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Wind tunnel protocol to study the effects of anti-soiling and anti-reflective coatings on deposition, removal, and accumulation of dust on photovoltaic surfaces and consequences for optical transmittance

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A B S T R A C T

A wind tunnel protocol is presented that allows to study the efficiency of anti-soiling and anti-reflective coatings under dry soiling conditions. Anti-soiling coatings are intended to reduce the accumulation of dust on photovoltaic modules and other surfaces. Dust accumulation is the combined result of sedimentation (or deposition) and syngenetic or post-genetic removal. In the field, the amount of dust present on a photovoltaic surface is always the result of accumulation. The protocol allows one to study the effects of anti-soiling and anti-reflective coatings on the processes of dust deposition and dust removal separately so that the specific operation of the coatings in comparison to uncoated glass can be better understood. Using an aeolian dust wind tunnel, dust deposition and dust removal measurements were performed under quasi-natural conditions on surfaces with and surfaces without an anti-soiling coating. Optical transmittance measurements were performed to determine the impact of anti-soiling and anti-reflective coatings on the amount of light passing through dust-polluted surfaces. We illustrate the protocol by comparing anti-soiling and anti-reflective coated surfaces with identical uncoated surfaces. The anti-soiling coating that was tested in this study has a dual functionality as it has both anti-soiling and anti-reflective properties. Results showed that the tested coatings did not affect the sedimentation of dust, but they did have a significant effect on dust removal, which started at a lower wind speed and cleaned the surface more rapidly compared to the uncoated surface. Additionally, the anti-soiling coating outperformed the anti-reflective coating regarding the wind speed at which dust removal started, indicating that dust adhesion forces on the anti-soiling coating are lower. Transmittance was always higher for the coated surfaces than for the uncoated surface, but the benefit of the coatings (higher transmittance) decreased as the glass surfaces became more polluted with dust.

1. Introduction

Soiling can be broadly defined as the pollution of surfaces (in this context: the cover glass of a photovoltaic solar collector, or the mirror of a solar thermal collector) by several kinds of substances such as mineral particles, plant products, soot, salt, bird droppings, or growth of organic species (Sayyah et al., 2014). In a more strict sense, it is the accumulation of particles on these surfaces. Soiling is particularly important in dry climates such as deserts, which are characterized by high aeolian activity. Most deserts are characterized by an almost continuous precipitation of fine mineral particles (dust). On the other hand, deserts are also characterized by a high number of cloudless days, and are thus ideal places for solar energy facilities. However, the year-round precipitation of dust on these facilities results in the pollution of the surfaces, and consequently, in a decrease of their efficiency (Araya et al., 2016; Piliougine et al., 2013; Cabrera et al., 2016). Although soiling is most problematic in deserts, it also occurs in more humid climates. For example, solar collectors installed near coastlines can be affected by salt accumulation, which, apart from soiling, may also enhance the chemical degradation of the surfaces (Illya et al., 2016). Solar collectors in industrial zones or in cities will be covered by a thin layer of mostly organic aerosols produced by combustion processes (Asl-Soleimani et al., 2001). Even rural areas experience a more or less continuous precipitation of aeolian fines, either because of agricultural activities (Goossens et al., 2001) or due to the deposition of pollen or other organic material (Rodríguez-Rajo et al., 2010).

The effect of soiling on the performance of photovoltaic (PV) surfaces has since long been recognized. Already in 1942, Hottel and

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Woertz studied the effects of dirt accumulation on the performance of solar collectors. Many studies on photovoltaic surfaces and mirrors of solar thermal collectors have been performed since then. Especially during the last decade, the topic has received much attention. Summaries of older and recent literature can be found in e.g. Mani and Pillai, 2010; Appels et al., 2013; Piliougine et al., 2013; Sarver et al., 2013; Ghazi et al., 2014; Jonkers, 2014; Said and Walwil, 2014; Sayyah et al., 2014; Maghami et al., 2016; and Menoufi, 2017. Most studies have reported on the decrease of reflectivity (for solar thermal surfaces) or transmittance (for PV surfaces), either in field measurements (Nahar and Gupta, 1990; El-Nashar, 1994; Bonvin, 1995; Pedersen, 2015; Cabrera et al., 2016) or in experiments set up in a laboratory (Hasan and Sayigh, 1992; El-Shobokshy and Hussein, 1993; Appels et al., 2013; Abrams et al., 2014). A combined experimental and theoretical study to determine the effect of particle contaminant on mirror scattering properties was already performed in 1976 by Young (Young, 1976). Other studies investigated the effect of dust deposition on the electrical performance of PV surfaces, in field conditions (Pande, 1992; Pande and Hill, 1995; Hasan and Sayigh, 1992; Ndiaye et al., 2013; Semaoui et al., 2015) or in laboratory experiments (El-Shobokshy and Hussein, 1993; Goossens and Van Kerschaever, 1999; Jiang et al., 2011; Jonkers, 2014). Studies that tested the effect of dust deposition on the reflection and absorption of glass surfaces used in PV collectors have been conducted (Garcia et al., 2011; Merrouni et al., 2015). The effect of dust on the loss of irradiance has also been studied (Zorrilla-Casanova et al., 2015). Theoretical models of the effect of dust on transmittance have also been developed (Wang et al., 2017).

