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ARTICLE

Enhancement of the Solar-Thermal Response of Flat-plate Collector Coated with a Heat-resistant Paint

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Abstract: A commercially available heat-resistant paint (HRP) is used as the primary component of a composite coating for low-temperature flat collector system. The same is mixed with small amounts of carbon black powder (CBP), lithium metal oxide (LMO) powder or both in an attempt to enhance the coating solar-thermal conversion characteristics. The optical characteristics of these coatings are investigated by means of optical microscopy, optical spectrophotometry and measurement of reflectance. The solar-thermal conversion characteristics are investigated by measuring the maximum collector temperature due to exposure to solar radiation. Results show that the solar-thermal conversion (maximum temperature) of the collector plate can be improved with the addition of CBP and LMO particles at low concentrations. The solar-thermal characteristics of the coatings are reported and compared with those of different coatings. The coatings prepared in the present work can easily be applied on the collector surface, which makes them suitable for flat-plate collector systems.

Keywords: Flat plat collector, Selective coating, Optical properties, Solar irradiance.

1. Introduction

Selective coatings are special types of coating layer(s) used in low- and high-temperature solar-thermal collectors [1-2]. These types of coatings are expected to absorb most of the incident solar radiation and convert it into thermal energy; this is the essential and most desirable property for energy-conversion applications. These coatings are designed to have the maximum possible absorbance and minimum reflectance of the incident solar radiation while maintaining a minimum emittance value. Many materials were designed to closely meet these specifications [3-4]. Various combinations of materials were investigated for flat-plate collector showing advantageous solar-to-thermal conversion characteristics, such as nickel-pigmented aluminum oxide (Al_2O_3) [5], nickel–aluminum (NiAl) alloy embedded into black paint [6], $CrNxOy/SiO_2$ on Cu(Si) substrate deposited by DC reactive magnetron sputtering method [7], black chrome or carbon-coating [8]. Recently, Lizama-Tzec et al. deposited black nickel coating on Cu substrate and compared its thermal and optical properties with those of the commercial FPC systems (i.e., CuO and nitrogen-doped TiO_2 coatings) [9]. They reported reduced thermal losses of their selective coating after thermal treatment at 200 °C, which was attributed to crystallinity characteristics of the coating. In 2020, Touaba et al. constructed an FPC which uses waste engine oil as a working and heat transfer fluid [10]. In the same year, D.M. Herrera-Zamora et al. deposited nickel/black cobalt selective coating on a copper substrate for solar thermal collector application and investigated its thermal and optical properties [11]. They reported a solar-radiation absorption of 95% and a thermal emission of 7%

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at 100 °C. While many composite coatings may prove to be potential candidates for solar-thermal conversion applications, other coating characteristics remain essential, such as easiness of fabrication and application, durability and cost effectiveness.

In the present work, a commercially available heat-resistant paint is used as a primary coating of a flat-plate collector. Additionally, carbon black powder (CBP) and lithium metal oxide (LMO) powder are air-sprayed on the top of the black paint to improve its solar-thermal conversion properties. These coatings are investigated by means of optical microscopy, optical spectrophotometry, total reflectance measurement and the measurement of the maximum collector temperature. Besides being a cost-effective solution, easily applicable on flat-plate collectors, the present coating composite proved to have enhanced solar-thermal conversion characteristics.

