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Degradation of concentrating solar thermal reflectors in acid rain atmospheres

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ABSTRACT

Given the importance that concentrating solar power technologies have had in recent years, the interaction between humid atmospheres in which SO_2 is the main pollutant and the metal reflecting layers of the solar concentrators is a major concern that should be addressed. Previous durability studies have urged the importance of designing an accelerated aging test protocol for simulating aggressive industrial atmospheres that solar reflector materials are bound to encounter. Therefore, three types of reflectors were tested in an acid-rain (or Kesternich) chamber at various temperatures and gas concentrations based on the DIN 50018 and ISO 6988 standards. The results showed the significant effect of high SO_2 concentrations rather than high temperatures on silvered-glass reflectors, although synergy should not be disregarded. Strong reductions in specular reflectance were found for one type of silvered reflector compared to another type, highlighting the significance of material processing and its effects on their final performance. Aluminum reflectors were not damaged as much as silvered-glass reflectors, but under microscopic inspection, a wide range of noticeable corrosion defects could be found in all the materials. Comparisons between the most representative Kesternich test and samples from an outdoor industrial site permitted realistic lifetime correlations for commercial silvered-glass reflectors.

1. Introduction

Concentrating solar thermal technologies (known as CSP, concentrating solar power) have undergone spectacular development in the last few decades [1]. While in 2006 CSP installed capacity was 0.5 GW_e worldwide, it has increased by a factor of 10 to over 5 GW_e today. It is estimated that CSP technologies will provide about 11% of total electricity production by 2050 [2], as a result of the huge effort made by numerous countries in the last few years in introducing noteworthy renewable-energy programs [3,4]. CSP plants may be located near industrial areas because of the availability of highly qualified personnel and infrastructures already in place there. In addition, industry is showing growing interest in the use of CSP technologies as the source of electricity, steam and process heat. However, these areas may face significant concentrations of sulfur dioxide (SO_2), which is the gas mainly responsible for atmospheric acidification [5]. This phenomenon, which has been of great concern in the last several years, has resulted in numerous studies [6–8]. Combustion of fossil fuels containing sulfur and smelting metal sulfide ores are the main sources of manmade emissions of SO_2 [9]. Although recent studies have reported a dramatic decrease in atmospheric SO_2 levels in several European cities, mainly due to the use of cleaner fuels and higher-efficiency engines [10], this airborne pollutant (alone or in combination with other corrosive gases and salinity) can cause serious degradation of metals [11] and in this case, of the metal CSP absorber and reflector parts used in CSP and solar thermal collector applications [12].

Of the current types of CSP reflectors, silvered-glass and aluminum reflectors are the most widely deployed, and both contain metals prone to corrosion, thus negatively affecting their optical performance. Silvered-glass reflectors are based on a thin silver reflective layer which is protected by a 1–4 mm glass substrate on the front and usually a copper layer and several protective coats of paint on the back. Due to their high performance and durability, they have been regarded as the most reliable technology to date [13]. On the other hand, aluminum reflectors consist of a physical vapor deposited (PVD) aluminum layer, on an aluminum substrate protected by transparent SiO_2 sol-gel coatings. They are frequently used in small-scale concentrators for process heat applications where atmospheres are likely to be polluted [14].

The importance of the interaction between gases in ambient air and the silver used in solar concentrator reflectors was identified by Schissel

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Nomenclature

Acronyms

CSP	Concentrating solar power
PVD	Physical vapor deposition
CASS	Copper-accelerated acetic acid salt spray
DIN	Deutsches Institut für Normung (German Institute for Standardization)
ISO	International Organization for Standardization
PTC	parabolic-trough collector
ASTM	American Society for Testing and Materials
SLR	Single-lens reflex

Symbols

T	Temperature [°C
RH	Relative humidity [%]
V	Volume [dm^3]
$\rho_{\lambda,\varphi}(660\,nm,15°,12.5\,mrad)$	Monochromatic specular reflectance at wavelength $\lambda = 660$ nm, incidence angle $\theta_i = 15°$ and acceptance half-angle $\varphi = 12.5$ mrad
$\rho_{s,h}([280,2500]nm,8°,h)$	Solar-weighted hemispherical reflectance in the wavelength range of $\lambda = [280,2500]$nm and at incidence angle $\theta_i = 8°$
N	Number of corrosion spots [dimensionless]
W	Scratch width [µm]
$[SO_2]$	Sulfur dioxide concentration [ppm]

