Solar Energy 150 (2017) 73–82

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Environmental mud adhesion on optical glass surface: Effect of mud drying temperature on surface properties

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ARTICLE INFO

Article history:
Received 19 September 2016
Received in revised form 16 April 2017
Accepted 17 April 2017

Keywords:
Environmental dust
Mud formation
Humid air
Glass surface
Optical transmittance

ABSTRACT

Mud formation in humid air ambient from dust particles on the glass surfaces is investigated. Mud drying temperature and the characteristics of mud liquid created at the interface between wet mud and the glass surface are examined. Effects of dried mud liquid layer on the glass surface are assessed using analytical tools including scanning electron and atomic force microscopes, energy dispersive spectroscopy, X-ray diffraction, and Fourier-transform infrared spectroscopy. Dry mud adhesion on the glass surface is evaluated incorporating the micro-tribometer and UV visible transmittance tests are carried out to determine optical properties of the glass substrate after dry mud removal. It is found that mud drying temperature has significant effect on the glass surface chemistry and topology; in which case, increasing mud drying temperature increases OH^- and KOH attack on the glass surface while forming cavities-like structures and randomly distributed few micro-cracks. The tangential force required for dry mud removal from the glass surface increases with increasing mud drying temperature. Transmittance of UV visible spectrum is suppressed by the mud residues on the glass surface, which is more pronounced at high temperatures.

1. Introduction

Climate change caused frequent occurrence of severe weather conditions in recent years, particularly in the Middle East, in terms of regular dust storms, increased humidity, and high air temperatures, which remain well above the yearly averages. Regular storms in desert environments carry the dust particles to urban areas while causing damages and performance degradation in energy harvesting systems such as PV panels, concentrated solar receivers, etc. (Semaoui et al., 2015). Creating self-cleaning surfaces, via mimicking the nature, provides the promising solution to the problem of dust accumulation in dry air conditions (Lin et al., 2016). The dust particles settle at the surface while forming a dust layer with varying sizes and compositions (Yilbas et al., 2016a). Some of the dust compounds are chemically active and cause local damages on the surfaces as well as alter the optical properties of the settled surface. Some of these surface properties are critical for transmittance, absorption, and reflection of the incident optical radiation. In humid environments, such as regions close to the seashores - as it is the case in the Arabian Gulf, water vapor condensate on the dust surfaces and gives rise to dissolution of some dust compounds, such as alkaline (Na and K) and alkaline earth metals (Ca) compounds. The solution composing of dissolved compounds and water remains chemically active and possesses the state of high bases that is high pH (Yilbas et al., 2016b). Since the dust particles consist of different sizes and shapes, when they settle at the surface, they form like pores structures with high permeability (Yilbas et al., 2016b). This provides access to the liquid solution, composing of dissolved compounds and water, passing among the dust particles and accumulating at the surface under the gravity. As the rate of condensation increases in humid air environments, water content increases on the dust particles while increasing the amount of dissolution of dust compounds. This further increases the bases state of the liquid solution and gives rise to a liquid film formation at the interface between the wet dust particles and the solid surface. As the air humidity reduces, the liquid film dries out and forms intermediate layer at the interface. The dried liquid layer not only alters the optical characteristics of the surface, but also increases the adhesion between the accumulated dust particles and the solid surface (Yilbas et al., 2016b). The effect of the dry liquid solution on the properties of the solid surface and the adhesion of the accumulated dust particles can change with air temperature due to changing of the drying rate at the surface. Consequently, investigation of the effect of dried solution, which is

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http://dx.doi.org/10.1016/j.solener.2017.04.041
0038-092X/

formed at different air temperatures, on the properties of the glass surface and adhesion characteristics of the accumulated dust particles becomes essential.

