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A Single Layer of Chromium Oxide Nanoparticles Films Coated with Carbon by Applying Exploding Wire Technique for Efficient Solar Selective Absorber

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Abstract

The efficiency of solar energy absorption in solar heaters is increased by the use of selective absorption coating that possesses high absorption of solar radiation in the UV-visible spectrum as well as low emission at the operating temperature in the infrared region. In this work, novel selective coatings were synthesized by improving the selectivity of chromium oxide (Cr_2O_3) nanoparticles by doping with carbon nanoparticles using the exploding wire technique for carbon rods by high current in suspended Cr_2O_3 particles. The structural properties and surface topography were studied by XRD and FE-SEM, which illustrate the carbon-coated Cr_2O_3 nanoparticles. The prepared nanoparticles were mixed with a support material, Polyvinyl pyrrolidone (PVP) as a matrix, for use as a selective coating for three metals, namely copper, aluminium and stainless steel (SST). Reflectivity measurements were performed within the UV-Visible spectrum to calculate the absorption of solar radiation using numerical integration. The reflectivity was also measured in the range from 2.5 to 25 µm to calculate the thermal emission of the solar heater within the proposed operating temperature of 373 K. The measurements showed good efficiency of using the produced material as a selective coating which was prepared in a simple way compared to conventional methods. The best sample with efficient absorptance (α) for solar spectrum and of lowest emittance (ε) in IR region was for Al substrate coated by Cr_2O_3:C:PVP of $\alpha = 0.886$ and $\varepsilon = 0.260$.

Keywords: Cr_2O_3 nanoparticles, Graphite, exploding wire, selective absorber.

طبقة واحدة من أغشية دقائق أكسيد الكروم النانوية المشوبة بالكربون عن طريق تقنية الأسلاك المتفجرة للامتصاص الانتقائي للطاقة الشمسية

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الخلاصة

يتم زيادة كفاءة امتصاص الطاقة الشمسية في السخانات الشمسية باستخدام طلاءات ذات امتصاص انتقائي والتي تمتلك امتصاصًا عاليًا للإشعاع الشمسي في الطيف المرئي والاشعة فوق البنفسجية بالإضافة إلى انبعاث منخفض عند درجة حرارة التشغيل في منطقة الأشعة تحت الحمراء. تم في هذا العمل تصنيع طلاءات انتقائية جديدة عن طريق تحسين انتقائية دقائق أكسيد الكروم (Cr_2O_3) النانوية عن طريق تطعيمها بالكربون المحضر بتقنية تفجير الأسلاك لقضبان الكربون بواسطة التيار العالي في معلق دقائق Cr_2O_3. تمت دراسة الخصائص الهيكلية والتضاريس السطحية بواسطة XRD و FE–SEM، والتي توضح الجسيمات النانوية Cr_2O_3 المغلفة بالكربون. تم خلط الجسيمات الناتجة مع مادة داعمة، Polyvinyl pyrrolidone (PVP) كمصفوفة، لاستخدامها كطلاء انتقائي لثلاثة معادن ، وهي النحاس والألمنيوم والفولاذ المقاوم للصدأ . تم إجراء قياسات الانعكاسية ضمن الطيف المرئي للأشعة فوق البنفسجية لحساب امتصاص الإشعاع الشمسي باستخدام التكامل العددي. تم قياس الانعكاسية أيضًا في النطاق من 2.5 إلى 25 ميكرومتر لحساب الانبعاث الحراري للسخان الشمسي ضمن درجة حرارة التشغيل المقترحة البالغة 373 كلفن، وأظهرت القياسات كفاءة جيدة في استخدام المواد المنتجة كطلاء انتقائي والذي تم تحضيره بطريقة بسيطة مقارنة بالطرق التقليدية. أفضل عينة ذات امتصاصية (α) للطيف الشمسي وأقل انبعاث (ε) ضمن منطقة الأشعة تحت الحمراء لأرضيات الالمنيوم المطلية بـ Cr_2O_3: C: PVP كانت $\alpha = 0.886$ و $\varepsilon = 0.260$.

