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Measurement of dust sweeping force for cleaning solar panels

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ABSTRACT

A new methodology has been developed to evaluate cleaning efficiency of dust particles on solar panels. Those particles have an average diameter of 2.3 µm and were collected in Doha, Qatar. A brush-disk configuration was constructed to measure the sweeping force as a polymeric tip sliding through a dusted glass substrate. The sweeping force was measured under various applied loads on samples treated in environment of various humidity. Experimental results showed that the cleaning efficiency of dry dust particles was independent of the applied load, reaching higher than 90%. However, the adsorption of water molecules showed pronounced effects on the cleaning efficiency. In order to increase the efficiency in humid environment, the applied load thus needed to be increased. The higher the applied load, the higher the sweeping force, the higher the cleaning efficiency, indicating more power is needed to clean the surface. This research presented an alternative approach to evaluate the cleaning efficiency of dust particles.

1. Introduction

Dust soiling has been an important issue for the performance of photovoltaic (PV) panels especially to those deployed in the Middle East and North Africa region [1]. The production of electricity from PV panels depends on the absorption of photons. Dust soiling means that accumulation of dust particles blocks the light transmission from outer layer surfaces leading to declining performance of PV panels [2]. It has been reported that the power loss due to dust soiling extensively occurs on solar-energy systems such as PV panels or concentrating solar–thermal power (CSP) systems [3,4]. The soiling rate, referred to power loss over a period, may vary based on geographic locations and chemical and physical properties of dust particles [5]. To mitigate dust soiling, various anti-soiling technologies have been developed such as active electrodynamic dust shield (EDS) technology [6–8] to repel dust by electrostatic force, or passive anti-soiling coatings with optically transparent, self-cleaning, and anti-reflective properties [9–12].

To effectively remove particles, it is needed to understand the fundamentals between particles and substrate surfaces. The particle adhesion and removal on surfaces has been extensively studied over the years. Possible factors including surface roughness, particle size, electrostatic force, and relative humidity, have been reported to affect the pull-off force. To evaluate the required force for particle removal, it is common to measure the pull-off (adhesion) force by various methods including atomic force microscopy (AFM) [13–16], centrifuge method [17–20], and vibrational techniques [21,22]. Table 1 lists the major methods and related examples for measuring the pull-off force. Nonetheless, there are limitations for each method. For AFM measurement, using a single dust particle as a probe on a cantilever can measure pull-off force directly; however, it is a limitation to measuring only single dust particles, which were characterized to be a mixture of minerals with irregular shapes. On the other hand, the centrifuge method can do the measurements on many particles simultaneously. However, the measurement of ultra-fine particles with only a few microns in diameter is restricted due to the stability of materials at higher rotating speed. For recently developed methods such as Hopkinson bar method [23], high detachment force induced by vibration may cause plastic deformation and damage to particles. For the drop test method with simple experimental setup [24], better imaging systems including high-speed video are still required for analysis.

In this study, we developed a simple methodology to evaluate cleaning efficiency of dust particles using a brush-surface configuration under various conditions. Compared to pull-off forces, the measurement of sweeping force is more relevant to real situations. The sweeping forces were measured with a polymeric tip sliding against the glass surface. To better understand the effect of environment, the sweeping forces were measured under a range of loads and humidity treatments to find optimal cleaning efficiency.

Abbreviations: DAR, dust accumulation rate; RH, relative humidity

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Table 1
Summary of reported methods measuring particle-surface adhesion force.

Method	Materials (Particle/Substrate)	Particle size	Adhesion Force	Relative Humidity	Reference
Colloidal probe (AFM)	Insulin particle/ ABS[a], PP[b]	10~16 µm	a. 175~750 nN b. 500~1700 nN	5%~95%	[13]
Colloidal probe (AFM)	Glass sphere/ Quartz	2.5[a]; 20[b] µm	Hydrophilic: 71.32[a];29.08[b] nN Hydrophobic: 18.53[a]; 7.72[b] nN SH: 4.36[a]; 1.53[b] nN	45%	[14]
Colloidal probe (AFM)	Dust/Aluminum[a], Copper[b], PVC[c], Glass[d]	30~35 µm	a.25 nN b.45 nN c.175 nN d.200 nN	50%	[15]
	Activated Carbon/ Aluminum[a], Copper[b], PVC[c], Glass[d]	20~30 µm	a.25 nN b. 78 nN c. 80 nN d. 96 nN	50%	
Centrifuge	Polystyrene spheres/ Stainless steel, aluminum, plastic	146.1 ± 1.99 µm	19.91 ± 1.15 µN; 14.11 ± 2.65 µN; 14.68 ± 2.43 µN	85%	[18]
Centrifuge	Microcrystalline cellulose/ cellulose tablet[a], cellulose ester[b]	9~60 µm	a. 100~ 1000 nN b. 80~ 700 nN	35%~45%	[17]
Centrifuge	Starch[a], lactose[b]/ stainless steel	32~ 75 µm	a. 857~1738 nN b. 272~ 552 nN	50%	[19]
Electrostatic Detachment	Alumina/Vinyl, Rubber Spore/Vinyl, Rubber	1.28 µm 0.9 µm	0.108 nN 0.0293 nN	40% 40%	[25]
Hopkinson Bar (Vibration)	Polystyrene particles / Polystyrene-coated stainless steel	4~10 µm	100~1500 nN	45%	[23]
Drop test	Silanised glass bead/ silanised glass side	60~120 µm	2.7~ 3.81 µN	45%~60%	[24]

