



INFLUENCE OF ELEMENT OXYGEN ON THE ABSORPTIVITY AND EMISSIVITY OF 434-L STAINLESS-STEEL SOLAR SELECTIVE ABSORBER FOR SOLAR THERMAL CONVERSION APPLICATION

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Abstract

In this study, stainless-steel selective solar absorber was synthesized via a simple hydrothermal treatment method. The aim is to investigate the influence of element oxygen (O) on the solar absorptivity and thermal emissivity for solar collector applications. The Energy-Dispersive X-ray Spectroscopy (EDS), Ultraviolet-Visible-Near infrared Spectroscopy (UV-Vis-NIR), and Fourier transform infrared spectroscopy (FT-IR) were used to characterize the elemental component, absorptance (α), and emittance (ϵ) of the synthesized samples. EDS measurement and analysis confirmed that the as-received 343-L stainless-steel (SS) is composed of the elements: C, F, Si, Cr, and Fe while the Oxidized SS is composed of similar elements with the exception of F and Si. The additional elements contained in Oxidized SS includes O and Na respectively. UV-Vis-NIR Spectroscopy shows that the as-received SS exhibits highest reflectance of about 50 % in UV-vis-NIR (0.25 – 2.50 μm) while the Oxidized SS exhibits the lowest reflectance of about 4 % in the same wavelength regions. Similarly, FT-IR Spectroscopy revealed that the as-received SS exhibits highest reflectance of about 85 % in the mid-far IR wavelength region while the Oxidized SS sample exhibits lowest reflectance of about 70 % in the same wavelength zone. The absorptance (α) and emittance (ϵ) analysis of the as-received SS is 0.35 and 0.19 while the corresponding value of the Oxidized SS is 0.921 and 0.34 respectively. These results confirmed that the element 'O' have a significant influence on the ' α ' and ' ϵ ' values of the Oxidized SS.

Keywords: *Elemental component, Hydrothermal treatment, Stainless steel, Metallic oxides*

Introduction

Concentrated solar power (CSP) and solar photovoltaics (PV) are two main techniques for harvesting solar energy (Yu et al., 2014). In contrast to standard PV arrays, which convert solar energy directly into electricity via the photoelectric effect, CSP generates electricity using the heat collected from the incident solar radiation by its component called selective solar absorber (Karas et al., 2018). Selective solar absorber is the heart of the CSP which converts solar energy into thermal via heat-transfer fluid. In comparison to PV arrays, CSP offers storable energy during the periods of low or no solar insolation. Solar selective absorber coatings for CSP systems have been an essential research in the field of solar energy. They convert solar energy efficiently into heat with the minimal losses of thermal radiation in the infrared (IR) region (Akoba et al., 2021; Yu et al., 2014). A selective solar absorber, sometimes called a selective surface, is a material or coating which exhibits optical selectivity; that is, optical properties which vary significantly from one spectral wavelength region to another. In the field of solar energy, a selective solar absorber efficiently captures solar energy in the Visible and Near-infrared spectral wavelength region while exhibiting poor radiating properties in the Far-infrared wavelength zone. Accordingly, a selective coating will absorb and retain a high amount of energy from the sun while a non-selective surface, such as an ordinary black paint, will lose much of its absorbed energy significantly (Abdullahi et al., n.d.). An oxidized metal is one of the simplest single layer selective solar absorbers because the oxide phase provides the required absorption property in the UV-Vis wavelength region while the metal itself provides high reflectance property in the IR wavelength zone. Metallic oxides appear to be extremely promising if they can be stabilized and engineered to exhibit stable optical properties (Abdullahi et al., 2021; Lampert, 1979). Indeed, metal atoms (precisely, transitional metals) are made up of an incompletely filled d-shell of metallic ion. When this metallic ion is combined with oxygen, the electrons become localized, forming a new material with a high energy absorption property known as metallic oxide. The free electrons within the atoms of metal are responsible for their high infrared reflectance property, whereas the bonded electrons contribute to their absorption characteristic. Thus, the oxidized surface of the metal exhibits a high absorption characteristic, whereas the transitional base metal exhibits high infrared property, which aids in minimizing thermal emission loss from the selective solar

