Solar Energy Materials and Solar Cells 170 (2017) 102–113

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

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

Design of high-temperature solar-selective coatings for application in solar collectors

Dimitris V. Bellas*, Elefterios Lidorikis

Department of Materials Science and Engineering, University of Ioannina, Ioannina 45110, Greece

ARTICLE INFO

Keywords:
Concentrated solar collectors
Finite-difference time-domain
Energy conversion efficiency
Metal-dielectric absorbers
Spectrally selective filters
Surface texturing

ABSTRACT

We present a comprehensive theoretical design and evaluation study for the performance of nano-composite metal-dielectric absorbers combined with selective filters for high temperature applications in high concentration solar energy harvesting, e.g. in parabolic trough collectors. Improving the spectrally selective coating of the receiver and optimizing the operating temperature above the current standard of 400 °C represent a good opportunity for improving the efficiency of solar collectors and thus reducing the cost of solar electricity. The objective of our effort is to get the design rules for efficient selective coatings in higher temperatures exhibiting maximum absorption in the solar spectrum and minimum emissivity in the infrared spectrum. While these optical characteristics are the required ones for maximum energy conversion efficiency, they become increasingly difficult to satisfy for increasing temperatures because of the overlapping of the two spectral regions. Using finite-difference time-domain simulations we model different nano-composite metal-dielectric coatings, composed of materials that are stable at high temperatures, combined with spectrally selective filters and calculate the solar absorption and thermal emission coefficients. Taking also into account the optical parameters of the collector structure (sunlight concentration factor and optical losses) and the theoretically predicted Carnot efficiency, we get the total conversion efficiency of a solar collector. We evaluate the performance of the designed coatings for a wide temperature range from 400 °C up to 1000 °C and obtain maximum efficiencies at ~850 °C operating temperature. For our best coating candidate (Cu nanoparticles in a low index dielectric matrix, e.g. SiO_2) this results into a total conversion efficiency of 52%, or about a 30% performance increase compared to operation at 400 °C.

1. Introduction

Solar electricity has seen a large capacity increase in the last decade, and still has a long way to go given that it still only accounts for a small percentage (~1%) of the word's power consumption [1,2]. There are two mainstream technologies utilized for this purpose, photovoltaics (PV) and Concentrated Solar Power (CSP). The first involves the use of solar cells to generate electricity directly via the photovoltaic effect. The latter captures the solar thermal energy as heat by using mirrors or lenses to redirect and concentrate the solar flux onto a receiver, to generate steam that is used to power up a turbine or a heat engine and generate electricity. Currently CSP systems only constitute a mere ~3% of total solar electricity installations, but are seeing a large growth given their large overall efficiencies (> 30%) [3] and their potential for 24 h electricity production when combined with efficient heat storage [4]. In this work we will concentrate on the CSP technology [5–9].

Sun-tracking concentrating collectors utilize optical elements to focus large amounts of radiation onto a small receiving area and follow the sun throughout its daily course to maintain the maximum solar flux in their focus. Single axis tracking systems consist of parabolic trough collectors, cylindrical trough collectors and linear Fresnel reflectors, whereas, two axis tracking systems consist of central tower receiver, parabolic dish reflector and circular Fresnel lens. In CSP systems the receiver is located at the focal line or focal point of the reflectors, and consists of an absorbing medium that converts the sun's rays into heat. A special heat-transfer fluid pumped through the absorber tube gets heated to about 400 °C [6,7] and is used to generate steam which turns the engines that generate electricity. The receiver tube is vacuum sealed inside a bigger glass tube so to minimize thermal conduction and convection loses. The absorbing receiver is coated with solar selective coatings designed to have high values for solar absorbance and low values of thermal emissivity in the infrared. Clearly the absorber and its coatings must be chemically and structurally stable over the entire operating temperature range of the concentrating solar system. The design of solar selective coatings [5] is complicated because absorbance and emittance are temperature and wavelength depended and strongly

* Corresponding author.
E-mail address: dbellas@cc.uoi.gr (D.V. Bellas).

http://dx.doi.org/10.1016/j.solmat.2017.05.056
Received 8 February 2017; Received in revised form 22 April 2017; Accepted 24 May 2017
Available online 03 June 2017
0927-0248/

affected by the micro-structure [10,11]. In addition, there must be a compromise, because as the operating temperature increases, the spectral regions of thermal emission start overlapping with the spectral region of sunlight (300–2500 nm).

