High-temperature stable spinel nanocomposite solar selective absorber coating for concentrated solar thermal application

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Abstract

A new Cu-Ni-Co ternary spinel/SiO_2 nanocomposite oxide absorber with tandem layer approach is designed and developed for medium and high temperature solar selective receiver tube in concentrated solar thermal applications. The base absorber layer, developed by combining of nanostructured, transition metal spinel and composite oxides with a series of transition metal based salts (Co, Ni, and Cu) in wet chemical method. By optimizing the sol concentration, withdrawal speed and annealing temperature, uniform absorber layer with solar absorptance (α) of 0.91 and emittance (ε) of 0.14 were achieved in a single layer coating with a composite oxide formation. On top of the base absorber layer, coating integrated with silica (SiO_2) nanoparticles added as an optical enhancement layer to make the coating more selective (α: 0.95 & ε: 0.13). A thorough characterization has been done for the optical and physiochemical properties of the samples. Besides, the optimized spinel coating exhibits a low radiative loss of about 0.18 thermal emissivity at 500 °C and 89.3 % photothermal conversion efficiency at 500 °C, which identifies that the spinels are a very good candidate for medium and high temperature solar selective absorbers.

Keywords: Tandem absorber layer, Cu-Ni-Co spinel oxide, optical enhancement layer, selective solar absorber

1. Introduction

Out of all renewable energy sources, solar energy conversion techniques are affordable, accessible and sustainable with eco-friendly nature. Among the various solar energy conversion techniques, mainly two approaches like solar photovoltaics (PV) and concentrated solar thermal power (CSP) got popularized throughout the world. Solar PV is a one-step process to convert solar radiation into electricity, whereas the CSP system is a two-step process, conversion of solar radiation to heat and then to electrical energy by using different components. Here, out of these two techniques, solar PV has got maturity in terms of efficiency and economics, but the CSP technologies have not yet attained the economics even after attaining the good efficiency values for electricity generation (IRENA, 2018). The gap in the CSP system is because of the complexity and the components (like concentrators, receiver tubes, optical tracking systems and heat engines etc.) involved in the system lead to high cost. However, Concentrated Solar Thermal (CST) has attracted a substantial renewed interest from past one decade due to its diversity and compatibility in various applications like industrial process heating and space cooling (Settino et al., 2018).

In CST, one of the important components of the system is a receiver tube, where the researchers are more focusing on this component from past so-many decades to design a collector with maximum solar energy conversion efficiency (Moon et al., 2014). The cost-effective receiver tube and selective properties of absorber coating will make the CST system more efficient and economic. Here, the major role of solar receiver tube is to absorb all incoming solar radiations in the wavelength region of 0.3 to 2.5 µm and converts them into thermal energy. The photothermal conversion efficiency (Bogaerts and Lampert, 1983) of solar receiver tube majorly depends upon the solar absorber coating type. Therefore, the coating in the solar receiver tube should be selective absorber coating (Granqvist, 1985). That means the coating should absorb all the incoming solar radiation and should not emit heat radiations. These properties like absorptance (α) and emittance (ε) can be measured at different wavelength regions depending upon the transition wavelength of the CST operating temperature. Solar absorptance (α) can be evaluated by the following equation 1

$$\alpha = \frac{\int_{\lambda 1}^{\lambda 2} (1-R(\lambda)) I_S \, d\lambda}{\int_{\lambda 1}^{\lambda 2} I(\lambda) d\lambda} \qquad \text{(eq. 1)}$$

where Is is the solar radiation intensity (AM 1.5, ASTM G173-03, ISO) and R represents the total reflectance of the sample. Spectral emittance (ε (λ, T)) can be characterized by using Kirchhoff's law in the infrared region (2.5 to 25 µm) for an opaque substance from equation 2

$$\varepsilon(\lambda, T) = 1 - R(\lambda, T) \qquad \text{(eq. 2)}$$

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The photothermal conversion efficiency (η) of Solar Selective Absorber Coating (SSAC) at a particular working temperature T can be calculated as in equation 3

$$\eta_T = \alpha - \frac{\varepsilon_T \sigma T^4}{CI} \qquad \text{(eq. 3)}$$

where σ, is the Stefan-Boltzmann constant ($5.67X10^{-8}$ $Wm^{-2}K^{-4}$), C denotes the concentration factor (parabolic trough C = 80) and I denotes solar intensity of radiation. To improve η, the SSAC should attain a maximum solar absorptance (α = 1) in the solar spectrum range and maintain a minimal thermal emittance (ε = 0) in the infrared region (Bogaerts and Lampert, 1983).