absorber; thus, the combination of the two phases produces a good selective solar absorber with the required optical properties for photo-thermal conversion application (Amri et al., 2014). A solar selective absorber is a surface that has a high degree of absorption in the solar spectrum and retains energy by suppressing thermal radiation emissions at infrared wavelengths. Photo-thermal conversion requires the use of solar selective absorbers, the technology for which is speedily developing. Harnessing solar energy at a reduced cost involves the use of solar selective absorber operating with enhanced thermo-physical, optical, and selectivity properties. Solar-to-thermal collectors can easily produce hundreds of watts of electrical power (Akoba et al., 2021).

In this work, the stainless-steel solar selective absorber was synthesized via a simple hydrothermal treatment method, and the influence of oxygen on the optical absorptivity and emissivity is investigated systematically. The results reveal that oxygen plays a crucial role in the absorptivity (α) and emissivity (ϵ) properties of the synthesized stainless-steel solar selective absorber. Measured reflectance data were analyzed to obtain α , and ϵ respectively.

Experimental Methods

Sheet of 434-L stainless-steel (SS) with square shape of size 2.00 cm \times 2.00 cm, NaOH in pellet form (500 g), ethanol (200 Proof, Anhydrous, $\geq 99.5\%$) and acetone (Laboratory Reagent, $\geq 99.5\%$) were purchased from Sigma Aldrich. While Teflon-line autoclaves used for the hydrothermal synthesis were purchased from KIMIX Chemical & Lab Suppliers.

Hydrothermal technique was used to oxidize the surface of the SS in order to enhance its optical properties such as absorptance (α). Firstly, the sample was cleaned in ethanol, followed by acetone, and finally rinsed using deionized water. Thereafter, it was placed in an autoclave containing the alkaline solution (NaOH) and heated in a laboratory oven for 3 h at 200 °C. In order to examine the influence of oxygen (O) which was induced in the process of hydrothermal treatment on the surface of SS, another sheet of SS was kept un-oxidized to serve as a reference.

Results and Discussions

Characterization

Energy-Dispersive X-ray Spectroscopy (EDS) Analysis

EDX measurement and analysis was conducted to obtain the elemental composition of the (a) as-received SS and, (b) Oxidized SS. Fig. 1 shows the results of the EDS while Table 1 summarized the elemental composition of each of the sample obtained.

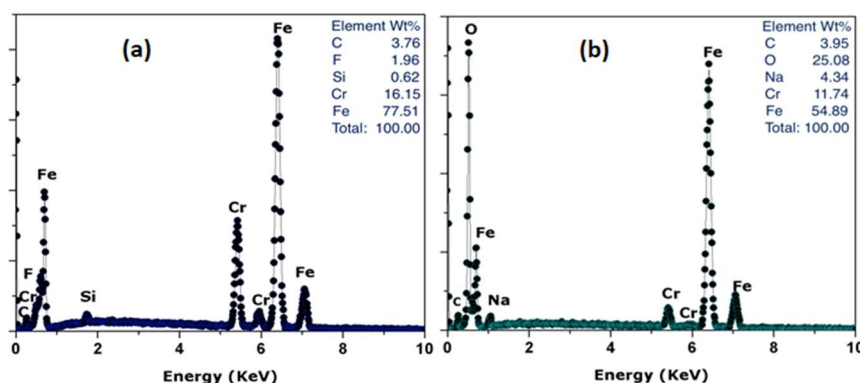


Fig. 1: EDX pattern of the (a) as-received SS and, (b) Oxidized SS

Table 1: EDS elemental composition of the (a) as-received SS and (b) Oxidized SS

Element	Percentage weight (W %)	
	(a)	(b)
C	3.76	3.95
F	1.96	-
Si	0.62	-
Cr	16.15	11.74
Fe	77.51	54.89
O	-	25.08
Na	-	4.34
Total	100.00	100.00

