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Aging of solar absorber materials under highly concentrated solar fluxes

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ABSTRACT

This article introduces an experimental approach to study the aging of absorber materials used in the receivers of CSP power plants. The term 'aging' is discussed in the case of solar absorber materials and a definition is suggested. A two-layer material (metal + paint coating) that is commonly used in solar tower receivers is studied. Accelerated aging tests are performed on this material with the Solar Accelerated Aging Facility (SAAF) available at PROMES laboratory (Odeillo, France). To evaluate the aging state of the samples after being solar-treated, the thermoradiative and thermophysical properties that characterize the aging of the coating are estimated with two experimental devices. The results show the influence of the mean irradiance, amplitude, period, and exposure time of the radiative cycles on the estimated properties. The absorptance appears to be the most sensitive property causing the thermal performance to decrease. Particular attention should be paid to the application of the paint coating which needs to be vitrified carefully in order to obtain optimal and stable absorption properties.

1. Introduction

To ensure the successful development of CSP (Concentrating Solar Power) systems, scientific efforts need to be pursued to reduce the costs and increase the reliability of future solar power plants. This can be achieved by complementary actions such as increasing the system efficiency, developing innovative concepts that simplify or improve the solar energy conversion, using cheaper materials, and reducing maintenance costs [1]. In particular, two crucial questions need to be addressed toward reaching long term reliability and cost effectiveness: How can we estimate the durability of solar power plants? And how can we extend it? Currently, these two questions cannot be answered accurately and novel methods are required in order to analyze the durability of the key components of solar power plants.

One of the most critical elements in CSP power plants is the receiver. It is exposed to highly concentrated solar fluxes and high temperatures, which are known to be major aging factors. Furthermore, the alternation of day and night and possible cloudy spells may generate brutal solar flux variations causing thermal shocks to the absorber materials. Even though specific materials are developed to meet the strength and efficiency requirements of solar receivers, their thermal performance decreases gradually until a failure time when they are considered not efficient enough and need to be restored or replaced. Studies have been done to assess the durability of solar materials used as thermal panels [2–4] or as heliostats [5,6], but none of these has thoroughly investigated the aging processes of materials in extremely harsh working conditions. Existing accelerated testing standards [7] need to be complemented with new methods that predict the service lifetime of high-temperature solar absorbers.

The type of absorber material which is used in the tube receivers of solar towers such as SOLAR TWO (USA), IVANPAH (USA), and GEMASOLAR (Spain) is an especially interesting candidate because of its strong resistance to both high temperatures and oxidation. The European scientific research project SOLHYCO (Solar-Hybrid Power and Cogeneration Plants) [8] designed to generate a net electrical power of 100 kW uses this kind of material as a solar energy absorber. The SOLHYCO receiver is made of metal tubes coated with an absorbing black paint, allowing an enhancement of the solar absorptance, an improved protection against oxidation and other environmental stresses, as well as easier maintenance procedures (high efficiencies can be maintained on long periods by regularly repainting the receiver). In a previous study of this two-layer material [9], the different aging factors were investigated. Thanks to a numerical model that simulates the thermal behavior of the material, it was possible to highlight the boundary conditions that should be chosen in order to increase the aging factors and therefore accelerate the aging mechanisms. Furthermore, the material properties that affect the aging were identified as the solar absorptance, the thermal

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Nomenclature

A	irradiance amplitude (W m^{-2})
h	convection coefficient (W m^{-2} K^{-1})
T	temperature (K)
R_{tc}	thermal contact resistance (m^2 K W^{-1})
e	thickness (m)
t	time (s)
a	thermal diffusivity (m^2 s^{-1})
b	thermal effusivity (J s$^{-1/2}$ m^{-2} K^{-1})
P	thermal performance (-)

Greek symbols

Φ	flux (W)
φ	irradiance (W m^{-2})
λ	thermal conductivity (W m^{-1} K^{-1})
α	normal solar absorptance (-)
τ	period (s)

