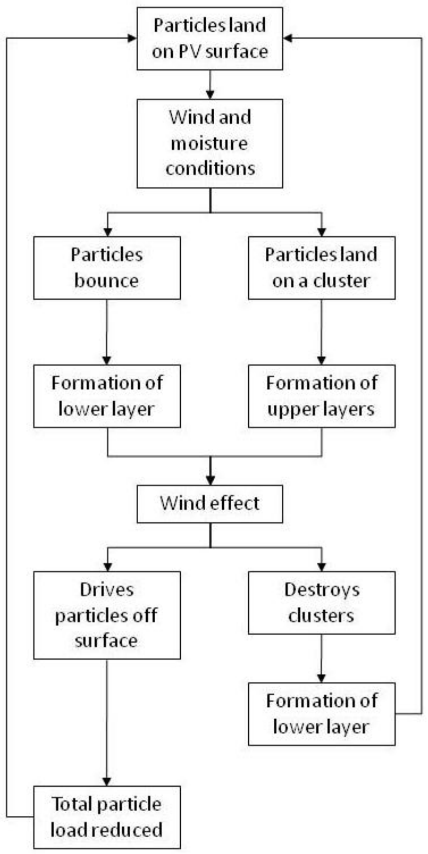

Fig. 6: Process of sand and dust accumulation on PV modules in dry regions.

The results from our experiment and models allow us to develop a picture of the process which is illustrated in Figure 6. Our results have two important implications for potential cleaning strategies. The first of these is that air-based or vibration-based systems can in principle, reduce PV performance if they break-up clusters and cause more particles to rest on the glass. It is therefore important that the cleaning technique imparts enough energy to remove particles completely from the PV array. The second implication is that moisture can inhibit the removal of particles from the PV array. We suggest that the absence of moisture on Mars contributed to the observation that Martian winds removed dust from the surface of PV modules on the Exploration Rover, thereby prolonging its mission lifetime [10].

Conclusions

We have modelled the process of sand accumulation on PV modules and validated the modelling using basic experiments. Our work qualitatively describes other existing experimental data and provides the basis of an engineering tool to assist building designers working on BIPV projects. To that end however, it is necessary to develop the model to account for more realistic field conditions. Further work will concentrate on incorporating the effects of tilt, temperature and humidity into the model in addition to investigating potential cleaning strategies.

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