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Soiling of solar collectors – Modelling approaches for airborne dust and its interactions with surfaces

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ABSTRACT

This literature review deals with the well-known problem of soiling in solar plants, which it severely affects the energy yield of solar power plants. A loss of reflectivity due to soiling reduces the entire productivity of the plant by limiting the energy harvested (i.e. the incoming direct normal irradiance is not properly reflected towards the right focus). On the other hand, the costs of maintenance and cleaning of the collectors represent a significant component of the plant operational costs. Therefore, in this paper, a multi-disciplinary literature review is conducted with the aim of collecting existing models for the key processes, organising them into a ‘dust life cycle’. This cycle is divided into four steps: Generation, Deposition, Adhesion, and Removal; with emphasis on the interaction between dust particles and solar collectors’ surfaces. Generation deals with the loading of atmosphere with dust particles, deposition concerns the processes that actually bring airborne dust onto the collectors’ surface, adhesion and removal represent the competing forces whose balance determine which particles remains adherent on the collectors and which are detached. The intent is to provide a complete framework for the development of a future physical model for the prediction and estimation of the actual soiling of the solar collectors, which engineers can implement in order to maximize the revenues of CSP plant, pushing towards more clean and sustainable energy production technologies.

1. Introduction

Concentrated Solar Power plants are considered one of the most suitable technologies for the future large-scale exploitation of solar energy. The main advantage of CSP is the adoption of thermal storage system which allows decoupling the electricity production from the hourly availability of solar energy (the so called dispatchability). To date, conventional thermal storage concepts are significantly cheaper than electric storages (i.e. batteries). The main limit of CSP system has traditionally been the higher Levelized Cost of Electricity (LCOE) when compared to the traditional fossil fuel-fired power plants and renewable energies [1]: the cost of electricity for CSP is in the range of 140–290 €/MWh, depending on the specific CSP technology considered, compared to 50–60€/MWh [2–5] for conventional fossil fuel power stations.

Most studies agree that plant operation and maintenance (O & M) represent a significant cost, accounting for 14–17% of the LCOE (including fixed O & M costs, 10–11%, and personnel and consumables, which account for 4–6%) [1,6,7]. In addition to its significance, the International Renewable Energy Agency [7] identifies O & M as a key potential area for overall cost reduction.

The solar field consists of the most expensive components of the plant [8], with technologies and issues specific to the industry, while the other sections of the solar plant (i.e. Power Block) have similar issues to traditional plants [9]. According to the analysis carried out by Kutscher et al. (2010) at NREL (National Renewable Energy Laboratories, Colorado, USA) the O & M costs related to the Solar Field accounts for about 23% of the total O & M costs [6], which are substantially composed of labour, materials and consumables for the maintenance and cleaning of the collectors [1]. The majority of sites that are suitable for CSP installations are in arid or semi-arid areas, where the quantity of dust (or sand) carried by wind gusts and storms in atmosphere is significant and the water required for the standard cleaning methodologies is usually scarce [10,11] and expensive [10]. In parallel to direct O & M costs, many studies have indicated the loss of reflectance as one of the most important detrimental factors in CSP plant productivity [6,7]: reflectance can drop by about 10–15% points, making mirror cleaning fundamental to achieve good performance [8]. Bethea et al. (1983) identified the deposition of dust on mirror surfaces as a main reflectivity degrading factor [11], and more recent studies

