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Research Paper

Development of cost efficient solar receiver tube with a novel tandem absorber system

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HIGHLIGHTS

- A novel tandem absorber was designed for high performance Organic Ranking Cycle (ORC) based solar thermal applications.
- Tandem consists of Cr-Mn-Fe oxides/ZrO_2-SiO_2 or Cr-Mn-Fe oxides/ZrO_2-SiO_2/SiO_2 layer.
- Two layers tandem exhibits a high absorptance (α = 0.94.9) and low thermal emittance (ε = 0.122 at 300 °C).
- This tandem shows an excellent thermal and corrosion stabilities.

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ABSTRACT

New single layer, double layer and triple layer absorber tandems were designed and developed for high performance Organic Ranking Cycle (ORC) based solar thermal applications. A Cr-Mn-Fe composite oxide based absorber layer is devolved by controlled chemical oxidation and designed to have a nanoporous structure. It is covered with double antireflective layers a ZrO_2-SiO_2 nanocomposite layer developed by the sol-gel route and a porous SiO_2 layer obtained from SiO_2 nanoparticle suspension. Double and triple layer tandem absorbers were developed by a combination of chemical, sol-gel and nanoparticle suspension methods. By varying process parameters like duration, temperature and withdrawal speed, different combinations of Cr-Mn-Fe oxides/ZrO_2-SiO_2 double layer tandem and Cr-Mn-Fe oxides/ZrO_2-SiO_2/SiO_2 triple layer tandem composite absorber layers with varying refractive indices were developed on an economical variety of SS substrate. The optimized thickness of the absorber layer along with the antireflective layers shown a high absorptance (α = 94.9) and low warm emittance (ε = 0.122 at 300 °C). More specifically, this novel double layer tandem coating has excellent optical properties along with high corrosion resistance (withstands > 200 h in salt spray test). It has good thermal stability in an open air atmosphere and is well suited for low and medium temperature solar thermal applications.

1. Introduction

Solar thermal power represents a leading approach in solar energy conversion, which is used in concentrating solar power (CSP) systems. It is expected that by 2050, with appropriate support, CSP will provide >10% of global electricity [1]. The common base of all CSP technologies are the solar receivers play an important role in heat generation for electrical power production. In principle the absorber coatings in the collector system convert photon energy of sunlight to thermal energy which is then converted to electrical energy [2–6]. Absorber surfaces are typically classified as selective and non-selective depending on the absorptance to emittance ratio [7]. Conventionally, most of the selective absorber coatings preferred for concentrated solar collector applications are developed by the expensive Physical Vapour Deposition route, particularly by magnetron sputtering [7–19]. Currently, the entire CSP program is working to reduce the cost of solar thermal power technology. One of the approaches is to operate the CSP system using cost effective solar receivers in open air atmosphere conditions instead of using expensive evacuated solar receivers. To accomplish this, efficient selective receivers that have optical properties and high stability against corrosion, in addition to enhanced thermal properties are needed. For efficient photo thermal conversion, solar receivers must have high solar absorptance (α) in an active solar region (300–2500 nm) and a low thermal emittance (ε) in the IR radiation wavelength range (3–25 μm) at an optional operational temperature. Most of the current coatings do not have stability against corrosion and temperature and this is the main problem faced while operating the receivers in an open

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atmosphere [7,20]. Moreover, the coatings need to be stable in air in case the vacuum is breached.

Solar selective coatings can be improved to have high optical properties, stability against air at operational temperature, long environmental stability, high scratch and abrasion resistance and high mechanical integrity. Coatings prepared by an economic process, e.g. electrochemical deposition technique [21–24], thermal oxidation [25–29], chemical oxidation [30,31], sol-gel process [20,32,33] etc. on easily available substrates (e.g. stainless steel) with a combination of above mentioned properties would be a great choice for power generation by a CSP system. Nowadays, solar absorptance of most common high-quality commercial absorbers is about 95% and the thermal emittance is <10% at the process temperature range of 100–400 °C. The techniques that have been attempted so far for cost efficient solar absorber coatings have faced many challenges to produce coatings with high optical efficiency as well as high environmental and thermal stability.

Very few studies have reported high optical efficiency with temperature and corrosion stabilities for solar absorber coatings made by sol-gel process. For example, such a coating was prepared from polysiloxane as a binder and Co_3O_4 as a spinel pigment on 304 stainless steel by spin-coating [34]. Spectrally selective absorber coatings were prepared by spin-coating of nickel nanoparticles embedded in alumina and coated with an antireflective layer made of silica, alumina, or silica–titania mixture [32]. Vince et al. [35] reported doping of CuCoMnOx by Ti in a polysiloxane resin. The films were used in order to increase the weather resistance and showed absorptance of 0.86–0.91 and emittance below 0.036. Tulchinsky et al. [20] reported the thermal chemical reaction between a titania sol–gel precursor with a copper manganese spinel to form a new material, $Cu_{0.44}\,Ti_{0.44}\,Mn_{0.84}Fe_{0.28}O_3$, having a bixbyite structure. Although solar absorptance of the films was reported around 97.4%, there was no information about thermal emittance of the film. Chao-Ching Chang [36] reported poly (urethane)-based solar absorber coatings containing copper chloride and nano gold composite synthesised by solution-chemical technique. The solar absorptance and thermal emittance of this coating were shown to be only around 0.846 and 0.09, respectively. Copper–cobalt oxide thin films deposited on aluminium substrates via a facile sol–gel dip-coating method showed solar absorptance of around 83.4 [37]. A higher value of solar absorptance and better stability is needed for the films to be suitable for concentrated solar thermal power application.