and Czanderna in 1980 [15]. As reported in previous studies [16,17], humid atmospheres in which SO_2 is the main corrosion agent are aggressive and harmful to many metals (silver, copper, etc.), which are also present in the reflective layer of solar reflectors, thus compromising their optimal performance. More recent studies have carried out extensive laboratory and outdoor exposure testing of solar reflector materials. The most appropriate accelerated aging test that reproduced similar degradation to outdoor defects in silvered-glass reflectors was reported to be the copper accelerated salt spray (CASS) test [18,19]. Nevertheless, an additional accelerated aging test campaign simulating aggressive industrial environments was considered necessary. A wide variety of accelerated aging experiments have been applied to aluminum reflectors and some correlations with representative outdoor sites derived [20]. One type of corrosion mechanism reproduced with the CASS test and acceleration factors for three different types of reference sites have been assigned accordingly. However, this is only a first step in lifetime prediction of solar reflector materials. To date, few solar reflector durability studies have succeeded in providing realistic lifetime estimates [21], and only a few of them have been devoted to the effect of humid sulfur-containing atmospheres [5,22,23]. It is therefore considered a major issue that must be addressed and studied carefully. Special attention should be given the Kesternich test [24,25], which uses high concentrations of SO_2 in water-saturated atmospheres and has been used before to simulate the degradation of materials normally subjected to atmospheric SO_2. This standardized aging experiment has been used, for example, to study the degradation and corrosion of historical stained glass windows [26], Zn protective coatings used in medical equipment [27] and the suitability and durability of an anti-graffiti product for porous materials in monuments and historic buildings [28]. Nevertheless, there are various procedures for studying the many types of solar reflector degradation, mainly focused on the effects of erosion [29] and corrosion [30].

In view of the significant corrosion of the metals in solar reflectors by atmospheric SO_2, the aims of this study were to:

- Examine the behavior of three different types of conventional solar reflectors subjected to a number of accelerated aging tests based on the current Kesternich test methods. Several scenarios were explored, including different temperatures and corrosive gas concentrations at 100% relative humidity.
- Select the most suitable accelerated-aging conditions for solar reflector applications and the best reflector material for high-humidity SO_2-containing atmospheres.
- Compare accelerated aging results with exposure to outdoor industrial environments of industrial interest and establish preliminary correlations between them.

To approach these objectives, three reflector materials were weathered in eight different corrosion tests with a wide range of ambient conditions and several evaluation methods were used to assess their performance. Finally, the acceleration factor in one of the aging experiments was calculated by comparing it to one real outdoor exposure.

2. Material and methods

This section includes a description of the reflector materials studied, the aging tests carried out and the evaluation techniques used to characterize their degradation.

2.1. Reflector materials

Three candidate commercial solar reflectors were selected for the corrosion experiments, two second-surface silvered-glass reflectors (Types 1 and 2) and a first-surface aluminum reflector (Type 3), as described in [31]. Fig. 1 shows a 10 × 10 cm^2 sample of each glass reflector and a 12 × 12 cm^2 sample of the aluminum reflectors. Three replicates were used to ensure representative results of corrosion tests. Type 1 silvered-glass reflector samples were cut from larger commercial parabolic-trough collector (PTC) mirror facets having unprotected edges. The samples were also scratched so that all the protective and reflective layers were penetrated, exposing the metal directly to the corrosive atmosphere. The scratch has already been used in the literature [31] to represent damage that reflectors may already have undergone at a real site due to aggressive external conditions, such as sandstorms [32], careless handling, cleaning procedures [33], etc.

As seen in Fig. 1 left, Type 1 silvered-glass samples are the most unfavorable case of silver exposed to the corrosive environment, because all three have unprotected cut edges and a 2-cm-long scratch in the paint on the back. In contrast, the silver in Type 2 silvered-glass reflectors (Fig. 1 center) is less exposed, since they were specifically manufactured to a 10 × 10 cm^2 format specification with four original, protected edges and no deliberate damage. Therefore, Type 1 reflectors are referred to as predamaged silvered-glass reflectors and Type 2 as undamaged silvered-glass reflectors. Both Type 1 and Type 2 samples were produced by the same commercial silvered-glass reflector manufacturer. Edges are not protected in aluminum reflectors for real applications, and so first-surface aluminum reflectors (Fig. 1 right) include both unprotected edges and a 2-cm scratch on the front, to expose the reflective layer to the corrosive atmosphere. The main features of the reflector materials studied are summarized in Table 1.

2.2. Weathering experiments

An HK 300 M weathering chamber, also known as a Kesternich cabinet (Fig. 2left), was used for the corrosion experiments (Kesternich tests) following the ISO 6988 and DIN 50018 standards [24,25]. The test temperature, T, may be varied from + 5 °C to + 50 °C and the SO_2