Solar Energy Materials & Solar Cells 155 (2016) 253–263

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Experimental study of honeycomb SiCSi under highly concentrated solar flux: Evolution of its thermo-radiative properties

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ARTICLE INFO

Article history:
Received 11 February 2016
Received in revised form
2 June 2016
Accepted 13 June 2016
Available online 20 June 2016

Keywords:
Volumetric solar receiver
SiCSi
Reflectivity
Absorptivity
Ageing
Durability

ABSTRACT

The material that is used in solar receivers is subjected to intense cyclic thermal stresses and extreme temperatures, which are directly dependent on the intermittence of the solar resource. These factors accelerate the ageing mechanisms and reduce the durability of the receivers because of a reduction of their thermal performance.

This study presents guidelines to study the thermo-radiative properties of an absorber material that is subjected to a highly concentrated solar flux. The material was a square honeycomb SiCSi structure that is typically used in volumetric air receivers. Accelerated ageing tests were performed by means of crashing thermal treatments, in which the modulus and period of the incident flux and the boundary conditions of the material were varied.

The reflectivity and absorptivity of the material were experimentally characterized before and after the thermal treatments. The measurements were performed using two different reflectometers, one monochromatic and one in the solar band; the latter can measure at ambient temperature or high temperature that is representative of the operational conditions (400–700 °C). However, only the solar band reflectometer working at high temperature was able to detect the evolution of the thermo-radiative properties of the material, which highlights the important role of the temperature and the wavelength. Furthermore, the thermal treatments in which the samples were water-cooled and in which the solar flux was medial more quickly accelerated the ageing mechanism of the material and reduced its absorptivity.

1. Introduction

Concentrating Solar Power (CSP) is a promising source of clean energy in modern society. While solar energy offers the highest renewable energy potential to our planet, CSP can provide dispatchable power in a technically viable way by means of thermal energy storage and/or hybridization [1]. One of the main challenges of CSP is to reduce the levelized cost of electricity to improve its competitiveness with respect to conventional electricity generation. To achieve this goal, the durability of the materials is a crucial issue for designing reliable systems with high efficiencies and low maintenance costs [2]. Durability is defined as the capability of withstanding repeated use over a relatively long period of time to fulfil the design conditions.

Solar receivers are one of the main subsystems of CSP. They absorb the concentrated solar flux and transfer it to the heat transfer fluid with the greatest possible efficiency. Therefore, the receivers are exposed to highly concentrated solar fluxes, intense thermal stresses and high temperatures, which are known to be the major ageing factors of the materials [3]. From this perspective, specific materials have been developed to fulfil the requirements of solar receivers and maintain their performance over time. However, the early evolution of some of the critical properties of the materials, such the thermo-radiative properties (absorptivity, emissivity) and thermo-physical properties (diffusivity, effusivity), causes the thermal efficiency of the receiver to deteriorate gradually to the failure limit, at which point the efficiency is not sufficient, and the receiver has to be replaced.

The most reliable way to assess the durability of the receiver's material is to test it under real operational conditions over long periods of time. However, this method is expensive and delays the development of technology. Therefore, the idea of performing thermal treatments (TTs) under extreme conditions, which accelerate the ageing of the receiver, has arisen. This method allows large numbers of extreme cycles to be performed over short periods of time, which aids in predicting the evolution of the

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http://dx.doi.org/10.1016/j.solmat.2016.06.032
0927-0248/

Nomenclature

Abbreviations

A	Samples in which the incident flux is intercepted by the sheet side.
B	Samples in which the incident flux is intercepted by the honeycomb face.
BC	Boundary conditions.
CSP	Concentrating solar power.
DISCO	Solar band reflectometer.
DNI	Direct normal irradiance.
nt	Non-treated or raw sample.
REFFO	Monochromatic optical fibre reflectometer.
SAAF	Accelerating age facility.
TT	Thermal treatment.

Symbols

E	Energy per unit surface area [W/m^2].
k	Conductivity [W/m K].
T	Temperature [K].
T_{amb}	Ambient temperature [K].
α	Absorptivity [-].
$\alpha_s^{\perp}$	Normal absorptivity [-].
ε	Emissivity [-].
ϕ_{air}	Absorbed solar flux [W/m^2].
ϕ_i	Incident solar flux [W/m^2].
η_{rec}	Receiver efficiency [-].
$\rho_s^{\perp\cap}$	Hemispherical reflectivity [-].

