EPJ Web of Conferences **287**, 05017 (2023) https://doi.org/10.1051/epjconf/202328705017
EOSAM 2023

Innovative selective solar absorber for high vacuum flat panel

Daniela De Luca[1,3], Antonio Caldarelli[1,2], Eliana Gaudino[1,2], Paolo Strazzullo[1,2], Marilena Musto[1,2], Umar Farooq[1,3] Emiliano Di Gennaro[1,3], Roberto Russo[1,]*

[1] National Research Council of Italy, Napoli Unit, Institute of Applied Sciences and Intelligent Systems, 80131 Napoli, Italy
[2] Industrial Engineering Department, University of Napoli "Federico II", 80126 Napoli, Italy
[3] Physics Department, University of Napoli "Federico II", 80126 Napoli, Italy

Abstract. Selective Solar Absorbers (SSAs) are the critical element of high-vacuum flat plate collectors, as these are subject to elevated operating temperatures and thus experience high radiation losses. Here we design and optimize an SSA based on a multilayer design made of HfC_x, Si_3N_4, and SiO_2 layers. The structure of the proposed SSA has been optimized to maximize the solar-to-thermal energy conversion efficiency in high vacuum solar thermal panels working at 200 °C, reaching thermal emissivity values much lower than absorbers currently available on the market (<0.02 Vs >0.07) and obtaining unprecedented performances.

The potential of solar energy to meet thermal and electrical energy demand worldwide is high. However, nowadays, a considerable percentage of heat and electricity still comes from non-renewable sources, contributing heavily to global CO_2 emissions and the increasingly relentless climate change we face daily [1].
Annually, 74% of the final energy consumption in industries is used for heat generation, and more than half of it is used for processes up to 400 °C. Thus, high vacuum flat plate collectors (HVFPs) are ideally suited: the high vacuum insulation eliminates both convective and conductive losses, guaranteeing good performance even at elevated temperatures (i.e., much higher than the canonical 80 °C reached with conventional flat plate collectors). However, at high temperatures, radiation losses become massive. Hence, absorber plates with selective properties must be considered. Ideally, these Selective Solar Absorbers (SSAs) have the maximum absorptance in the solar spectral region while zero emittance above a specific cut-off wavelength, which depends on the operating temperature [2].
Several designs of SSA have been investigated in the past years [3], including cermets, nanomaterials, photonic crystals, etc. Here, we focus on multilayer design, as it also satisfies the requirement of an easy fabrication for large-scale production. Typically, multilayer designs are based on Dielectric/Metal/Dielectric structures, and the metal layer absorbs most of the solar energy available. Hence, we propose a new SSA design made exclusively of dielectric and insulating materials: HfC, Si_3N_4, and SiO_2. The structure is shown in Fig. 1: these materials were chosen because they are characterized by high melting point and good thermal stability (especially HfC with a melting point > 3600 °C), and they can easily be included in the design and fabrication of optical structures for applications that require high operating temperatures, such as in thermo-photovoltaic and solar thermal devices, as well as in thermal energy grid storage.

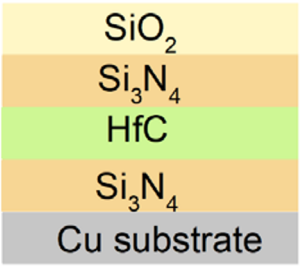

Fig. 1: Schematic representation of the multi-layered SSA.

The most useful quantities to evaluate the performance of an SSA are the solar absorptance and thermal emittance, defined as follows:

$$\alpha = \frac{\int_0^\infty [1-\rho(\lambda)]\cdot S(\lambda)d\lambda}{\int_0^\infty S(\lambda)d\lambda} \quad (1)$$

$$\varepsilon(T) = \frac{\int_0^\infty [1-\rho(\lambda)]\cdot E_{BB}(\lambda,T)d\lambda}{\int_0^\infty E_{BB}(\lambda,T)d\lambda} \quad (2)$$

where $\rho(\lambda)$ is the reflectivity spectra of the SSA, $S(\lambda)$ and $E_{bb}(\lambda,T)$ are the solar radiation spectrum and the blackbody radiation spectrum, respectively, depending on the radiation wavelength λ and temperature T.
Note that, according to Kirchhoff's law of thermal radiation [4,5] and the principle of conservation of energy, the emissivity of an opaque object at thermal equilibrium satisfies the following relation:

$$\varepsilon(\lambda) = \alpha(\lambda) = 1 - \rho(\lambda). \quad (3)$$

* Corresponding author: roberto.russo@na.isasi.cnr.it

Thus, thermal emittance and solar absorptance can be easily evaluated from the reflectivity spectra of the SSA.