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Nomenclature

a	contact radius
a_0	contact radius at zero external force
$a_{0,e}$	contact radius at zero external force for elastic deformation
$a_{0,p}$	contact radius at zero external force for plastic deformation
a_s	contact radius at separation
A_C	area of the contact surface
A_H	Hamaker constant
A_{xy}	area projection
C	capacitance
C_C	correction factor for slip effect
C_d	dust concentration in air
C_D	drag coefficient for momentum
D_p	particle diameter
$\overline{E_s}$	mean kinetic energy
f	correction factor for wall effect
f_m	correction factor for wall effect
f_v	fraction of dust contained in V
F	dust deposition flux
F_{12}	electrostatic force particle − surface
F_{adh}	adhesion force
F_c	capillary force
F_{cp}	capillary pressure force
F_d	drag force
F_{ec}	standard Coulomb force
F_{ed}	dielectrophoretic force
F_{ei}	image force
F_{el}	electrostatic force
F_{ep}	polarization force
F_g	gravitational force
F_{ip}	interparticle force
F_l	lift force
F_Q	electrostatic force at constant charge
F_{st}	surface tension force
F_t	fluid dynamic drag force
F_v	vertical dust flux
F_V	electrostatic force at constant potential
F_{vdW}	van der Waals adhesion force
H_0	equilibrium distance
k	Boltzmann constant
k_2	dielectric constant (plane)
k_s	static friction coefficient
K	composite Young modulus
l	contact perimeter
m_s	typical mass of saltators
M_t	fluid dynamic torque
n_s	number of impacting saltators per unit area
N_C	number of bumps in contact
P	external force
Q	electric charge
Q_1	electric charge (sphere)
Q_h	horizontal saltation flux
r_1, r_2	radii of curvature
r_d, r_g, r_{ip}	moment arms
r_r	radius of asperity
R_p	particle radius
s	separation distance
Sc	Schmidt number
St	Stokes number
T	temperature
u_*	friction velocity
u_{*ft}	threshold friction velocity
U	wind speed
v_d	deposition velocity
v_i	inertial deposition velocity
$\overline{v_{imp}}$	mean saltator impact speed
v_{rem}	removal velocity at the centroid of the particle
v_s	terminal velocity (Stokes law)
V	electric potential
V_r	removed volume
W_{ij}	work of adhesion
y_{max}	height of asperity
Y	yield strength of material
α	angle of liquid meniscus
α_s	sandblasting efficiency
β	bumps radius
γ	surface tension
$\gamma cos\alpha$	vertical component of surface tension
γ_i	interparticle forces parameter
ε_0	air permittivity
$\overline{\varepsilon_A}$	aerodynamic particle inertial coefficient
ε_k	efficiency of kinetic energy conversion
θ	contact angle
μ_{air}	air dynamic viscosity
ν_0	liquid molecular volume
ρ_a	air density
ρ_b	bulk density of soil
ρ_p	particle density
ρ_r	density of asperities
τ_z	vertical turbulent flux of horizontal momentum

performed at Sandia and NREL laboratories predict a reduction of the LCOE of 2–2.5 €/MWh with an absolute improvement of 2% in mirror cleanliness [2,6].

Taken together, these estimates show that cleaning costs and productivity losses due to soiling have both a significant and comparable effect on the LCOE. An optimal cleaning schedule [6,7] therefore balances productivity losses and cleaning costs. In order to find the correct balance, a CSP O & M operator would highly benefit from deep understanding of soiling mechanisms, in order to assess and predict solar collectors' performance degradation and therefore properly define an economically optimal cleaning schedule. Direct measurements of reflectivity loss through optical reflectometers [12] already offer the possibility (in some countries at a non-negligible labour cost) of sampling the degradation of heliostat performance at regular time intervals; however the availability of a soiling model would have a series of benefits: (i) the model allows for a more informed selection of plant placement in the design phase, including the estimation of soiling losses and their impact on the future O & M costs in different possible plant locations; (ii) it would also improve operators' and investors' confidence in the plant O & M budget, which remains one of the most uncertain cost components in CSP (O & M); and (iii) the ability to simulate different scenarios (even with a certain degree of uncertainty on model parameters) would enable a qualitative (but detailed) understanding of the importance of weather parameters and plant design choices (e.g. geometry of the field) on the soiling of the collectors. This would in turn allow a better allocation and scheduling of cleaning resources and activities considering seasonal and weather-dependent trends. The coupling of recurring measurements of reflectivity/soiling with this model would provide further benefits: on one hand the measurement would provide a continuous calibration and refinement of the model, and on the other hand the model would largely improve the predictive capabilities of an otherwise simple measurement-based extrapolation of future soiling. This, in turn would allow the plant operators to extend with confidence the scheduling of future cleaning activities and analyse their field cleaning strategy under different weather scenarios.