Solar selective coatings have been fabricated and categorized into a number of different types [12–14] including: i) intrinsic [15], ii) semiconductor-metal [16,17], iii) multi-layer [18,19] vi) cermets or metallic composite materials [20–26], and finally v) textured surfaces [10,27–30]. Here, we focus on the computational design and optical optimization of a nano-composite (NC) metal-dielectric coating for high temperature application in high concentration collectors. These composites consist of metallic nano-particles (NPs) or nano-wires (NWs) in a dielectric matrix. We explore different dielectric matrices and metals, various metal-to-dielectric volume ratios and different kinds of nano-texturing on their surface in order to maximize the total solar harvesting efficiency. The investigated nano-composites are combination of categories (vi) and (v) above. The metal-dielectric composites known as cermets are of special theoretical [31–35] and experimental [36] interest because their high stability makes them particularly suitable for high-temperature applications in photo-thermal solar energy conversion. Increasing the operating temperature above the current limits of 400 °C for parabolic trough collectors [37] and 600 °C for central tower receiver [38] can improve power cycle efficiency and reduce the cost of solar electricity [39].

Many materials have been studied and optimized as candidates for spectral selective coatings. Chester et al. [31] reported a heating efficiency (absorption minus thermal emission) of 84.3% for a four layer silica-tungsten cermet (W NPs in a SiO_2 matrix) at 400 K with unconcentrated sunlight, and a heating efficiency of 75.59% for 1000 K at 100 suns concentrator. Similar heating efficiencies have been reported from Sakurai et al. [32] for a three layer silica-tungsten cermet: 82.7% (400 K), 85.91% (700 K), and 76.63% (1000 K) for solar concentrators 1, 50 and 100 suns respectively. Tungsten had also been studied from Zhang et al. [33] but in a different aluminum oxinitride (AlON) matrix, where they report a maximum 85% heating efficiency at 350 °C under a concentration of 30 suns (different antireflection coatings and IR reflector metal substrates had been examined). Nejati et al. [34] had investigated the novel case of two-layer composite structure, with metal (Au, Cu or Steel) and ceramic (Al_2O_3 or SiO_2) components. The calculated results are within the range of 91–97% for solar absorbance and 2–7% for thermal emission at room temperature. Finally, Farooq and Hutchins [35] studied the performance of various materials such Ni, W, V, Co, Cr inclusions in a SiO_2 and Al_2O_3 matrix. Solar absorbance of 98% and 96% was achieved by simulation and experimental findings with less than 7% thermal emission at 300 K for a four-layer system of V:Al_2O_3. Other designs showed lower optical performance for all the material combinations. Common evidence from all the above theoretical works is that gradually changing the concentration of the metal particles from a low metal particle density at the air/cermet interface to high metal particle density at the cermet/substrate interface improves the spectral selectivity of the coatings. However, a comprehensive study taking simultaneously into account all material combinations, surface roughness, substrate, spectral filters, solar concentration and operating temperature, coupled with the Carnot efficiency in order to get the global optimal design for solar-to-electricity conversion, is still missing.