Since the performance of multilayer-based absorbers is strongly related to the thickness of each layer, by using an optimization procedure based on a genetic algorithm [6], we optimized the design of SSA in Fig. 1 for a working temperature of 200 °C.
The algorithm is based on the transfer matrix method and relay on the experimentally measured refractive index of the materials constituting the multilayers (HfC [7], Si_3N_4 [8]) or on literature data that have been verified to be experimentally consistent with our materials (SiO_2 [9] and Cu [10]). After calculating the SSA reflectance ρ(λ) at each wavelength, it allows the evaluation of the solar absorptance α and thermal emittance ε(T) as defined by Eqs. (1) and (2), respectively. The values of α and ε(T) are then used to calculate the SSA solar energy conversion efficiency at different operating temperatures:

$$\eta(T) = \alpha_S - \frac{\varepsilon(T)\sigma(T^4 - T_{amb}^4)}{H} \qquad (4)$$

T_{amb} (K) is the ambient temperature, H_{abs} (Wm^{-2}) the Sun irradiated power, and σ ($Wm^{-2}K^{-4}$) the Stefan-Boltzmann constant. The main results are reported in Fig. 2.

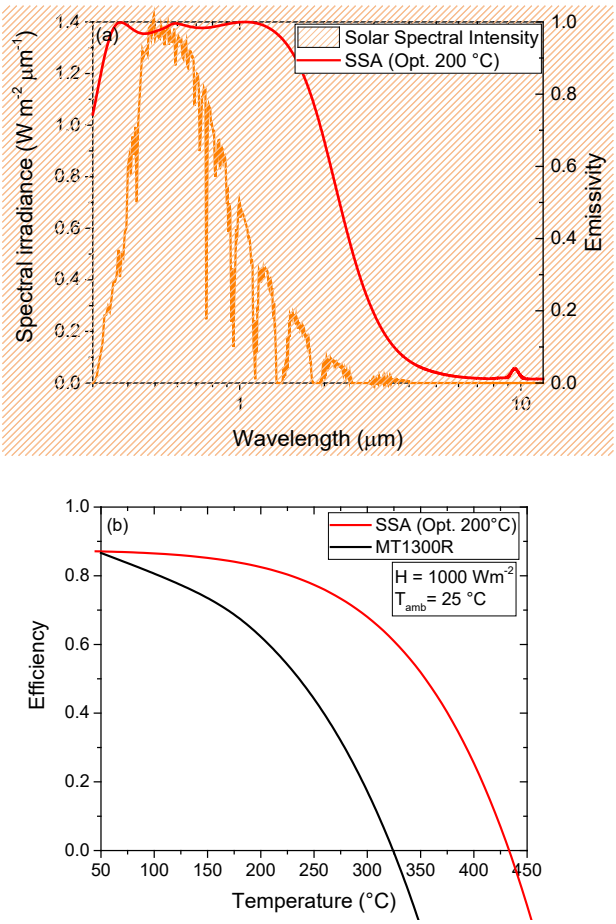

Fig. 2: (a) Left axis: Solar spectral irradiance at the Earth's surface (orange filled area); right axis: simulated spectral emissivity of the designed SSA, optimized at 200 °C (red line). (b) Temperature-dependent efficiency of the proposed SSA compared with that of the commercial SSA installed in the high vacuum flat panel.

Overall, the proposed SSA show an excellent selectivity, with high solar absorptance (α=0.95) and very low thermal emittance, that guarantee efficiencies higher than 50% even at medium temperatures (up to 300 °C) and high stagnation temperatures (> 400 °C). These values are considerably improved compared to the performance of the SSA installed in the HVFP collectors currently on the market. They could extend the use of unconcentrated solar collectors at temperatures higher than 180 °C.

References

1. Energy, BP - Statistical Review of World. Available: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.
2. Ning, Y. Et al. Sol. Energy Mater. Sol. Cells 206, 110219 (2020).
3. P. Bermel et al. Annual Review of Heat Transfer 15, 231–254 (2012)
4. D. W. B. Brace, et al. The Laws of Radiation and Absorption: Memoirs by Prevost, Stewart, Kirchhoff, and Kirchhoff and Bunsen, 1901
5. R. Siegel, J. R. Howell, Thermal Radiation Heat Transfer, Hemisphere Publishing Corporation, 1981
6. D. De Maio et al. Solar Energy Materials & Solar Cells. 242, 111749 (2022)
7. D. De Luca et al. Solar Energy Materials & Solar Cells 255, 112304 (2023)
8. D. De Luca et al. Thin Solid Films 737, 138951 (2021).
9. J. Kischkat et al. Applied Optics 51, 6789-6798 (2012)
10. M. R. Querry. Optical constants, Contractor Report CRDC-CR-85034 (1985)