In order to get high absorptance and low thermal emittance for SSACs, different design of coatings like semiconductor, textured surface, composite metal-dielectric and multilayer tandem etc. are available (Kennedy, 2002). These coatings can be deposited by different techniques like vapour deposition, wet chemical, oxidation and spray pyrolysis, etc. (Selvakumar and Barshilia, 2012). Conventionally, most of the commercially available receiver tubes are comprised of coatings developed by an expensive route of vapour deposition and a sputtering process. In view of the above, herein, we reported a novel tandem absorber coating system with high selectivity by wet chemical method in a spinel matrix for cost effective receiver tube in CST application.

2. Experimental

To get high photothermal conversion efficiency, we have designed a double layer tandem absorber (Fig. 1), namely base absorber layer (spinel composite oxide) and an optical enhancement layer (Zou et al., 2015). The wet-chemical based ternary metal (Ni, Cu and Co) spinel absorber has been prepared as reported in elsewhere (Atchuta et al., 2019) by dip coating method. Here, we have achieved optical properties of α: 91% and ε: 14% for the ternary metal based spinel ($Cu_xNi_yCo_{z-x-y}O4$) absorber in a single layer deposition. Further, to improve the optical properties of optimized spinel absorber layer, an optical enhancement layer using 2 wt% SiO_2 nanoparticles Sol on top of the base absorber layer has been added with the help of dip coater and then films were cured at 300 °C temperature.

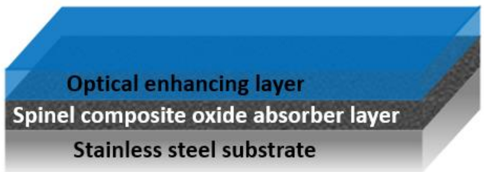

Fig. 1: Schematic of tandem solar selective absorber layer

UV-Vis-NIR spectrophotometer was used to measure the total absorptance of the absorber layers using the weight average calculation of Eq. 1. The total reflectance values were obtained from diffuse reflectance accessory with 110 mm dia integrating sphere of Cary Varian Model 5000. Polytetrafluoroethylene coated disc was used as a reference plate and the measurements were done at room temperature in the region of 300-2400 nm with a scanning speed of 600 nm/min. The spectral emittance measurement in the infrared wavelength region (2.5–25 µm with a scanning velocity of 2.5 kHz) was carried out by a Bruker Vertex 70 Fourier Transform Infra-Red (FTIR) spectrometer equipped with a standard integrating sphere using an evaporated gold mirror as a reference plate. Thermal emissivity measurements were also carried out at different temperatures from 100 to 500 °C using an FTIR instrument (Bruker, VERTEX70) attached with high-temperature cell and blackbody source. Here, the measurements are carried out by switching off the IR source and heated the sample in a temperature cell and blackbody for a particular temperature. The emission from a blackbody and the sample at a particular temperature was collected separately and calculated the emissivity by dividing the sample emission with the blackbody emission for that particular temperature. The photothermal conversion efficiency of an absorber coating was calculated by assuming that the only loss is radiation from the absorber surface (thermal emissivity) at that particular temperature by using the equation 3.

3. Results and Discussion

3.1 Optical properties and radiative loss of coatings

The optimized reflectance spectra of combined UV-Vis-NIR and FT-IR ternary metal based spinels ($Cu_xNi_yCo_{z-x-y}O_4$) with single and tandem layer approach of coatings as explained in the experimental are compared with AM1.5 and Ideal emittance spectra in Fig. 2(a). The effect of tandem layer approach on the base absorber layers by using SiO_2 layer and their optical properties enhancement are reported in the Table 1.

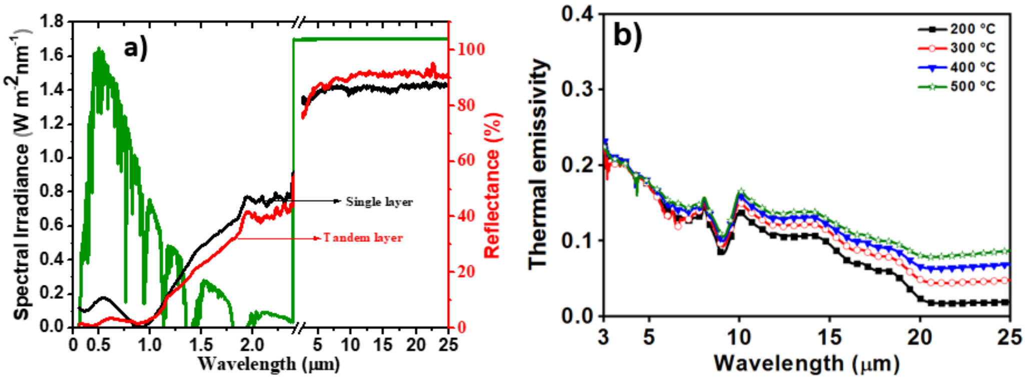

Fig. 2: a) The combined UV-Vis-NIR and FT-IR spectra of the optimized single and tandem absorber layer coatings with ternary metal base spinels compared with standard solar AM1.5 spectrum and ideal emissivity; b) thermal emissivity of the best optimized tandem SSAC at different temperatures.