1. Introduction

Recently, the search for new types of renewable energies, including the exploitation of solar energy, has emerged due to the increasing global demand for energy and the need to reduce the problem of pollution and global warming due to emissions associated with energy production from fossil fuels [1]. Solar energy is exploited in three main ways by converting solar energy into electrical, thermal and chemical energy [2]. One of the ways to exploit solar energy is through direct heat absorption by solar collectors and condensers for heating water to generate steam to run turbines [3, 4]. Several studies have focused on increasing the efficiency of selective solar coatings for high absorbance of solar radiation in addition to low emission within the IR spectrum at the black body radiation of operating temperature of the solar absorber [5]. Although black paint has a high capacity to absorb solar energy, it has a high heat emission, so it is not considered a good selective surface [6]. Mixtures of different materials are used as selective absorbers like copper oxide and chromium oxide [7].

The absorption of solar energy can be obtained using the solar spectrum by multiplying it by (1-reflectance), which represents the absorbed energy, then finding the ratio between the area under the curve of absorbed energy to the area under the solar radiation curve. While the emissivity is calculated based on Kirchhoff's law [7], using the reflectivity at infrared range within the black body emission range of the operating temperature for the solar heater [8].

Explosive wire technology is one of the promising technologies for generating nanoparticles. It is a simple, cheap, and effective technique for producing high purity nanoparticles in large quantities [9]. The size and properties of the produced particles can be controlled by many parameters such as the current applied, the diameter of the wires, and the nature of the surrounding environment [10].

In this paper, the effect of coating chromium oxide particles by carbon nanoparticles using an explosive carbon rod on the structural properties and surface morphology was studied. In addition to studying the effect of this merge on the efficiency of these nano particles, as a selective absorber, after mixing them with support material to adhere the substance on substrates as a selective absorbent using different mineral substrates.

2. Experimental

Chromium oxide (Cr_2O_3) powder with a purity of 99.5% (US Research Nanomaterials, Inc.) was used to prepare the aqueous dispersion, by mixing 0.1 of the powder with 100 mL of distilled water using ultrasonic bath. Electrically exploding a graphite rod of 0.9 mm diameter for 30 pulses was done using 100 A current by contacting the positive graphite rod with the negative graphite plate immersed in the suspensions to coat the Cr_2O_3 particles with a nano layer of carbon. Three types of substrates were used (copper, aluminum sheets, and 304 stainless steel) with an area of 2×2.5 cm^2. The surfaces were treated with 3 stages of polishing, finally cleaned with ethanol in ultrasonic bath for 10 minutes and dried with an air blower. The Cr_2O_3 nanoparticles and carbon coated and Cr_2O_3 were used to make a composite with poly vinylpyrrolidone (PVP), in which the extracted powders were mixed with 2 mL of distilled water with 0.1 g of PVP powder in a glass beaker by adding it gradually on a hot plate magnetic stirrer at 60°C with stirring until a homogeneous mixture was obtained , within 30 minutes. The thick films were spread on the different substrates using a screen printing technique. A nylon screen (mesh No. 355) was used for screen printing. A suitable mask was prepared with an area (1.5×2 cm^2) using the standard photolithography process. The printed samples are left for 20 minutes in air to settle and then dried in an oven at 60 ° C for 10 minutes to adhere firmly to the substrate surface. The reflectance patterns of the prepared absorbent layer were measured using a reflection spectroscopy (Avantes DH-S-BAL-2048 UV-Vis), within the range of 200 to 1100 nm, and using a Fourier transform infrared spectroscopy (FTIR Bruker ALPHA II Spectrophotometer) with a reflection mode in the range of 2.5 to 25 μm before and after coating with the prepared selective absorbent and with Cr_2O_3 particles.

3. Results and Discussions

Figure 1 displays the X-ray diffraction pattern for Cr_2O_3 nanoparticles coated by carbon layer using exploding wire technique. Poly-crystalline structure of trigonal chrome oxide structure appeared (standard card No. 96-900-0047) with peaks located at 24.4129°, 33.5227°, 36.1364°, 39.6970°, 41.4205°, 50.1705°, 54.7727°, 63.4091°, and 65.0379° matched with lattice planes of (110), (211), (10-1), (222), (210), (202), (312), (310), and (2-1-1), respectively. An additional peak appeared at diffraction angle of 26.5152° corresponding to (002) direction of hexagonal graphite structure matched with standard card No. 96-900-0047. Table 1 shows the XRD peaks and their interatomic spacing compared with standard values, and the calculated crystalline size for Cr_2O_3 nanoparticles coated by carbon layer using exploding wire method.