Due to the negative effect of dust accumulation, methods to clean solar panels have extensively been studied. They include techniques that use natural agents such as rain, wind or gravity, or apply artificial cleaning such as controlled water spray, high-pressure water jet cleaning, or a combination of scrubbing and water flow (Abd-Elhady et al., 2011; Appels et al., 2013; Sarver et al., 2013; Sayyah et al., 2014; Jonkers, 2014). Electrostatic repulsion to prevent accumulation has also been tested (Sims et al., 2003; Mazumder et al., 2013). Another solution to reduce dust accumulation is to apply an anti-soiling coating. Anti-soiling coatings for both dry-dust and moisture-dust conditions have been proposed (Sarver et al., 2013). Many of these coatings have superhydrophilic or superhydrophobic properties to stimulate the cleaning by running water. Other coatings create a micro roughness, which is supposed to affect accumulation and/or post-depositional cleaning.

This study presents a laboratory protocol to test the efficiency of anti-soiling coatings under dry conditions by using an aeolian dust wind tunnel. It has two important advantages compared to previous anti-soiling tests:

- By using a dust wind tunnel, dust deposition occurs under semi-natural conditions. Many techniques have been used to deposit dust on a photovoltaic surface: dry sieving (Appels et al., 2013; Beattie et al., 2012), settling in a vertical tube (Hirohata et al., 2015; Pedersen, 2015; Cabrera et al., 2016; Mathiak et al., 2016), settling in a sedimentation chamber (Brophy et al., 2015; Abrams et al., 2014; Glaubitt and Löbmann, 2011; Jiang et al., 2011), spraying (Barletta et al., 2014; Abrams et al., 2014; Burton and King, 2013), putting the glass surface in a dusty space and waiting until a dust layer has spontaneously formed (Sansom et al., 2013), or even simply applying sediment over the surface and then gently tapping the glass in a vertical position (Chen, 2013). However, none of these techniques result in a dust deposition pattern that perfectly mimics the patterns that are formed in field conditions. Only a dust laden airflow (dusty wind) can create the sedimentological micro patterns that spontaneously form on a flat surface such as the cover glass of PV modules. These patterns are very important because they determine the amount as well as the organization of the open space on the surface through which light can penetrate the dust cover and reach the solar cell. Glass covered by the same amount of dust but with a different sedimentation pattern will show a different transmittance. By using a dust wind tunnel, such as in the study by Goossens and Van Kerschaever (1999), we are confident that sedimentological patterns very similar to those seen in the field are obtained. Wind tunnels have already been used earlier to contaminate a surface with sediment (see Bethea et al., 1983 and Cooper, 1985), but under considerably less controlled conditions compared to the study by Goossens and Van Kerschaever (1999).
- In the field, the amount of dust that occurs on a surface is always the result of accumulation. Accumulation is the combined result of sedimentation (or deposition) and syngenetic or post-genetic removal. For a correct interpretation of the efficiency of an anti-soiling coating, it is necessary to know the effect of the coating on dust sedimentation and dust removal separately. This is difficult to assess in field measurements because there, dust patterns are always the result of accumulation. By using a wind tunnel, the response of the coating to the sub-processes of sedimentation and removal can be studied separately. Another advantage of using a wind tunnel is that it is possible to carry out the measurements in a strictly controlled environment, allowing repetitions under identical conditions. In the field, wind speed, wind direction, airborne dust concentration, humidity and temperature are highly variable, making it impossible to control the environmental conditions.

We illustrate the protocol by applying it to two different coatings: an anti-reflective coating and an anti-soiling coating with combined anti-reflective functionality.

2. Instrumentation

2.1. Wind tunnel

The experiments were carried out in the closed-return wind tunnel of the Geography and Tourism Research Group at KU Leuven, Belgium. This wind tunnel has been specially designed to study aeolian dust dynamics and contains two test sections. The deposition experiments were conducted in the largest test section, which is 760 cm long, 120 cm wide and 60 cm high. For the dust removal experiments, where high wind speeds are required, we used the small test section. This section is 150 long, 35 cm wide and 30 cm high.

2.2. Dust cloud producer

To create a homogeneous dust coverage on the test surfaces, we connected an Engelhardt KDA-FS 300N laboratory dust cloud producer (KTG Engelhardt GmbH, Nürnberg, Germany, http://www.ktg-engelhardt.de) to the tunnel. This apparatus ensures a continuous feed of dust particles to the airflow, and allows the operator to adjust dust discharge. The dust was added to the flow in the return section of the tunnel via a small but wide opening in the tunnel roof. During its passage through the tunnel, the dust is fully dispersed over the test section. The exact distribution of the dust at the location where experiments are carried out is accurately known so that the appropriate corrections can be made when necessary. No dust was added to the airflow during the removal experiments.

2.3. Wind speed measurements

Wind speeds were determined with an accuracy of 0.01 m s^{-1} using (1) a mini pitot tube (Vanderheyden, Brussels, Belgium) connected to a digital Furness FC016 manometer. (Furness Controls Ltd., Bexhill, UK), and (2) a Testo 0635-1048 hotwire anemometer (Testo NV, Ternat, Belgium). Turbulence was measured with the Testo 0635-1048 hotwire anemometer.