It can be observed in both Fig. and Table 3.1 that the W% of Carbon (C) increased by 0.19% while fluorine (F) and silicon (Si) vanished to 0 % after the hydrothermal treatment of the sample (b). It can also be observed that the Chromium (Cr) and Iron (Fe) decreased by 4.41 and 22.62% after the treatment. Cr and Fe are transitional metals that possess high infrared reflectance which is responsible for their low emissivity property in the IR

wavelength zone. It was further observed that the elements oxygen (O) and sodium (Na) are not present in the sample (a) but present in (b). The presence of O in sample b (Fig. 1) implies that the sample has been oxidized after the hydrothermal treatment. The source of these elements (O and Na) can be attributed to the solution of NaOH used for hydrothermal treatment.

UV-Vis-NIR Diffuse Reflectance Analysis

The optical property of the samples such as reflectance in solar and thermal spectra was investigated by analysing the UV-vis-NIR diffuse reflectance data in the wavelength region of 0.2 – 2.5 μm (solar spectra) and FT-IR reflectance data in the wavelength region of 3.0 – 20.0 μm (Thermal spectra), as depicted in Fig. 2 and 3 respectively.

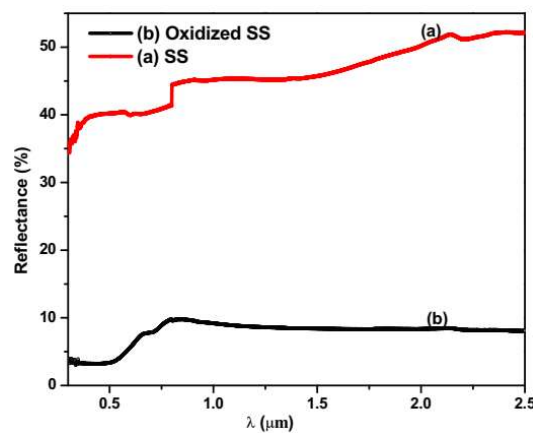


Fig. 2: UV-Vis reflection spectra of the (a) as-received SS and, (b) Oxidized SS

Fig. 2 shows that the (a) as-received SS exhibits highest reflectance of about 50 % in UV-vis-NIR (0.25 – 2.50 μm) while the (b) Oxidized SS exhibits the lowest reflectance of about 4 % in the same wavelength regions. This implies that the reflectivity of the sample has been drastically reduced after the oxidization via hydrothermal treatment.

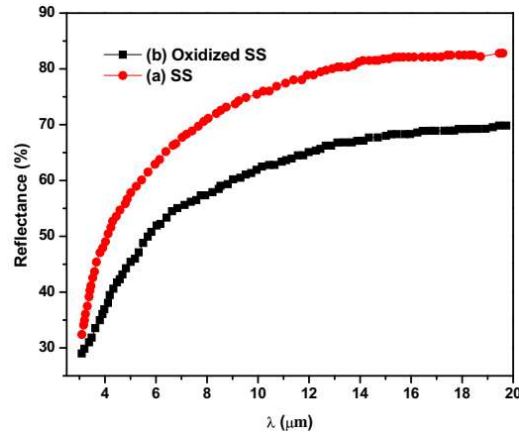


Fig. 3: IR reflection spectral of the (a) as-received SS and, (b) Oxidized SS

Fig. 3 revealed that the (a) as-received SS exhibited highest reflectance of about 85 % in the mid-far IR wavelength region while the (b) Oxidized SS exhibited lowest reflectance of about 70 % in the similar wavelength zone. This shows that the reflectivity of the sample has been reduced after the hydrothermal treatment. The decrease in reflectance spectra exhibits by the samples at both UV-Vis and IR wavelengths zone can be attributed to surface oxidation induced by the NaOH, which was used for hydrothermal treatment as confirmed by EDS analysis in the previous section. It has been reported that the main requirement for the solar selective absorber is the high absorptance (low reflectance) in the short wavelength zone of the solar spectrum and low emittance (high reflectance) in the mid/far wavelength of the thermal spectrum (Gao et al., 2016). Therefore, the results of this research are in good agreement with the findings of the literatures.

