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Investigation of factors affecting condensation on soiled PV modules

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ABSTRACT

Condensation contributes to soiling of photovoltaic modules by trapping dust particles and, in certain conditions, leaving a material bridge between particles and the surface after evaporating. This study investigated the effects of four parameters on condensation on soiled surfaces: (i) relative humidity (RH), (ii) surface–dew point temperature difference, (iii) hygroscopic dust content, and (iv) surface wettability. Natural and synthetic dust mixtures of various compositions were studied via water adsorption isotherms, XRD, ion chromatography and optical microscopy, on hydrophilic and hydrophobic surfaces, in the lab and field. It was found that water uptake by surface dust was strongly dependent on its content of hygroscopic material, and such material allowed microscopic condensation droplets to exist on a soiled glass coupon even when it was significantly warmer than the dew point. A hydrophobic PTFE surface did not greatly retard the onset of condensation, compared to a glass surface, but did inhibit its growth. The implications for anti-soiling coatings are that it would be a difficult goal to eliminate condensation, and their performance will be influenced by dust composition and factors affecting condensation run-off such as RH and tilt angle. Variation in such parameters may partly explain inconsistent results from coating field trials reported so far.

1. Introduction

Accumulation of dust on photovoltaic (PV) modules can greatly reduce their efficiency, especially in deserts where there is little natural cleaning by rain (Costa et al., 2016; Sarver et al., 2013; Sayyah et al., 2014). High humidity can occur even in deserts, which leads to capillary adhesion between particles and surfaces (Wu et al., 1992; Nicholson, 1988; Ibrahim et al., 2004). When present, capillary adhesion dominates other adhesion mechanisms such as van der Waals force (Tomas, 2004; Jones et al., 2002), thus PV soiling has been found to correlate with ambient humidity (Nayshevsky et al., 2017; Figgis, 2016a). Moisture can further bond particles to the surface by the process of cementation, in which soluble matter in the dust dissolves in condensation, and upon drying re-solidifies as a strong material bridge between particles and the surface (Cuddihy, 1980; Bethea et al., 1981; Detry et al., 2011; Ilse et al., 2016; Hassan et al., 2016; Yilbas et al., 2015). The chemical species involved in cementation vary with location (Ilse et al., 2016), but in all cases it occurs through cycles of condensation and evaporation.

While moisture has a potent role in PV soiling, the exact conditions under which condensation forms on dust-laden surfaces are not fully established. This study aimed to study factors influencing condensation, in the context of PV soiling in desert environments. Four parameters were considered: relative humidity (RH), surface-dew point temperature difference, hygroscopic content of the dust, and surface wettability. Previous research on these factors is discussed in Sections 1.1–1.4 respectively.

1.1. Relative humidity

Relative humidity is defined as the ratio of prevailing water vapor pressure to the saturation vapor pressure at that temperature, hence water nominally condenses at 100% RH. However a nano- or micro-scale meniscus of liquid water can condense in surface scratches or crevices between particle and surface in RH less than 100% (Jones et al., 2002; Kim et al., 2008; Ranade, 1987; Grant, 1974), and persist there as RH decreases to even lower RH (Ranade, 1987). The meniscus is stable at RH below saturation because water molecules at the liquid's

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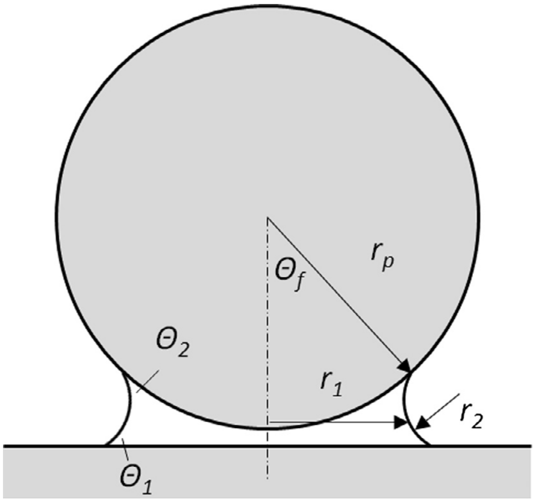

Fig. 1. Capillary adhesion force of a particle to a flat surface is dependent on the dimensions and curvature of the meniscus. r_p – particle radius, r_1 and r_2 – meniscus radii of curvature, Θ_f – filling angle, Θ_1 and Θ_2 – contact angles.

(concave) surface experience attraction to more neighboring molecules than do molecules on a flat liquid surface, which inhibits evaporation. This effect is described by the Kelvin equation:

$$\ln\frac{p}{p_0} = \frac{2\gamma V}{r_k RT} \tag{1}$$

where p is the vapor pressure near the liquid's surface, p_0 is the saturation vapor pressure, γ is the liquid's surface tension, V its molar volume, r_k its radius of curvature, R is the gas constant, and T is temperature of the system. The radius r_k is related to the radii of curvature of the meniscus as illustrated in Fig. 1:

$$\frac{1}{r_k} = \frac{1}{r_1} + \frac{1}{r_2} \tag{2}$$

The difference between the atmospheric pressure (p) and pressure inside meniscus (p_o) forces the particle to the surface; this is the Laplace or capillary pressure p_L given by:

$$p_L = \gamma/r_k \tag{3}$$

Surface tension at the liquid-solid edge also contributes to the capillary force, however it is negligible compared to the Laplace pressure unless the meniscus volume is very small or the contact geometry sharp (Jones et al., 2002; Curry and Kim, 2004; Kim et al., 2016; Brambilla et al., 2017).