Tab. 1: Solar absorptance and emittance data of the best-optimized base absorber layer and tandem absorber layer

Layer	Absorptance (AM1.5) α	Emittance ε
Base absorber layer	0.91	0.14
Base absorber + optical enhancement layer	0.95	0.13

To calculate the photothermal conversion efficiency of the optimized tandem absorber coating, one need to have known about the radiative loss of the coating at that particular temperature. For this, as mentioned in the experimental by using the FT-IR with blackbody and temperature cell, the sample and blackbody heated at a particular temperature and measured the emission spectra over a range of 2.5–25 μm wavelength region. The collected data has been processed for the thermal emissivity (Fig. 2(b)) calculation, which is the ratio of sample and blackbody radiative emission at that particular temperature. The measured data for different type of absorber layers over a wide range of temperature from 200 to 500° C with an interval of 100 has been noted in the Table 2. The value of ε (500 °C) has been suppressed as low as 0.18 and the value of α reached to 0.95 with the tandem absorber layer coating.

Tab. 2: The thermal emissivity values of optimized tandem absorber layer at different temperatures

Temperature (°C)	Thermal emissivity of absorber layer
200	0.09
300	0.14
400	0.17
500	0.18

3.2 Photothermal conversion efficiency of coatings

The photothermal conversion efficiency (η) of an absorber coating is calculated by assuming that the only loss is radiation from the absorber surface at that particular working temperature by the equation 3. Here, we have considered the parabolic trough concentration ratio of 80 in order to attain the temperatures of 500 °C and DNI of 800 W/m^2 for the calculation. The photothermal conversion efficiency of 89.3 % at 500 °C has been achieved with the tandem layer approach of coating for the best optimized SSAC coating.

In field condition, there are other losses like conductive and convective losses will happen during the operation of CST system through receiver tube apart from the reported radiative losses. The receiver efficiencies are greatly increased by creating the vacuum between the absorber and glass envelope to make the conductive and radiative losses are low. The other loss of convective losses is majorly depending upon the glass envelope temperature, wind speed and ambient temperature. Hence, with the good mechanical design and conditions, one can achieve the overall receiver thermal efficiency to about 70% by using the spinel based absorber material in a cost-effective wet-chemical method.

4. Conclusion

A novel tandem layer design of Cu-Ni-Co ternary spinel/SiO_2 nanocomposite oxide selective absorber layer developed on stainless steel substrate has obtained an excellent selectivity of solar absorptance 0.95 and emittance 0.13 along with low thermal emissivity of 0.18 at 500 °C. The photothermal conversion efficiency of this novel design selective absorber has obtained the value of 0.90 and made the concentrated solar thermal system more efficient at high operating temperature. Therefore, nanocomposite spinel oxide absorbers are a very good candidate for medium and high temperature solar selective receiver in a cost-effective wet chemical method.

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6. References

Bogaerts W.F., Lampert C.M., 1983. Review Materials for photothermal solar energy conversion. J. Mater. Sci. 15, 2847–2875.

Granqvist C.G., 1985. Spectrally Selective Coatings for Energy Efficiency and Solar Applications. Phys. Scr. 32, 401–407.

IRENA, 2018. Renewable Power Generation Costs in 2017. IRENA - International Renewable Energy Agency, International Renewable Energy Agency. https://doi.org/10.1007/SpringerReference_7300

Kennedy C.E, 2002. Review of Mid- to High-Temperature Solar Selective Absorber Materials, Tech. Rep. NREL/TP-520-31267, 1–53.

Moon J., Lu D., VanSaders B., Kim T.K., Kong S.D., Jin S., Chen R., Liu Z., 2014. High performance multi-scaled nanostructured spectrally selective coating for concentrating solar power. Nano Energy 8, 238–246.

S.R. Atchuta, S. Sakthivel, H. C. Barshilia, 2019. Transition metal based $Cu_xNi_yCo_{z-x-y}O_4$ spinel composite solar selective absorber coatings for Concentrated Solar Thermal applications. Sol. Energy Mater. Sol. Cells 189, 226–232.

Selvakumar N., Barshilia H.C., 2012. Review of physical vapor deposited (PVD) spectrally selective coatings for mid- and high-temperature solar thermal applications. Sol. Energy Mater. Sol. Cells 98, 1–23.

Settino J., Sant T., Micallef C., Farrugia M., Spiteri Staines C., Licari J., Micallef A., 2018. Overview of solar technologies for electricity, heating and cooling production. Renew. Sustain. Energy Rev. 90, 892–909.

Zou C., Huang L., Wang J., Xue S., 2015. Effects of antireflection layers on the optical and thermal stability properties of a spectrally selective CrAlN-CrAlON based tandem absorber. Sol. Energy Mater. Sol. Cells 137, 243–252.