2. Materials and Methods

A commercially available heat-resistant paint (HRP) of matt black color from Rust-Oleum, USA was used as the primary coating of the flat-plate collector. Some of the HRP specifications are shown in Table 1. The CBP was acquired from EMFUTUR Technologies, Spain. The metal oxide powder was synthesized by the sol-gel method, as illustrated in reference [12]. The powder synthesized was then annealed at 800 °C for 48 hours and subjected to dry ball-milling at 300 rpm for 6 hours to produce the fine powder of the material. The compositional and structural properties of the metal oxide powder are reported elsewhere [12]. The flat plate substrates were made of aluminum sheets of square shape having dimensions of 4×4 cm^2. These substrates were initially cleaned by detergents and acetone, washed thoroughly by deionized water and dried in furnace at 120 °C for 3 h. The HRP-coated substrates were left to dry for 24 h. Other substrates, to which CBP or LMO particles or both were added, were coated initially with the HRP. The CBP and LMO particles were added immediately on the top of the wet HRP to ensure that these powders embed well in the paint. The powders were applied by air-spraying method from a distance of 30 cm to maintain a homogeneous distribution of the particles on the paint surface. Four different coatings were prepared accordingly; these are plain HRP, HRP with CBP, HRP with LMO and HRP with both powders added. The four substrates with the coatings applied are shown in Fig. 1.

TABLE 1. Some specifications of the heat-resistant paint from Rust-Oleum (USA).

Property	Description
Resin type	Silicon-modified alkyd
Pigment type	Black manganese ferrite
Solvent	Acetone, xylene, toluene (fluorescents also contain hexane) and liquefied petroleum gas propellant
Dry time at 22 – 27 °C at 50% relative humidity	2-4 hours

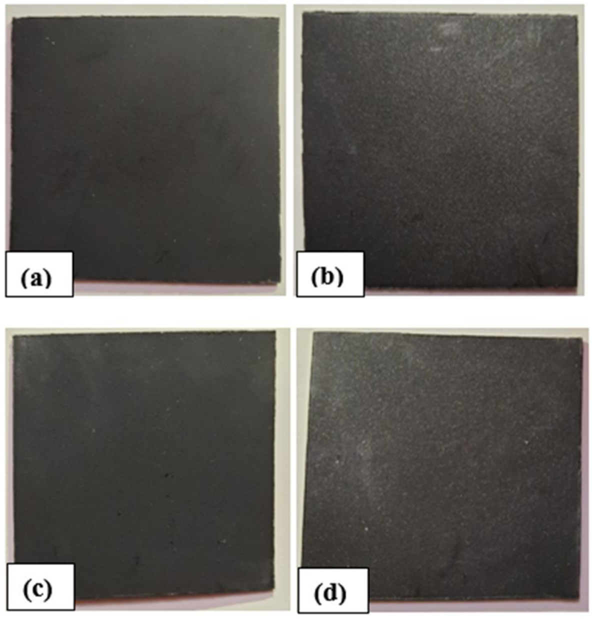

FIG. 1. The aluminum substrates with different coatings applied (a) heat-resistant paint (HRP) (b) HRP with CBP (c) HRP with LMO particles (d) HRP with CB and LMO particles.

The four specimens were investigated under an optical microscope to confirm that the coatings are homogeneously applied on the substrates. In order to measure the total reflectance of the coatings, a TES1333R datalogging digital power meter was used, as illustrated in Fig. 2. The measurement setup is such that the solar radiation falls on the specimen coating after passing through the tube shown in the figure. The axis of the tube makes an angle of 45 degrees with the plane of the specimen. The power meter makes a similar angle with the specimen, such that the angles of incidence and reflection of the solar radiation are equal. The tube setup is used to eliminate the effect of the diffused radiation in a similar manner to that implemented in the pyrheliometer device.

The solar thermal response of the flat-plate collector was investigated using a collector setup free of a working fluid, as shown in Fig. 3. This experimental setup is constructed using cardboard sheets lined with sheets of 4 mm thick compressed cork to maintain good thermal insulation of the collector system. The dimensions of the collector are 250×20×4 mm^3. A 4 mm thick transparent glass is used for the construction of the collector window. Two thermocouples were used to measure the temperatures of the collector plate and the glass window during the experiments. The thermal response is measured as the temperature of the collector plate *versus* the exposure time to the solar radiation.