In principle the capillary adhesion force is independent of RH when r_2 is small, but in experiments with real particles and surfaces it usually observed to increase with RH (Jones et al., 2002; Kim et al., 2008; Curry and Kim, 2004). This has been variously explained by gaps progressively "flooding" with condensation as RH rises so that the water layer covers surface asperities (Kim et al., 2016; Rabinovich et al., 2002), or by condensed water collecting into patches on the surface rather than forming a continuous film (Leite et al., 2012), or that r_2 is large enough to be comparable to r_1 which may be the case when the water layer is thick or the contact point sharp (Jones et al., 2002; Kim et al., 2008).

How prevalent is surface moisture in real-world conditions? In natural settings it is usual for common surfaces to possess a thin layer of adsorbed water vapor (Kim et al., 2008; Leite et al., 2012). On glass, water adsorption has been reported to commence at less than 25% RH (Grant, 1974) and near saturation it reaches several (Savoy and Escobedo, 2016; Corn, 1961) to tens (Grant, 1974) of molecular layers. Leite et al. (2012) measured the water film thickness on quartz at ~70% RH to be 0.4–0.8 nm, and cited that up to 90% RH the film thickness is less than 10 nm. These values illustrate the scale of the film thickness but cannot be reliably extended to other situations because the thickness varies greatly with surface conditions (Jones et al., 2002). The thickness of the adsorbed water film is said to control capillary adhesion (Jones et al., 2002; Leite et al., 2012; Savoy and Escobedo, 2016; Quon et al., 2000), although some researchers hold that a continuous film so thin is not sufficiently mobile to form a liquid bridge and instead capillary adhesion originates from droplets nucleating at discrete locations (crevices) (Grant, 1974; Corn, 1961; McCormick and Westwater, 1965). This highlights a terminology distinction: "Adsorbed water" generally describes a continuous film molecular-layers thick across a surface, whereas "capillary condensation" involves a volume of free liquid whose shape governs its behavior (by the Kelvin equation) and often exhibits a hysteresis between rising and falling humidity (Grant, 1974).

Regardless of the depth and mobility of surface moisture, it is the effect of RH on capillary adhesion force that is of interest. Atomic force microscopy has been useful for studying this relation (Jones et al., 2002; Curry and Kim, 2004; Quon et al., 2000; Xiao and Qian, 2000; Moutinho et al., 2017). Overall the adhesion force of particles to surfaces has been found to increase when RH exceeds 30–50%, and strengthens greatly when RH reaches 60–70% (Jones et al., 2002; Brambilla et al., 2017; Busnaina and Elsawy, 2000; Zimon, 1969). Some specific measurements from the literature are mentioned: Fuji et al. (1999) found that capillary adhesion of silica particles increased to "remarkable" strength when RH reached 60–80%; Grant (1974) found a rapid increase of water adsorption onto soda-lime glass at 70% RH; Kim et al. (2016) reported that on glass capillary adhesion becomes significant at 50–60% RH; Ranade (1987) reported that in decreasing RH liquid water may persist in the particle-surface contact area down to 50% RH; Jones et al. (2002) determined that capillary condensation dominates particle adhesion on glass when RH exceeds ~40%; and studies cited by Kim et al. (2016)) and Brambilla et al. (2017) showed that adhesion forces increased with RH above just 30% RH. Moutinho et al. (Moutinho) use AFM to measure the adhesion force of 15–60 µm Arizona dust particles and found that, on a smooth surface, the force increased essentially monotonically with RH rather than exhibiting a step-change as in the above-mentioned studies.

Roughness of the surface and particle tends to retard and weaken capillary adhesion forces (Kim et al., 2008). Rabinovich et al. (2002) reported that capillary adhesion commenced at 25% RH on a smooth surface (0.2 nm roughness) but at 70% RH on a rougher one (0.7 nm roughness). Moutinho et al. (2017) found that adhesion force of dust particles to glass decreased as the glass roughness (R_{rms}) increased from 0.3 nm to 22.2 nm (but changed little between 22.2 nm and 321 nm), especially in high RH. Further, they found that for 20 µm glass spheres there was no effect of RH on adhesion force when the surface was rough, but a large force increase with RH when it was smooth. These results indicate that roughness interferes with the establishment of liquid bridges between particles and a surface. Brambilla et al. (2017) estimated that capillary force would strongly diminish when surface roughness reached a few nanometers, i.e. of similar scale as the meniscus height. Jones et al. (2002) estimated that surface roughness decreased the measured adhesion force by 3–20 times in humid conditions, but by a far greater extent (~300 times) in dry conditions, possibly due to presence of a water film thick enough to cover surface asperities. Overall the literature indicates that surface roughness reduces particle adhesion at all humidity levels: in dry conditions it reduces contact area between particle and surface, and in humid conditions it obstructs the formation of a liquid bridge between particle and surface (until the water layer is thick enough to engulf the asperities).

In summary, capillary adhesion of dust on surfaces is essentially ubiquitous in natural environments (Quon et al., 2000), partly because a concave water meniscus is stable even at moderate RH. Experiments have shown that capillary adhesion on glass can be significant in the range 40–70% RH, and strengthen further at higher RH. Yet condensation and capillary forces are sensitive to surface and ambient conditions, hence it is not possible to accurately predict the RH at