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Exploring New Strategies Towards Cost-Efficient Anti-Soiling Coatings for CSP Plants

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Abstract

Power output of concentrated solar power systems (CSP) is strongly dependent on mirror reflectivity, which in turn, is affected by soiling and atmospheric conditions. Anti-soiling coatings can enhance efficiency of CSP plants while reducing operating and maintenance costs. Most of them however, suffer from poor endurance and performance. Transparent smooth coatings based on quaternarized silanes may be a viable approach in order to minimize energy losses attributed to soiling.

Introduction

Concentrated solar power (CSP) systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight into a receiver [1]. Electricity is generated when the concentrated light is converted to heat. Solar thermal energy generation is a promising technology that can successfully address future energy needs in a renewable and sustainable way. Worldwide, the installed capacity in 2016 was reported to be 4.8 GW [2]. Despite this level of penetration of the technology, the levelized cost of electricity (LCOE) still remains high as compared to conventional power plants. Apparently, the mirror's efficiency is critical to the system performance. Mirror reflectivity is one of several factors affecting the energy delivered by the solar field to the receiver, but varies significantly, due to soiling and atmospheric conditions. A 1% loss in reflectivity directly leads to a 1% increase in the levelized cost of electricity (LCOE). It is self-evident that soiling presents a significant problem which degrades performance and increases operational and maintenance (O&M) costs for plant operators. Plant O&M costs contribute about 11-15% to the LCOE, and mirror washing and water costs are a significant contributor to these costs [3].

Anti-soiling coatings may be an efficient solution to the above problem, since they can result in the reduction of O&M costs and water consumption while increasing the efficiency of a CSP solar collector field [4-9]. However, since the installed capacity is already enormous, anti-soiling coatings should be equally effective regardless if these are applied at the manufacturing stage or at an existing installation.

A New Approach towards Cost Efficient Anti-soiling Technologies

Various reports all over the world have revealed large decrements in the efficiency of existing solar power plants due to heavy soiling (including dust, dirt and pollen), exceeding 25% within a 6-month period especially at areas of high industrial pollution, at seaside locales with abundant salt mist, in deserts and at areas with volcanic activities and mining. Soiling on solar power systems, such as CSP and PV modules, is a complex phenomenon [4]. Scientific research has proven that surface soiling develops in two adjacent layers: one top layer which can be relatively easily removed by wind, rain or cleaning action and one sub-layer, which adheres strongly to the mirror/glass surface and forms a hard crust that reduces the amount of light reaching the solar collector. Besides energy losses, environmental conditions can also give rise to degradation or "corrosion" of the receiving surface.

Protective anti-soiling coatings provide a viable solution to the above problems [4-10]. The application of a non-stick barrier renders cohesion forces among same particles larger than adhesion forces among different particles and self-cleaning of dirty surfaces is facilitated. Although soiling rate, climate and types of soil vary by location the application of an anti-soiling coating improves efficiency by a non-negligible fraction. Coated surfaces accumulate dirt at a slower rate, exhibit in rainy conditions an enhanced self-cleaning effect, need less frequent cleanings and are easier to clean. Just like an improper surface structure however, some coatings may turn non effective and depending on environmental conditions transmittance may decrease below the threshold of uncoated surfaces.

Anti-soiling coatings can be either hydrophilic or hydrophobic [10]. Although hydrophilic coatings have a photocatalytic functionality being able to decompose organic matter by sun irradiation, they work well only on laboratory conditions. Furthermore, most of the environmental pollution is of inorganic nature, so it is rather pointless to apply a coating, which will work properly for destroying only a small portion of the existent organic dirt, especially in arid climates. On the other hand, hydrophobic anti-soiling coatings present more favorable characteristics [11,12]. At least 60% of liquid pollution can be self-cleaned by common hydrophobic coatings, while non-stick properties further aid in reducing soiling, thus significantly reducing cleaning costs. At the same time, the need of abrasive cleaning during regular maintenance is minimized, thus preserving the original optical properties of the receiver. However, most of the hydrophobic coatings in the market today are based on polydimethylsiloxanes or fluoropolymers [13,14] and suffer more or less by some of the following drawbacks: a) poor endurance, especially with regards to abrasion, cleaning chemicals and adverse environmental conditions such as sandstorms, sea mist, humidity, etc., b) inadeqaute homogeneity and lower overall mechanical strength, c) poor translucency and d) low water sliding angles. More efficient technologies and coatings are therefore urgently needed.

Towards this end, an interesting perspective is the use of acidic aqueous solutions containing quaternarized silanes. The latter can hydrolyze and co-condense to provide non-stick surfaces with high lubricity and pronounced antisoiling attributes [15,16]. Although the resulting layers may lack oleophobic properties, they might be possible candidates of sustainable implementation within larger power plants, such as CSP plants and large PV plants, since repetitive applications (for example, every six months) can provide periodic surface revitalizing of coated surfaces. The opportunity behind this prospect lies in the fact that a permanent coating no matter how effective it is, it will ultimately stain and/or degrade. So, perhaps a temporary coating that performs well even for shorter periods but that can be economically re-applied at regular intervals may be a better alternative. Results obtained after extensive testing of our patented coating systems in real field conditions have shown that such coatings can exhibit pronounced antistatic properties, too.