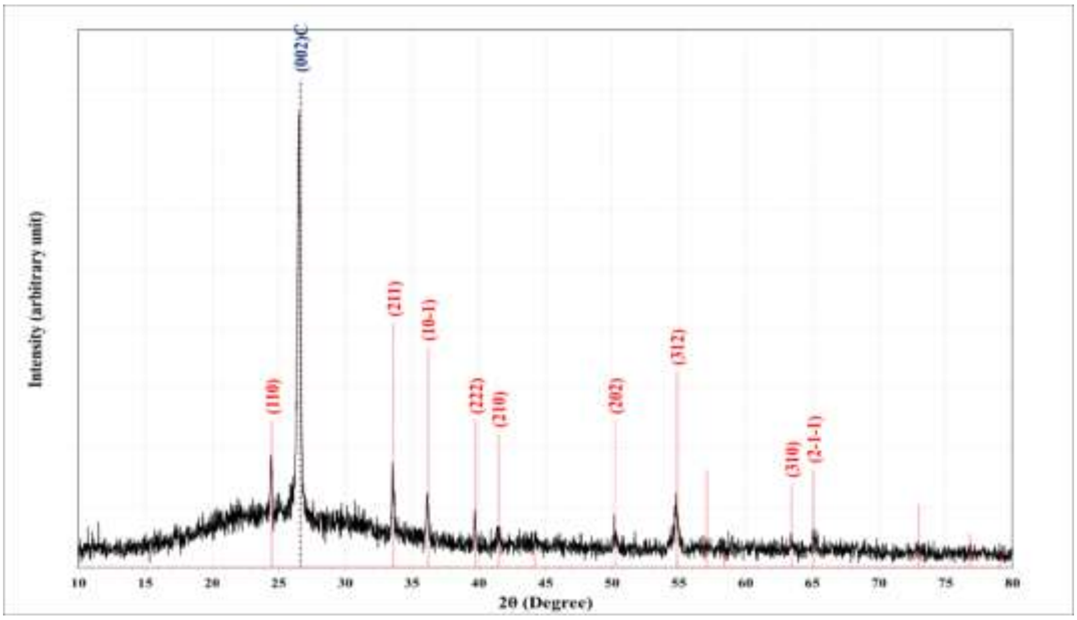

Figure 1: X-ray diffraction pattern for Cr_2O_3 nanoparticles coated by carbon layer using exploding wire method.

Table 1: XRD parameters for Cr_2O_3 nanoparticles coated by carbon layer using exploding wire method

2θ (Deg.)	FWHM (Deg.)	d_{hkl} Exp.(Å)	C.S (nm)	d_{hkl} Std.(Å)	hkl	Phase
26.5152	0.2590	3.3589	31.5	3.3447	(002)	Hex.C
33.5227	0.2083	2.6711	39.8	2.6646	(211)	Trigonal.Cr_2O_3
36.1364	0.1893	2.4836	44.1	2.4799	(10-1)	Trigonal.Cr_2O_3
39.6970	0.1514	2.2687	55.8	2.2649	(222)	Trigonal.Cr_2O_3
41.4205	0.2083	2.1782	40.8	2.1753	(210)	Trigonal.Cr_2O_3
50.1705	0.2273	1.8169	38.6	1.8153	(202)	Trigonal.Cr_2O_3
54.7727	0.3030	1.6746	29.5	1.6724	(312)	Trigonal.Cr_2O_3
63.4091	0.1894	1.4657	49.3	1.4648	(310)	Trigonal.Cr_2O_3
65.0379	0.2272	1.4329	41.5	1.4318	(2-1-1)	Trigonal.Cr_2O_3

Figure 2 shows the field emission scanning electron microscopy (FE-SEM) image for Cr_2O_3 powder. The figure shows that Cr_2O_3 particles have irregular shapes and sizes, and the particle diameters ranged from 500 to 3700 nm.

