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Sand erosion on solar reflectors: Accelerated simulation and comparison with field data

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ABSTRACT

Solar reflectors for concentrating solar power applications can be subject to performance losses due to their permanent exposure to the environment. There is still lack of experience regarding the destructive effects of sand and dust storms on reflector materials and no accelerated ageing guideline is formulated yet to account for the performance loss of solar mirrors due to particle erosion to a realistic extent. The work described here shows one approach to design an accelerated ageing test setup that simulates erosion processes on solar reflectors based on DIN 52348 standard. Furthermore, the results of the developed laboratory ageing method were compared with the effects on exposed outdoor samples from Zagora (Morocco). Laboratory experiments demonstrated a linear correlation between the amount of sand, which is used to erode the reflector samples and their specular reflectance loss. As well, the dependence of the impact angle on the severeness of erosion was investigated. The results are in agreement with earlier works where it was determined that erosion damage on brittle materials like glass is most pronounced for perpendicular impact and becomes weaker for decreasing impact angles. Four different silvered-glass mirrors and three different aluminium mirrors were investigated. Using the results from the laboratory experiments it was possible to attribute defect rates to the respective reflector materials and rank them regarding the resistance towards erosion, specific for this setup. All tested silvered-glass mirrors showed higher erosion resistance than the aluminium samples. The conducted microscope comparison between outdoor exposed samples and those tested under laboratory conditions prove that the developed method for accelerated ageing tests provokes realistic erosion damage.

1. Introduction

To guarantee the long-term efficient operation of Concentrating Solar Power (CSP) plants, the durability of the components is of major importance. Various meteorological and geological factors need to be taken into account which can potentially lead to performance losses, e.g. humidity, thermal gradients and cyclic day-night temperature changes, irradiation, corrosive atmospheres, mechanical wear etc. To simulate general outdoor effects on reflector surfaces, procedures have already been widely applied by research centres and manufacturers, which are standard practice for many applications, like the salt spray test according to ISO 9227 standard [1] for marine environments, the ISO 11507 standard [2] for long-term UV-radiation and cyclic condensation or the IEC 61215 standard [3] for the simulation of thermal cycles.

Another threat to CSP materials is that of sand and dust storms. These are natural events that occur widely around the world in arid and semi-arid regions, especially in subtropical latitudes. They are the result of air turbulences which spread a large mass of sand and dust in the atmosphere and are associated with wind velocities higher than 5–6 $m\,s^{-1}$ [4] and horizontal visibilities less than 1000 m [5,6]. Generally the visibility is a function of the sand and dust concentration in the air and the wind speed and can be reduced to several metres during severe sand and dust storm events [7]. On the one hand these wind entrained particles can decrease the efficiency of solar power plants by soiling, which is generally a reversible effect and was comprehensively reviewed by Sarver et al. [8]. On the other hand irreversible effects, presented by mechanical defects due to impact of wind entrained particles which lead to scratches and cracks on the reflector surface, can be

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Nomenclature

Symbols

m_a	specific sand mass per unit area [g cm^{-2}]
α	impact angle between sand flow and reflector surface [°]
γ	material specific defect rate of simulation [% g^{-1} cm^{2}]
φ	acceptance angle [mrad]
θ	incident angle [°]
λ	wavelength [nm]
ρ	reflectance [%]
ρ_{loss}	monochromatic specular reflectance loss [%]