Martin et al. [38] produced multi-layered chrome free black selective surfaces for solar thermal energy conversion by a low-cost sol-gel dip-coating method. The optical properties of solar absorptance and thermal emissivity at 100 °C of the Cu–Co–Mn–Si–O based nano crystalline thin films were shown to be around 0.95 and 0.12. The coatings were stable up to a maximum of 360 °C in air which surpasses that of the conventional robust black chrome coatings existing in the market. But there was no report on the weather stability of the novel multilayer absorber coating.

For CSP application, coatings are required on a large area and development of solar receiver tubes with all the properties like high solar absorptance, low thermal emissivity, high weather and thermal stabilities by an economic way is the main objective in order to reduce the cost of solar electricity production. In view of the above, herein, we report novel double and triple layer tandem absorber systems developed by a combination of chemical oxidation, sol-gel and nanoparticle suspension processes for high performance Organic Ranking Cycle (ORC) based solar thermal system operating at the range of 200–300 °C having excellent optical properties along with high corrosion resistance and good thermal stability in an open air atmosphere and their optical and structural characterizations.

2. Experimental section

2.1. Chemicals used for the preparation of single, double and triple layer absorber tandems

All chemicals in this work were purchased commercially and used without any further purification Sodium dichromate dihydrate (99%), isopropylalcohol (99%), sulphuric acid (98%) were purchased from Merck. Zirconium n-propoxide (70% in n-propanol), 3-glycidoxypropyl trimethoxisilane (GPTS, 97%) and 2-isopropoxyethanol (99%) were obtained from Alfa Aesar. SiO_2 nanoparticle suspension (Levasil 200-E, 20%) was obtained from Obermeier, Germany.

2.2. Sample preparation

In a preliminary step of the process, the stainless steel (SS) tubes are cleaned by ultra-sonication with a mild detergent solution followed by rinsing with tap water and then deionised water. They are wiped with a soft cotton cloth dipped in an organic solvent, preferably isopropyl alcohol (IPA), to make it free of any external impurities adhering to the surface. The cleaned substrates are then dried either by an air drier or by keeping them at 100 °C for 5–10 min in an air oven. The dimensions of SS tube used for this study were 500 mm × 25 mm × 1.25 mm (Length × Width × Thickness).

2.3. Development of nanoporous composite single absorber layer on SS 202 tubes

The thin nanoporous Cr-Fe-Mn composite oxide absorbing layers were developed on smooth, highly specular reflecting mirror of stainless steel substrates by a controlled chemical oxidation process. The special but economical stainless steel tube (SS-202) had a composition of C: 0.15, Mn: 7.5–10, P: 0.06, S: 0.03, Si: 1.00, Cr: 17–19 and Ni: 4–6; and Fe: 69–73 wt%. A precise temperature controllable chemical bath reactor was used with optimum conditions of molar concentration of chromium salt, acid and water ratio, temperature and process duration. 1M sodium dichromate salt dispersed in a mixture of sulphuric acid and water (3:5) was used for the development of nanoporous morphological structure absorber layer. The detailed preparation procedure of the absorber layer as described elsewhere [39]. In a preliminary step of the process, the SS tube sample is cleaned with a mild detergent solution and rinsed with tap water followed by deionised water and finally wiped with a soft cotton cloth using with an organic solvent, preferably isopropyl alcohol (IPA), to make it free of any external impurities adhering on the surface. The cleaned substrate is then dried either by an air drier for 2–5 min or by placing at 100 °C for 5–10 min in an air–oven.

The cleaned substrates were immersed into the acid bath for chemical oxidation in a temperature range of 80–90 °C for 20–30 min. The acid mixture for the development of selective absorber layer consisted of 15–30 wt% Na/K dichromate salt, 37.5–53 wt% deionised water and 21–34 wt% conc. sulphuric acid. The ideal ratio of the three components was 23.09:48.43:28.48 (wt%). During the chemical oxidation process, the metal atoms on the surface of substrates are partially oxidized by the acid mixture to obtain a type of nanoporous composite oxide layer. The SS tubes turned to grey colour with a glassy appearance after the chemical process. After that the SS tube was washed immediately with tap and distilled water and finally wiped with a soft cotton cloth using an organic solvent, preferably IPA. The tube was then dried by an air drier for 2–5 min.

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