We consider different transparent matrices starting from a high dielectric constant of ~7 (e.g. SiC) down to low dielectric constant of ~2 (e.g. SiO_2). For the inclusions we have considered many different metals like Cu, Ag, Cr, W, V and Ni. Based on their performance they are separated into two groups and so we choose two high melting point metals: Ni, a characteristic transition metal (1455 °C) known for high absorption, and Cu, a characteristic noble metal (1085 °C) known for high reflectance when it is a flat film and for localized surface plasmon resonances (LSPR) [40–42] when it is nanostructured. In Fig. 1 we plot the spectral absorption of bulk Cu and its NC (Cu NPs in SiC matrix) for flat and nano-textured (rough) surfaces, showing the superior absorption of rough NC. In the following we will evaluate how each component of the NC coating affects the spectrally selective performance. That is, we will explore various NCs for different: a) metal-to-dielectric volume ratio, b) nano–inclusions, i.e. NPs or NWs c) type of surface roughness (shape and height) d) thicknesses of un-roughed film e) type of substrate (flat or rough). This evaluation will be made not only in terms of photo-thermal efficiency as previous theoretical works [31–33], but also in terms of heat to work efficiency as predicted from the Carnot efficiency [43], over a wide range of operating temperatures (400–1000 °C) and concentration ratios (80–500 suns) to get the maximum theoretical energy conversion efficiency. Finally, we will work on the external glass envelope and study how special coatings on the glass like transparent conductive oxides (e.g ITO) can improve the overall efficiency by working as selective spectral filters.

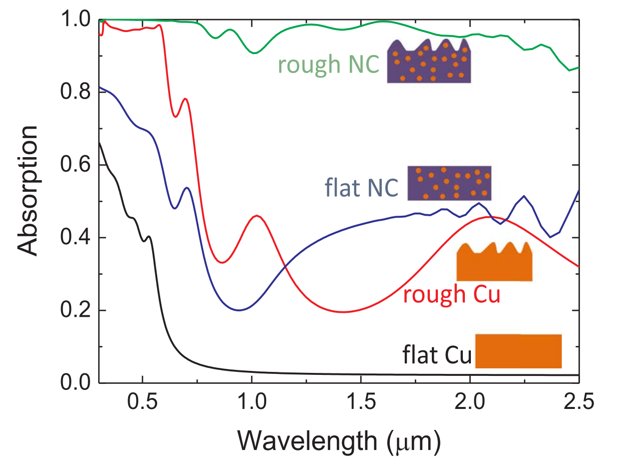

Fig. 1. Spectral absorption profiles of bulk Cu for flat and nano-textured (rough) surfaces and the corresponding nano-composites (Cu NPs inside a SiC dielectric matrix) for flat and bulk surfaces.

2. Methodology

2.1. Optical Properties

We use the finite difference time domain (FDTD) method, where Maxwell's equations are time-integrated on a computational grid [44–46]:

$$\nabla \times \mathbf{E} = -\mu \partial_t \mathbf{H} \tag{1}$$

$$\nabla \times \mathbf{H} = \varepsilon_0 \varepsilon_\infty \partial_t \mathbf{E} + \partial_t \mathbf{P}_0 + \sum_{j=1}^{N} \partial_t \mathbf{P}_j \tag{2}$$

Material polarization is taken into account through polarizabilities P

$$\partial_t^2 \mathbf{P}_0 + \tau^{-1} \partial_t \mathbf{P}_0 = \omega_p^2 \varepsilon_0 \mathbf{E} \tag{3}$$

$$\partial_t^2 \mathbf{P}_j + \Gamma_j \partial_t \mathbf{P}_j + \Omega_j^2 \mathbf{P}_j = \Delta\varepsilon_j \Omega_j^2 \varepsilon_0 \mathbf{E} \tag{4}$$

yielding a Drude-Lorentz model for the dielectric function

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\tau^{-1}} + \sum_{j=1}^{N} \frac{\Delta\varepsilon_j \Omega_j^2}{\Omega_j^2 - \omega^2 - i\omega\Gamma_j} \tag{5}$$

where the first term is the Drude free-electron contribution (intraband transitions) and the second contains Lorentz oscillators corresponding to interband transitions. ω_p and τ are the free electron plasma frequency and relaxation time, Ω_j, $\Delta\varepsilon_j$, and Γ_j are transition frequency, oscillator strength, and decay rate for the Lorentz terms. To accurately reproduce the experimental dielectric functions in the 300 nm to 40 μm regime, we treat these as fit parameters. The optical properties for Cu have been extracted from Ref. [47–49] and for Ni from Ref. [47,50] and fitted to a