Subscripts

h	hemispherical
s	solar

Acronyms

BRDF	bidirectional reflectance distribution function
CSP	concentrating solar power
D&S	Devices and Services
PIV	particle image velocimetry
PVD	physical vapour deposition
ROA	reflectance over acceptance angle
RPM	rounds per minute

generated. Thereby the optical efficiency decreases and the risk of electrochemical corrosion rises due to defects in the protective coatings of the reflectors [9–13]. However, no standard is available to predict the optical degradation of mirror materials during such natural events, that are expected to increase in number and severeness over the next decades [14]. The performed outdoor exposure testing campaign (presented in Section 3) showed that existing abrasion standards (MIL-STD-810G [15], ASTM D968-05 [16] and ASTM F1864-05 [17]) do not represent a realistic picture of the impact of aeolian sand and dust particles on reflector surfaces under desert environments. One reason for the so far unsuccessful simulation in the laboratory is that the physical parameters present in natural sand and dust storms are still not sufficiently characterized. The expected lifetime of CSP technology components ranges from 20 to 25 years [18] and there is no test procedure available to assure the owners of CSP plants, that the optical properties of the mirrors will maintain over this period in desert regions.

1.1. State of the art approaches

The working setups to simulate erosion due to sand and dust storms in the laboratory can be subdivided in three different methods, each exhibiting its distinct advantages and disadvantages:

- Sand trickling.
- Sand blasting or open loop wind tunnel.
- Closed loop wind tunnel.

The following review of literature summarizes the experiences of various groups working currently on the topic of sand erosion on CSP materials.

1.2. Sand trickling method

On the basis of the ASTM D968-05 [16] and DIN 52348 [19] Völker et al. [20] developed a laboratory sand trickling method and investigated aluminium and glass mirrors, the influence of the impact angle (45°, 60° and 90°) and the used sand mass (0.75, 1.5 and 3 kg). The sand used was quartz sand with a diameter range between 0.5 and 0.71 mm. By application of the law of free fall they assumed a sand particle impact velocity below 5.7 m s^{-1}. The increase of abrasion damage was quantified by a decrease of light transmission and was associated with increasing amount of trickling sand and decreasing impact angle. Glass samples turned out to be more resistant towards erosion than aluminium. This fact was ascribed to the higher hardness of glass. However, this testing method was considered as too extreme by the authors themselves and the following improvements were suggested to investigate the erosion behaviour of sand on components of solar energy systems under realistic sand storm conditions:

(1) Create a sand-laden air flow.
(2) Increase the particle velocity.
(3) Reduce the sand concentration.
(4) Establish a homogeneous distribution of the impacting sand particles on the sample surface.

1.3. Sand blasting method (open loop)

In their work, Völker et al. [20] also presented erosion simulation results achieved by the application of a sand blasting device. The setup complies with all the mentioned demands from the assessment of their sand trickling method. The used sand mass was 0.75, 1.5 and 3 kg, while the impact angle was kept constant at 45° and the velocity was set to 11.7 m s^{-1} using a fan blower instead of gravity as the driving force of movement. The same quartz sand was used as before. Although the velocity of the particles was significantly higher, they found much lower losses of reflectance of the respective samples for the same total sand masses. They call the lower and thus more realistic concentration of sand particles in the air stream to account for that fact.

Another sand blasting setup, named *erosion rig*, was investigated by Sansom et al. [13]. It is operated with pressurized air instead of a fan blower. They used two coastal sands from Libya and MIL-STD silica sand and glass mirror samples. 4 g of the different sand types were used to simulate a four hour lasting sandstorm for various velocities (5, 10 and 15 m s^{-1}). Only little effects of the treatment on the mirror were found at velocities below 10 m s^{-1}. The loss of reflectance that was found at 15 m s^{-1} was described as a possible result from adhering particles as well as erosion. They found differences in damage and adhesion properties of the tested sand materials.

The most comprehensive current work on the subject towards laboratory simulation of the surface erosion of solar glass mirrors was performed by Karim et al. [21]. Their *sand blower open circuit machine* is operated with an air compressor. It was possible to investigate the effects of the impact speed, the impact angle and the properties of the erosive particles on thin glass mirrors individually. Natural sand samples were obtained from two Moroccan sites and used as abrasive material. For comparative reasons, MIL-STD sand was used as well. They found a linear decrease of mirror reflectance with increasing sand mass, while the impact velocity showed a polynomial trend on the reflectance and the surface