Enhancing the solar-to-thermal energy conversion in high vacuum flat plate solar collectors

Roberto Russo[1,*], *Davide* De Maio[1,2,#], *Carmine* D'Alessandro[1,2,#], *Daniela* De Luca[1,3], *Antonio* Caldarelli[1,2], *Eliana* Gaudino[1,2], *Marilena* Musto[2,1], *Emiliano* Di Gennaro[3,1]

[1]Consiglio Nazionale delle Ricerche, Istituto di Scienze Applicate e Sistemi Intelligenti, 80131 Napoli, Italy
[2]Deparment of Industrial Engineering, Università degli Studi di Napoli "Federico II", 80125 Napoli, Italy
[3]Department of Physics, Università degli Studi di Napoli "Federico II", 80125 Napoli, Italy
[#] Present Address: TVP Solar SA, 10 rue du Pré-de-la-Fontaine ZIMEYSA 1242 Satigny (GE), Switzerland

Abstract. In solar flat plate collectors, the high vacuum insulation suppresses the convective losses increasing the collector efficiency. The solar-to-thermal energy conversion efficiency in such solar thermal collectors is mainly defined by the optical and radiation losses of the selective solar absorber. We present the full process of design, optimization, fabrication, and characterization of multilayer coatings specifically thought for working in high vacuum flat solar thermal collectors at different operating temperatures, from 100 °C to 300 °C. We discuss the relative importance of absorptance and emittance in determining the collector thermal efficiency. The robustness of the performance of the coatings related to the unpreventable errors in layer thickness during the manufacturing stage is also considered through a genetic optimisation algorithm.

Exploiting renewable energies such as solar, wind, waves, hydropower, etc., could open a path towards a cleaner world, through the mitigation of the greenhouse gases in the atmosphere.
Solar energy is by far the most abundant source of renewable energy [1]: despite about half of the solar radiation being either absorbed or reflected by the clouds and the atmosphere, the Earth's surface still receives enough power to meet the demands of the whole world [2,3].
Among the different types of solar energy collectors, the high vacuum flat plates (HVFPs) present clear advantages. The high vacuum insulation reduces to zero the convective and conductive losses, guaranteeing the best performance at low and medium temperature operation. In such collectors, the maximum operating temperature and the efficiency are limited by the thermal radiation losses.
The core component of HVFP collectors is the Selective Solar Absorber (SSA): ideally, its spectral absorptivity $\alpha(\lambda)$/emissivity $\varepsilon(\lambda)$[a] can be defined as follows:

$$\alpha(\lambda) = \begin{cases} 1 & if\ \lambda \leq \lambda_c \\ 0 & if\ \lambda > \lambda_c \end{cases} \tag{1}$$

where λ_c is the wavelength that maximizes the absorber thermal performance and it depends on the working temperature and the solar incoming power [4].

The solar absorptance α_S and thermal emittance $\varepsilon(T)$ can be evaluated from the reflectivity spectra $\rho(\lambda)$ of the multilayer solar absorbers using Eqs. (1) and (2), respectively [5]:

$$\alpha_S = \frac{\int_{0\,\mu m}^{\infty\,\mu m}[1-\rho(\lambda)]S(\lambda)d\lambda}{\int_{0\,\mu m}^{\infty\,\mu m} S(\lambda)d\lambda} \tag{2}$$

$$\varepsilon(T) = \frac{\int_0^{\infty}[1-\rho(\lambda)]E_{bb}(\lambda,T)d\lambda}{\int_0^{\infty} E_{bb}(\lambda,T)d\lambda} \tag{3}$$

where $S(\lambda)$ 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.

Among all the possible designs investigated [6] (cermets, nano and metamaterials, photonic crystals, etc.) selective absorbers based on multilayer allow controlling the thermal emission while ensuring excellent thermal stability and high solar absorption[7]. Indeed, the low emissivity substrate is responsible for the low emittance and the absorption of the solar radiation is guaranteed from the multiple reflections at the interfaces between the layers composing the multilayer.
Multilayers also satisfy the requirement of an easy fabrication for large-scale production in roll-to-roll systems, however, the performance of multilayer-based

[a] According to the Kirchhoff's law of thermal radiation, for any object in thermal equilibrium $\alpha(\lambda) = \varepsilon(\lambda)$.