More specifically, the deposition of a silane-based aqueous solution containing trimethoxysily-propyl dimethyloleyl-ammonium chloride on CSP samples can yield an extremely thin (30-50 nm) and smooth coating with acceptable mechanical strength and with WCAs lying in the range of 95-105°. Moreover, since the surface of CSP mirrors in anionic in nature the addition of quaternarized copolymers at low actives' levels in the coating solution may further enhance electrostatic attractions and thus, adhesion of the coating to the substrate. Synthesis of such formulations is quite straightforward. In addition, the coating thickness can be tuned in a way to match specific CSP requirements or even specifications of tempered glass sheets used in PV modules. For example, the wave length of the incoming light and the refractive index of the glass can be effectively combined, thus minimizing reflection losses. Even more importantly, this coating may be industrially produced by low concentrated raw materials, thus enabling a low-cost material. If one considers that this material can be applied during routine cleaning of CSP plants, the cost per square meter of coating can be extremely low, i.e., below 0.30 Euros/m^2.

Application of the coating at large surfaces can be preferably realized by spraying techniques, such as the HVLP technique. The latter allows fast application of the coating in a reproducible manner. Spray guns with nozzles of up to 1.4 mm and working pressures between 20 and 30 psi are preferable in terms of coating uniformity and hydrophobicity. Subsequently after application, fine polishing of the coating with the aid of a motorized felt pad or rinsing with water is necessary to remove coating residues and reveal a functional easy-to-clean/self-cleaning surface, since coating remnants are usually randomly-oriented self-condensed silica species which cannot consistently adhere to the surface, thus blocking its anti-soiling attributes.

Our company has developed a series of permanent and temporary anti-soiling coatings under the umbrella brand SolarSkin™ [17]. Although permanent coatings constitute the flagship of our SolarSkin™ product series, temporary coating variations have their own distinct features and advantages. Below some of their characteristics and specs:

a) Initial water contact angles of 95+ degrees, i.e., above the hydrophobic threshold of 90°. Maintenance of hydrophobic attributes after 3 months exposure in outdoor conditions with the recorded WCAs being constantly above the widely accepted easy-to-clean threshold of 80°, thus indicating long-term cleanability of mirrors.

b) Linear wear with less than 20% water contact angle reduction within a 6-month operational period.

c) Optically free-no transmission losses after aging.

d) Acceptable abrasion and UV resistance (assessed by preliminary evaluation of WCA reduction after 1 month of continuous exposure to environmental conditions).

e) Resistance to cleaners, organic solvents (e.g., alcohols), washing detergents and chemicals, up to pH values of 10.

f) Temperature stability of at least 120°C.

g) Resistance to temperature fluctuations. Minimal degradation after repeating heating cycles at 100°C.

h) Curing at ambient temperature.

i) Surface roughness of less than 10 nm.

j) Useful life-cycle of at least 6 months (meaning that the coating can be renovated during periodic cleaning of CSP plants without losing its functionality).

Considering especially techno-economical aspects of the existing anti-soiling coatings, it should be noted that, among the various factors affecting their performance, UV radiation has perhaps the most adverse impact [18]. Therefore, even the most enduring nano-coatings will inevitably degrade, no matter how they resist to abrasion or chemicals. In other words, the commonly employed industrial standards of wet scrub abrasion and chemical resistance are meaningless if they are not coupled with results from WCA degradation after real-field exposure.

Consequently, a "permanent" coating perhaps will not manage to perform optimally after a given time and, perhaps most importantly, more efficiently than a temporary coating, which may be periodically re-applied without additional labor costs, which usually account for more than 50% of the total application cost of a coating. BFP's modest calculations through the successful implementation of such an approach to current power plants predict power increment between 2 and 4.5%, depending on atmospheric conditions and type/rate of soiling, up to 7% increment in energy generation and up to 70% reduced soiling, all of which translate to lower LCOE and reduced O&M costs.

Of course, long term real-field testing vs. actual performance over time of coated mirrors and coated tempered glass samples will prove the validity of this reasoning. Our company is currently conducting a long-term real-field study at the PROTEAS CSP facility in Cyprus to evaluate effectiveness of the above approach. Analysis of large data sets such as minute-resolution meteorological conditions and daily reflectivity measurements are continuously monitored. The information is analysed and compared to industrial standards in order to identify the optimal solutions sought in terms of cleaning schedule. The analysis also includes a comparative study with coatings that define the technological level in the field, taking into account international standards and specifications, required infrastructure-application equipment, as well as energy benefits driven by the reduction of cleaning frequency. The aim is to quantify the impact of the proposed surface coatings on the annual energy yield and overall cost of the technology. The potential use of alternative washing techniques is explored, too. Finally, further gains that the plant operator can harvest are investigated and quantified. A thorough report on the findings obtained is underway.

Conclusions

Efficient anti-soiling coatings for CSP plants based on quaternarized silane hybrid oligomers can be produced in a facile way. They present interesting features, such as low surface energy, transparency, acceptable mechanical resistance and smoothness. They can be also periodically revitalized, thus maintaining long-term functionality without severe fluctuations in performance, which offers a distinct advantage over traditional permanent coatings. Long-term real field analysis is required to prove the effectiveness of this approach.

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Conflicts of Interest

All authors declare no conflicts of interest in this paper.

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