Absorptance (α) and emittance (ε) results

Solar absorptance (α) of the samples was calculated via equation (1) using the measured spectra reflectance data and weighted by solar irradiance based on standard air mass 1.5 solar spectrums in the wavelength region 0.25 – 2.50 μm while thermal emittance (ε) was obtained through equation (2) using the measured Blackbody reflectance data (Nuru et al., 2014).

$$\alpha = \frac{\int_{0.2}^{2.5} [1 - R(\lambda)] I_{sol}(\lambda) d\lambda}{\int_{0.2}^{2.5} I_{sol}(\lambda) d\lambda} \quad (1)$$

$$\varepsilon = \frac{\int_{3.0}^{20} [1 - R(\lambda, T)] B(\lambda, T) d\lambda}{\int_{3.0}^{20} B(\lambda, T) d\lambda} \quad (2)$$

where R , λ , and I_{sol} denote reflectance, wavelength, and direct normal solar irradiance, respectively, as defined by ISO standard 9845-1 (1992), with an air mass (AM) of 1.5. $B(\lambda, T)$ which denote radiance of a blackbody at temperature T (Abdullahi et al., 2021).

The “ α ” and “ ϵ ” results of the (a) as-received SS and (b) Oxidized SS are shown in Table 3.2.

Table 2: Absorptance (α) and, Emittance (ϵ) of the (a) as-received SS and (b) Oxidized SS

Sample	Absorptance (α)	Emittance (ϵ)
a	0.350	0.19
b	0.921	0.34

Table 2 revealed that the “ α ” and “ ϵ ” of the (b) Oxidized SS is higher than that of the (a) as-received SS. These increments are due to the presence of the element Oxygen which is the main driver of the sample oxidation. The increment in “ α ” is to the advantages of a solar absorber, whereas the increment in “ ϵ ” is not favorable to the solar absorber surface. This is due to the fact that at high “ ϵ ” energy absorbed by the surface is lost (Abdullahi et al., 2021). It has been reported that increment in oxidation causes reduction in reflectivity in the IR wavelength region, resulting in high emissivity in a material (Lampert, 1979; Smith et al., 2003).

Generally, metals have low infrared emittance properties and radiate very little heat, whereas the oxidized metal surface has high absorption properties in the solar spectrum, so the combination of the two surfaces gives excellent selectivity for solar thermal conversion systems (Selvakumar & Barshilia, 2012).

Conclusions

We have synthesized solar selective absorber on the 434-L stainless-steel using the hydrothermal technique, and investigated the effects of element O on optical properties of the samples (absorptivity and emissivity). The absorptivity (α) and emissivity (ϵ) value of the as-received SS are 0.350 and 0.19 while the Oxidized SS records 0.921 and 0.34.

The increments in both α and ϵ of the Oxidized sample can be attributed mainly to presence of the element oxygen (O) as revealed by EDS results. The increment in α is to the advantages of a solar selective absorber, whereas the

increment in ϵ is not favorable to the solar absorber surface. This is due to the fact that at high ϵ , energy absorbed by the surface is lost.

These results therefore confirmed that the element 'O' has a significant influence on the ' α ' and ' ϵ ' values of the Oxidized SS. The result also revealed that the Oxidized SS could be a good candidate for solar thermal collector applications.

Recommendations for future work

According to the literature, a good solar absorber surface must have a high absorptance (α) in the solar wavelength region and a low emittance (ϵ) in the thermal wavelength region (Abdullahi et al., 2021). In contrast, the emissivity of the synthesis SS in this work is too high and this will cause a significant loss of energy absorbed by the material. Therefore, further research into ways to reduce this emissivity is recommended. The hydrothermal synthesis temperature and alkaline concentration are the critical parameters that can affect the optical properties of the synthesis SS. As a result, a thorough examination of these critical factors would result in minimizing the emissivity value the SS.

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By checking the following box, the senior author acknowledges that they and the other authors have read, understood, and complied with the Instructions to Authors (ItA).