Subscripts

a	Adiabatic.
i	Isothermal.
s	Steady.
u	Un-steady.
1	Incident solar flux 1000 kW/m^2.
2	Incident solar flux 700 kW/m^2.
3	Incident solar flux 500 kW/m^2.

properties of the materials and their durability.

Few studies have focused on the evolution of the thermo-radiative properties of the materials that are used in high-temperature solar receivers. Carlsson et al. [4] studied the durability and methods to accelerate the ageing of materials that are used in low-temperature solar systems and developed a performance criterion for flat-plate receivers. Rojas-Morín and Fernández-Reche [5] studied the thermal fatigue lifetime of Inconel-625 exposed to high solar radiation. Boubault et al. [2] determined the optimal conditions to accelerate the ageing of a coated two-layer metal using a numerical thermal model that was validated with experimental tests. The results of the optimal tests were published two year later [3]. Capeillère et al. [6] simulated the thermo-mechanical behaviour of a ceramic plate solar receiver, and Fend et al. [7] experimentally determined the thermo-physical properties of porous materials that are used in volumetric receivers. However, the latter two studies were carried out on unexposed materials. Experimental studies of the durability of ceramic solar receivers, such as SiCSi, were not found in the literature.

Therefore, in this study, square honeycomb samples of SiCSi, which are typically used in air volumetric receivers, were thermally treated in a solar-accelerated ageing facility (SAAF) at the PROMES laboratory. The TTs consisted of constant irradiance cycles and periodic square variations of the irradiance, which led to an enhancement of the ageing mechanisms due to variations of the temperature and thermal gradients. To determine the degradation of the SiCSi samples, the normal absorptivity was estimated before and after the TTs and was compared. The normal absorptivity was calculated in three ways using two different devices: 1) a reflectometer of optical fibre (REFFO), 2) an optical fibre solar reflectometer (DISCO) at ambient temperature and 3) a DISCO at a high representative temperature. It was thus possible to determine the importance of the wavelength and temperature in measuring the thermo-radiative properties of the materials. Moreover, the degradation of the material can be studied as a function of the different ageing factors that were tested during the TT.

2. Study material

Over the past few decades, numerous materials have been used in solar receivers. The first receivers were built with standard stainless steels, which resulted in high corrosion and degradation [8]. Hence, a generation of high nickel alloys emerged to solve these problems. However, these high nickel alloys cannot withstand temperatures over 800 °C, so they need to be coated to improve the receiver absorptivity. The most common coating, the black paint *Pyromark*, undergoes high degradation under highly concentrated solar fluxes [9]. Although advanced metals are currently being developed, they all have problems associated with coating degradation. Therefore, the new generation of solar receivers that will be used in Brayton cycles, which reach temperatures up to 1000 °C, must be built with other types of materials, such as ceramic materials.

Ceramic materials have been successfully used in volumetric air receiver applications, such as HiTRec-I, HiTRec-II, Solair-200 and Solair-3000. The main problem of volumetric air receivers is the flow instability. However, in 1996, DLR showed that SiCSi honeycomb absorbers had the best results in terms of the application temperature, thermal shock resistance, and flow stability, which guaranteed a high thermal efficiency of the receivers [10].

SiCSi is used for high performance ceramic devices such as heat-exchangers, seal-rings, valve-discs and ceramic engine parts [11]. Its large field of applications is due to its outstanding properties, including good resistance to oxidation and corrosion, excellent thermal conductivity and high mechanical strength up to 1300 °C. However, at temperatures above 1400 °C, the mechanical properties (e.g., strength and creep) deteriorate due to the existing free silicon content [12]. Furthermore, this ceramic has particular advantages in terms of production and costs because it can be produced at relatively low temperatures. SiCSi is widely used in solar receiver applications due to its properties, which allow using the unspoiled material without a coating. For open volumetric receivers, the SiCSi is typically designed like a honeycomb.

This study analysed a honeycomb SiCSi structure from the company SCHUNCK with an absorptivity of 0.9 [7]. This material is equivalent to those used in the demonstration receiver Solair-3000 (Fig. 1). The main advantage of this honeycomb structure in an open volumetric receiver is that it produces a stable 2D air flow. However, during the receiver operation, hot spots can form and damage the receiver.

The selected honeycomb SiCSi structure is composed of 2 mm × 2 mm square channels with the same depth as that of the