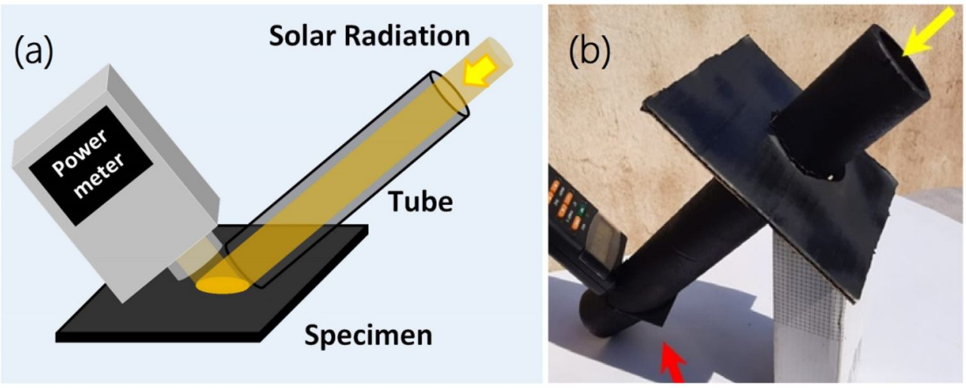

FIG. 2. The home-made, pyrheliometer-like measurement setup of the total reflectance.

FIG. 3. The flat solar thermal collector facing the sun and attached to the measuring units.

3. Results and Discussion

Fig. 4 shows the optical microscope images of the coatings (before and after the powders' addition) at a nominal magnification of 200 X. The images proved the homogeneous distribution of CBP and LMO particles. The degree of opacity of the black-colored paints to the bare eye and its dependence on the coating composition can easily be noticed and compared with the respective microscope images. Addition of CBP and LMO particles affects the blackness of the coating. This, however, does not indicate the solar-thermal conversion response of the coating, because the coating appearance is decided by the eye sensitivity to a narrow portion of the solar radiation. The solar-thermal conversion characteristics are finally investigated using the collector setup mentioned in Section 2.