Considerable research studies were carried out to examine the dust accumulation on the surfaces and its effects on the performance of the energy harvesting devices. Paudyal and Shakya (2016) highlighted the importance of dust accumulation on PV panel modulus. The dust accumulation at the bottom of the PV modules resulted in a high risk of hot spots, which could eventually lead to permanent module damage. Rifai et al. (2016) presented the removal mechanism of the dust particles from the rotating disk incorporating the centrifugal forces. The force balance revealed that the centrifugal forces remained higher than the adhesion, friction, drag, lift, and gravitational forces in the region away from the rotational center. In addition, the dust particle size and rotational speed significantly influenced the rate of dust removal from the disk surface. Zaihidee et al. (2016) studied the degradation of PV panel surfaces and the findings revealed that the degradation depended mainly on the dust deposition density, which was governed by the various factors. The dust accumulation of 20 g/m^2 on a PV panel reduced a short circuit current, open circuit voltage and efficiency by 15–21%, 2–6% and 15–35%, respectively. Al-Shehri et al. (2016) investigated the cleaning of photovoltaic panel from dust particles. It was demonstrated that cleaning efficiency of the nylon brushes was not as high as the cleaning by using water and delicate wipers. Moreover, some small damages were observed on the glass surfaces after brushing; however, this was shown not to have a permanent effect on the optical characteristics of the glass. Sarver et al. (2013) performed a comprehensive overview of soiling problems, primarily those associated with the dust particles (sand) and combined dust–moisture conditions. They reviewed the key indicators of dust effects on the device performance. Klimm et al. (2016) examined the soiling behavior of the surfaces due to dust accumulation. The soiling decreased the transmittance while limiting the overall performance of the solar devices. Qian et al. (2012) developed a scaling analysis to identify a single key dimensionless parameter influencing photovoltaic panel efficiency and determined the optimal values for turn-on and turn-off voltage ratio in terms of the parameters selected. The findings revealed that the efficiency decreased rapidly as the turn-off voltage ratio was raised above the optimal value. Yilbas et al. (2016c) studied dust and mud accumulation of laser textured and sol-gel coated alumina surfaces. The laser treated and sol–gel coated alumina surfaces provided superior surface characteristics in the harsh environments because of the weak adhesion between the mud formed from the dust particles and the coating surface. This was associated with the small texture height of the sol–gel coating, which lowered the area of the interfacial contact between the mud and the coated surface, and relatively lower surface energy of the sol–gel coating as compared to that of the laser treated surface. Dastoori et al. (2016) examined the impact of the static electric charge of the accumulated dust particles on the photovoltaic module performance. The charge level of the accumulated dust particles had significant impact on photovoltaic module output and the dust particles accumulation was not strongly associated with panel tilt angle. Sueto et al. (2013) studied the effects of anti-soiling photocatalytic coating on surfaces characteristics. The findings revealed that the presence of electrostatic charges on the surfaces was the main factor for the adhesion of sand, and it could be suppressed by the anti-soiling photocatalytic layer. Elminir et al. (2006) demonstrated the reduction of transmittance due to surface soiling. In this case, the dust deposition density, in conjunction with the plate tilt angle, and the orientation of the surfaces, with respect to the dominant wind directions, influenced significantly the surface soiling. Tanesab et al. (2015) showed the type of dust particles deposited on PV module surface. The dusts were dominated by the fine particles of quartz (SiO_2), followed by calcium oxide (CaO) and some minors of feldspars minerals ($KAlSi_3O_8$). In this case, quartz particles were the main contributors for lowering the transmittance and reducing the PV module performance. Klugmann-Radziemska (2015) investigated degrading performance of a crystalline photovoltaic module due to the dust deposition on the surface. The findings revealed that performance loss was closely related to the tilt angle of the module, the exposure period, site climate conditions, wind movement, and the dust properties. In addition, the energy yield losses took place due to the dust deposition on the photovoltaic modules. Smallwood et al. (2016) introduced a finite element modeling to compute the adhesion factor of the particles for dielectrophoretic adhesion. In the analysis, the density of particles and the dielectric constant were incorporated. Sayyah et al. (2014) reported the degradation performance of the solar thermal system. The analysis was introduced for the advantages of cleaning processes that included natural, manual, automatic, and passive methods. The type of solar collectors, geographical location, local climate, and exposure period of the collectors influenced the efficiency of the solar thermal system. Yilbas et al. (2015) investigated laser texturing of alumina surfaces and dry mud effect on the textured surfaces. The laser texturing increased the microhardness and enhanced surface hydrophobicity due to the formation of nitride species. The mud residues did not influence the fracture toughness and microhardness of the laser textured surface; however, they reduced the surface hydrophobicity significantly. Hegazy (2001) showed, in dusty environment, the surface transmittance strongly related to the dust deposition in conjunction with plate tilt angle, as well as on the exposure period and site climate conditions. In this case, the empirical correlation was developed for the reduction of transmittance of a glass wafer with a fixed tilt angle. Beattie et al. (2012) described the reduction of the active surface area due to the formation of clusters of particles on the surface. Such clusters could support particles in upper layers which reduced the available area for photon capture by a much smaller amount than the particles resting directly on the glass surface. Javed et al. (2017) characterized the dust particles accumulated on photovoltaic panel surfaces over a period of ten months in a solar test facility located in Doha, Qatar. The findings revealed that the dust collected after dust-storm events had higher proportions of halite and quartz contents than non-dust-storm days, depending on the direction of the wind. Also, dust particles accumulated on photovoltaic panels appeared to agglomerate as the exposure time increased. Abderrezek and Fathi (2017) demonstrated the importance of dust type on the photovoltaic panel performance; in which case, variation of the physical parameters including level of optical transmittance and the glazing temperature resulted in photovoltaic panel performance change. Kazem and Chaichan (2016) examined the dust depositions on photovoltaic modules. It was demonstrated that the weight and shape of dust particles had a significant effect on their deposition behavior while influencing the photovoltaic device performance.

Although dust accumulation and mud formation on glass surfaces in humid air environments was studied earlier (Yilbas et al., 2015, 2016a, 2016b), the main focus was the mud formation in standard air temperature on the glass surfaces (Yilbas et al., 2015) or mud formation on the polycarbonate surface (Yilbas et al., 2016a, 2016b). However, the effect of air temperature on the dry mud adhesion and its after effects on the glass surfaces were left for future study. In the present study, the dust accumulation and the mud formation on the glass surfaces at different air temperatures are investigated. The properties of mud the solution and its influence on the characteristics of the glass surface are assessed using the analytical tools including scanning and atomic force microscopes, X-ray diffraction, energy dispersive spec-