Subscripts

i	incident
$front$	front face
$rear$	rear face
amb	ambient
p	paint
m	metal
max	maximum
$mean$	mean
hi	high
lo	low
$loss$	thermal losses
∞	infinite
sl	service life
l	limit
$fluid$	fluid
e	exposure

diffusivity, effusivity, conductivity of the paint coating, and the thermal contact resistance between the coating and the substrate. A Solar Accelerated Aging Facility (SAAF) was built in order to perform accelerated aging tests consisting of constant or periodic solar irradiance treatments. In order to determine the optimal solar treatments that lead to an accelerated aging while remaining consistent with normal aging, the effect of solar radiation on the material was investigated. The aging of the material under constant irradiance solar treatments (first strategy) has been assessed previously [10]. In this work, samples were treated with periodic square variations of the irradiance (second strategy) leading to an enhancement of the aging mechanisms due to variations of temperature and thermal gradients [11]. Depending on the mean irradiance, the amplitude, the period and the exposure time of the radiative cycles, different aging mechanisms may occur at different rates. The most representative material properties in terms of aging were estimated for each sample using two different devices, namely (1) an optical fiber solar reflectometer which was used to estimate the solar absorptance, and (2) an impulse photothermal method, used to estimate the diffusivity, the effusivity of the coating, and the thermal contact resistance between the coating and the metal substrate. The influence of the solar irradiance variations on the evolution of each property was scrutinized.

2. Aging of absorber materials: What criteria?

Aging generally refers to the degradation of given abilities over a certain period of time. For solar absorbers, the most essential abilities are the absorption of solar radiation and the heat transfer to a heat transfer fluid. Furthermore, the mechanical integrity of the materials needs to be ensured. Absorbers are usually made of ceramic or metallic materials. Ceramics are fragile materials and may break at an early stage of their service life (catastrophic failure). Consequently, their mechanical strength is an important aging criterion to take into account. On the other hand, metallic materials are supposed tensile enough to assume that catastrophic failures will not occur. This is why only the thermal performance is taken into account as aging criterion in this particular case. Thus, aging can be defined as the evolution of the thermal performance of a material due to the evolution of its geometrical and thermophysical properties over time. Fig. 1 shows a representation of the heat transfer through an elementary section of an absorber material.

Several expressions of the thermal performance can be defined depending on the specific ability that needs to be qualified or quantified. As we need to characterize the ability of a material to absorb and transfer the maximum amount of heat, we introduced an instantaneous thermal performance $P(t)$ which is defined as the ratio of the heat flux transferred to the fluid through the rear face $\Phi_{rear}(t)$, to the incident solar flux $\Phi_i(t)$ on the front face when the material is working in steady state conditions Eq. (1):

$$P(t) = \frac{\Phi_{rear}(t)}{\Phi_i(t)} \quad (1)$$

$P(t)$ is function of three groups of parameters which may vary over time: the boundary conditions, the geometric parameters, and the material properties. In order to evaluate the thermal performance while avoiding the influence of boundary conditions and transient effects, all the measurements need to be performed with the same boundary conditions (for example standard operating conditions) and in steady state conditions.

The service lifetime of an absorber material can be defined as the length of time t_{sl} during which the thermal performance of the material remains greater than a lower limit P_l Eq. (2):

$$\begin{cases} P(t \le t_{sl}) \ge P_l \\ P(t \ge t_{sl}) \le P_l \end{cases} \quad (2)$$

Thus, a material will be considered 'durable' if its service lifetime t_{sl} is greater than a minimum acceptable service lifetime t_l.

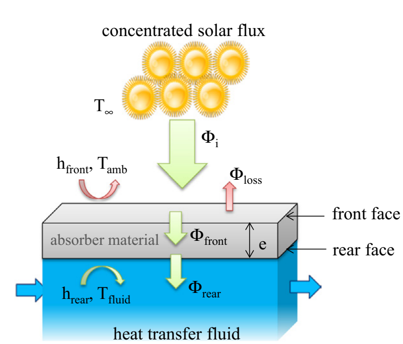

Fig. 1. Heat transfer through a solar absorber material.