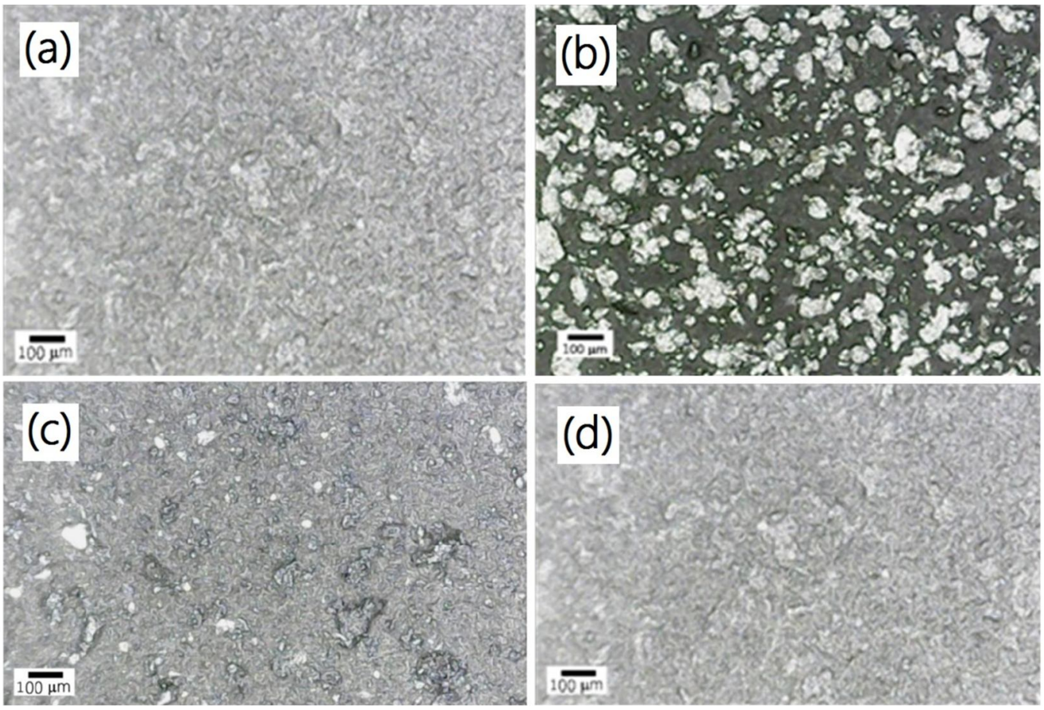

FIG. 4. The composite coatings under optical microscope (a) Heat-resistant paint (HRP) (b) HRP with CBP (c) HRP with LMO particles (d) HRP with CBP and LMO particles.

The spectral reflectance of the coatings (i.e., the dependence of reflectance on the incident wavelength) is presented in Fig. 5. The reflectance spectra were recorded in the wavelength range 200 – 1000 nm and presented, for clarity of features, in the range 400 – 800 nm. The spectra were also compared with the reflectance spectra of an ordinary painted glass mirror and uncoated aluminum substrate. All the spectra exhibit a two-peak feature irrespective of the coatings applied. These peaks are well distinctive taking place in the visible region of the electromagnetic radiation at wavelengths near 445 nm and 577 nm. No additional peaks were observed in the wavelength range of measurement (i.e., 200 – 1000 nm). The intensity maxima of the peaks and the total areas under the spectra were recorded and listed in Table 2. The peak intensity was found to vary with the coating type as does the area under the curve. The area under the spectrum can be associated with the total reflectance and absorbance of the surface. Our calculations of the area under the curve indicate that the HRP-LMO coating exhibits the highest total absorbance to the incident radiation as compared with the other coatings. This emphasizes that the coating has the highest solar-to-thermal conversion characteristics. The addition of the CBP particles to the heat-resistant paint was found to affect the absorption characteristics negatively.

The home-made pyrheliometer-like setup, mentioned in Section 2, is utilized to measure the total reflectance measurement. This is accomplished to verify the analysis results of the reflectance spectra. Fig. 6 shows the total reflectance of the coatings compared with those measured for the glass mirror and the uncoated Al surface. The reflectance % is calculated as the ratio of the reflected intensity to the incident intensity of the solar radiation (i.e., the beam irradiance). The solar irradiance and the beam irradiance during the measurements were 1225 ±10 W/m^2 and 1132±10 W/m^2, respectively. The relatively high value of the solar irradiance is due to an interfering effect of the scattered radiation from a nearby building to the experiment setup location. Such an effect was found to increase the solar irradiance by ~10% of its global value (see Table 3). The total reflectance values of all the coatings were less than 4.08% of the incident radiation. The HRP showed an average value of total reflectance ratio of 2.64%, which decreases with the addition of the powders. A slight decrease of reflectance was measured after adding the CBP, while a minimum reflectance of 1.78% was achieved with the addition of LMO particles to the HRP. These values and the variation of the total reflectance with the coating composition agree with the results obtained from the spectral-reflectance analysis.