2. Materials and method

2.1. Dust particles

The dust particles used in the study were collected from PV panels during daytime at the solar test field of Qatar Science and Technology Park (QSTP) in Doha, Qatar. The dust particles were used in the following tests without further treatment. The crystal structure of dust particles was characterized using an X-ray diffractometer (XRD D8, Bruker). The morphology and the chemical composition of dust particles were observed and examined through scanning electron microscopy (SEM, JEOL JSM-7500F) and energy-dispersive X-ray spectroscopy (EDS) respectively. The dust particles were sprinkled on carbon tape and coated with 5 nm conductive coating of platinum. To calculate the size distribution of dust particles, images were taken using a digital optical microscope (VHX-2000, Keyence), and the acquired images were further processed using a software called ImageJ (NIH) to calculate the particle size distribution.

2.2. Sweeping experiments

For dust sweeping test, it was conducted using a tribometer (CSM Instruments) to measure the sweeping force. The schematic of the sweeping test setup is shown in Fig. 1(a). The polyoxymethylene (POM) sphere with the diameter of 3/16″ was glued on a pin locked to a cantilever. The POM is used as a tip in the study since it possesses the properties of good wear-resistant, low friction and excellent dimensional stability. The sweeping force was recorded when the POM tip was sliding on the glass substrate. The pre-cleaned glass slides (Thermo Scientific, pre-cleaned plain microscope slides) were used as substrates. To get a uniform single-layer of dust, the dust particles were initially sprinkled on the glass substrates until the glass surface was fully covered with dust. The glass slide was then knocked gently several times to remove loose dust particles on the surface. Based on the starting location of the POM tip, part of the glass slide was cleaned with a brush and it was divided into a clean region and a dusted region. Three different

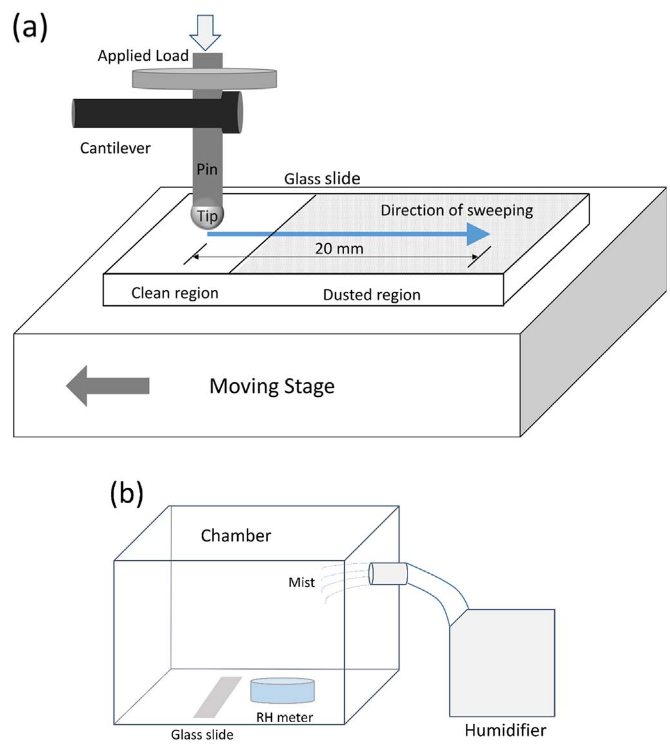

Fig. 1. The schematics of experimental setup of (a) the dust sweeping test, and (b) the moisture adsorption test.

applied loads, 0.154 N, 0.318 N, and 1 N were used in the sweeping test. The tip was sliding on the glass slide in a halfway reciprocating motion. The entire sliding distance was set at 20 mm and the maximum sliding speed was 1 cm/sec. The sampling frequency was 10 Hz, indicating that the value of sweeping force was recorded per one-tenth of a second. The sweeping force fluctuates a lot based upon the condition