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

absorbers can be strongly affected by the thickness variation of the various layers. Such variations can be difficult to avoid at the industrial level and one must take into consideration the robustness of the performance of the coating for unpredicted errors in the thickness of the various layers.
In this work, we present different multilayer selective absorbers based on SiO_2, Cr_2O_3, and Cr, sputter-deposited on a low emissive copper substrate. Those are optimized for different working temperatures, from 100 °C to 300 °C.
To assess which is the thickness package that ensures the highest performance and proper robustness for given errors in layer thickness, a fast and reliable genetic algorithm for the optimization of the coating, particularly for emerging HVFPC technology, has been developed in MATLAB. The code is based on the transfer matrix method and relay on the experimentally measured refractive index of the materials constituting the multilayers[8].
To optimize the absorber properties, the algorithm calculates the reflectance $\rho(\lambda)$ of the stack at each wavelength, allowing the evaluation of the solar absorptance α_S and thermal emittance $\varepsilon(T)$ according to Eqs. (1) and (2), respectively. The values of α_S and $\varepsilon(T)$ are then used to calculate the coating solar energy conversion efficiency according to the equation:

$$\eta_{coat} = \alpha_S - \frac{\varepsilon(T)\,\sigma_{SB}(T^4 - T_{amb}^4)}{H_{abs}}$$

and the coating efficiency η_{coat} is maximized at different operating temperatures (T_{amb}(K) is the environmental temperature, H_{abs} (Wm-2) the Sun irradiated power, and σ_{SB} ($Wm^{-2}K^{-4}$) the Stefan-Boltzmann constant). At a given operating temperature the maximum efficiency can be obtained using different combinations of α_S and $\varepsilon(T)$ resulting from different layer thicknesses arrangements.
The numerical solutions are then tested against layer thickness variations and the most stable solution is retained.
Figure 1 shows the results of the simulated reflectivity and thermal emittance of the three selective solar absorbers.

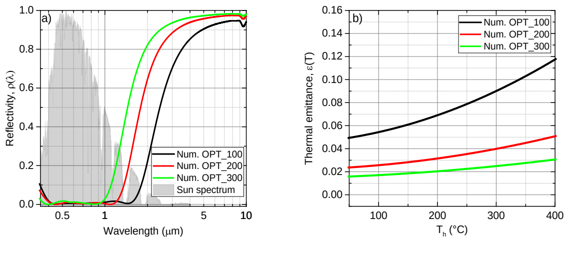

Fig. 1: Optical simulations. (a) Spectral reflectivity of three coatings optimized for a target temperature of 100 °C, 200 °C, and 300 °C (black, red, and green curve, respectively). Normalized Sun spectrum, grey filled area. (b) Temperature-dependent thermal emittance of three coatings optimized for a target temperature of 100 °C, 200 °C, and 300 °C (black, red, and green curves, respectively).

Multilayers have been deposited by a multi-target magnetron sputtering system and their optical and radiative properties were measured in a custom set-up [9]. The experimental reflectivity curves are in agreement with simulated ones and the thermal stability test indicates that the produced multilayer can safely work up to 300°C.

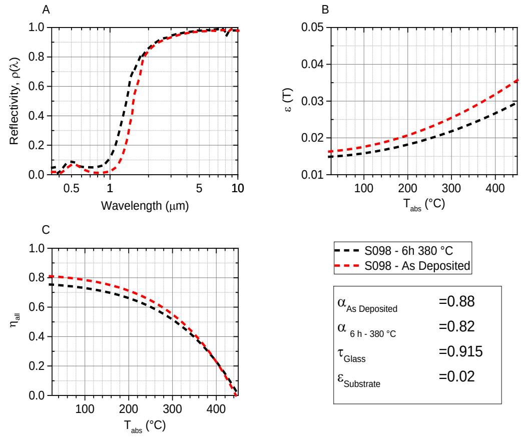

Fig. 2: Measured spectral reflectance of solar selective coating optimized to work at 300 °C before and after heating in vacuum at 380 °C for 6 hours. The

The obtained results indicate that multilayers are an excellent solution to achieving high efficiency with good thermal stability in HVFP collectors, contributing to the desired renewable energy transition.

References

1. R. Perez and M. Perez. “A fundamental look at energy reserves for the planet.”
2. C. Lauterbach et al. Renewable and Sustainable Energy Reviews **16**, 5121–5130 (2012).
3. A. Shahsavari and M. Akbari. Renewable and Sustainable Energy Reviews **90,** 275–291 (2018).
4. Ning, Y. Et al. Sol. Energy Mater. Sol. Cells **206**, 110219 (2020).
5. Forouhi, A.R.; Bloomer, I. Phys. Rev. B **34**, 7018–7026 (1986).
6. P. Bermel et al. Annual Review of Heat Transfer **15**, 231–254 (2012)
7. D. De Maio et al. Energies **14**, 900 (2021)
8. D. De Maio et al. Solar Energy Materials and Solar Cells. **242**, 111749 (2022).
9. R. Russo R, M. Monti, F. di Giamberardino, V.G.Palmieri, Opt. Express **26**, A480 (2018).