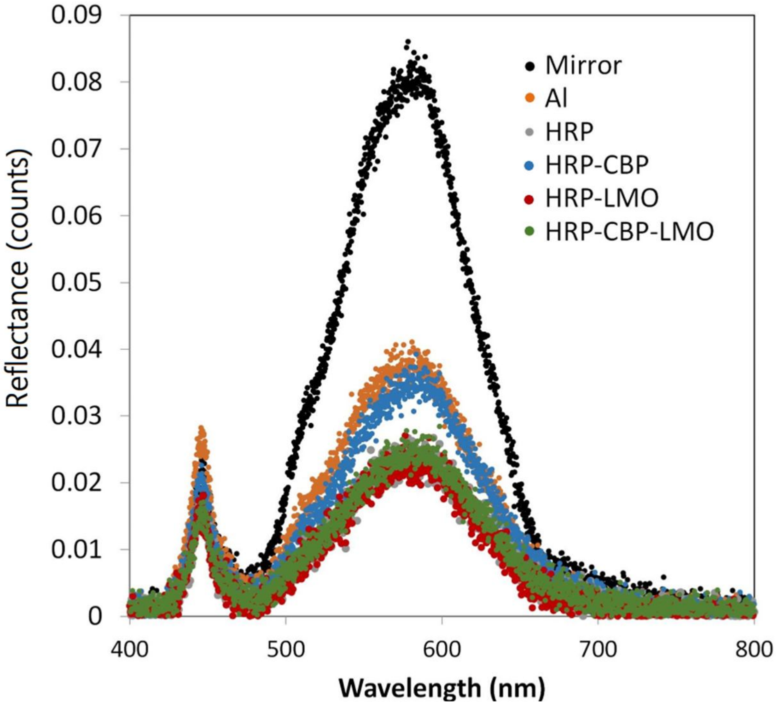

FIG. 5. Reflectance spectra of the composite coatings.

TABLE 2. The spectral parameters of optical spectrophotometry measurements.

Coating type	**Intensity of Peak #1 at 445 nm**	**Intensity of Peak #2 at 577 nm**	**Area under the spectrum (a.u.)**
Glass mirror	0.024	0.0851	9.3
Uncoated Al substrate	0.028	0.040	5.0
HRP	0.016	0.026	3.1
HRP-CBP	0.022	0.039	4.5
HRP-LMO	0.018	0.027	2.9
HRP-CBP-LMO	0.017	0.027	3.3

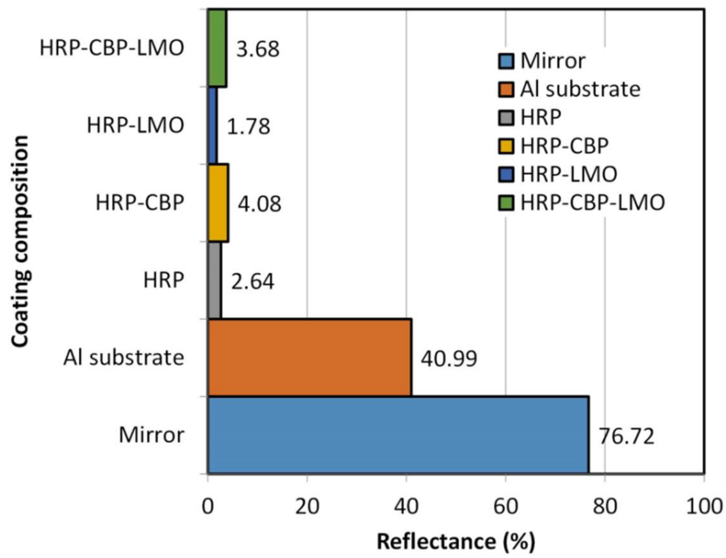

FIG. 6. The total reflectance of the composite coatings using solar radiation. The solar irradiance and the beam irradiance during the measurements were 1225 ±10 W/m^2 and 1132±10 W/m^2, respectively.

The solar-thermal responses of the coatings are presented in Fig. 7 as the rise of collector temperature with time of exposure of the collector to solar radiation. The temperature of the flat-plate collector increases with time from the ambient temperature. The measurements were stopped five minutes after no rise in temperature was observed. The results show that the maximum temperatures of the plate collector are 88.7°C, 86.1°C, 90°C and 94.3 °C of the plain HRP, HRP-CBP, HRP-LMO and HRP-CBP-LMO coatings, respectively. This emphasizes that the addition of LMO and CBP particles to the HRP resulted in the enhancement of the solar-thermal conversion of the plate collector. It was predicted that the HRP-LMO coating would show the highest conversion response as compared with the HRP-LMO-CBP coating. This is attributed to the variance in the solar irradiance values during the measurements. Table 3 shows the irradiance values, summarizes the measurements and compares our results with those accomplished by other researchers with different coatings. It is clear that the present coatings exhibited superior solar-to-thermal conversion characteristics as compared with other coating, emphasizing their potential and competing appropriateness to solar-thermal conversion applications. Table 3 shows that CuO nanoparticles resulted in slightly higher collector temperatures. This is attributed to the fine tuning of the nanoparticle sizes leading to better absorption of the solar radiation. Such tuning has not been accomplished in the present work, which may have resulted in higher collector temperatures. It is worth mentioning that few affecting parameters were not taken into consideration in the present work, such as the fluctuation in the solar irradiance during the measurements, the ambient temperature and the wind speed. Other features, such as paint durability, adhesion and corrosion characteristics, are beyond the scope of the present investigation.

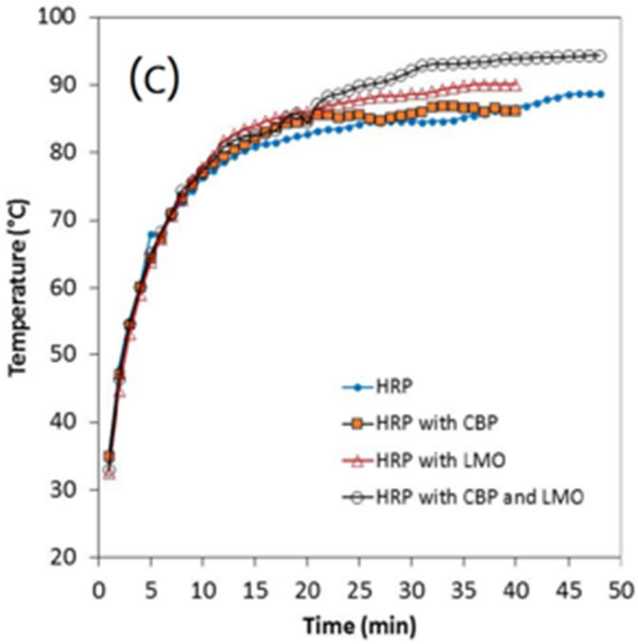

FIG. 7. Comparison of the solar-thermal conversion curves of the composite coatings.

TABLE 3.The solar-thermal conversion response in terms of the maximum collector temperature for different coatings.

	Coating / Paint	Irradiance (W/m^2)	($T_{max.}$) (°C)	Ref.
1	HRP	1220 – 1270	88.7	Present Work
	HRP-CBP	1200 – 1270	86.1	
	HRP-LMO	1190 – 1230	90	
	HRP-LMO-CBP	1200 – 1250	94.3	
2	250 Selective Black Thurmalox Solar Collector Coating, Graphene, CuO,	919	43, 72, 57	[13]
3	CNT-CuO NPs dispersed in black paint	964	84.3	[14]
4	NiAl Alloy embedded in black paint	1000	69.7	[15]
5	CuO NPs mixed with black paint	1100	97	[16]
6	Plasmonic Copper/Carbon foam/Cotton Fabric	912	78.7	[17]

4. Conclusions

Selective coatings for solar-thermal conversion application in low-temperature flat collector systems were successfully prepared from commercially available heat-resistant paint. Additional components of carbon black powder and lithium transition-metal oxide powder were successfully utilized to improve the solar-thermal conversion behavior of the solar collector. The optical and solar-thermal conversion characteristics of these coatings were investigated by means of optical microscopy, optical spectrophotometry, total reflectance measurement and measurement of the maximum collector temperature. While the heat-resistant paint resulted in a maximum collector plate temperature of 88.7°C, a maximum collector plate temperature of 94.3 °C could be achieved by adding small amounts of carbon black powder and lithium metal oxide particles on the top of the paint. The composite coatings prepared in the present work exhibited superior solar-thermal characteristics to other selective coatings. The present coating can easily be applied on the surfaces of flat-plate collector systems.

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