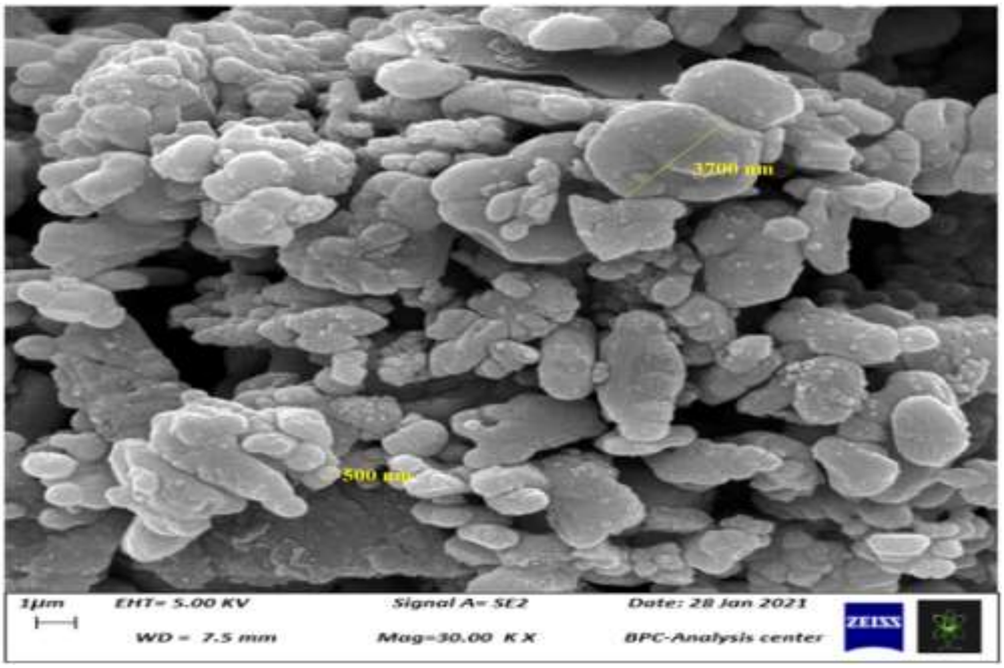

Figure 2: FE-SEM image for Cr_2O_3 powder.

Figure 3 illustrates the FE-SEM images, in two magnifications, for Cr_2O_3 powder coated with carbon NPs by simple exploding of graphite rod using high current, and dried on glass substrate. The Cr_2O_3 appear in irregular shapes and sizes covered by small nanoparticles of carbon of a diameter about 200 nm at different areas.

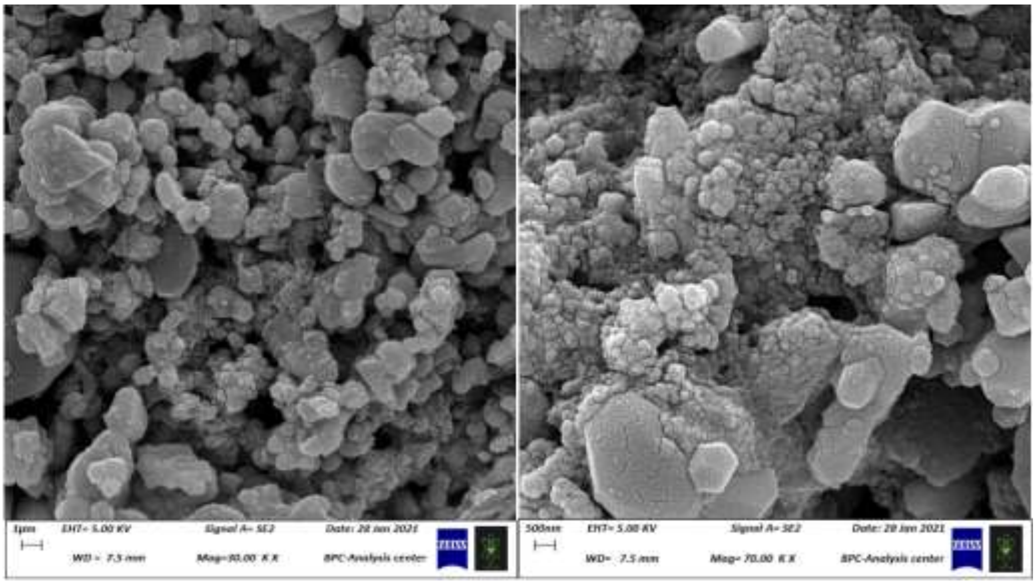

Figure 3: FE-SEM image at two magnifications for Cr_2O_3 powder coated with carbon NPs.

The comparison between the normal solar spectrum (AM 1.5 G standard solar irradiance curve) and the absorbed energy for the bare substrates, and coated with Cr_2O_3 particles, Cr_2O_3 mixed with PVP and Cr_2O_3 coated by carbon nanoparticle mixed with PVP, as adhesive material, are shown in Figures 4 to 6 for the different substrates (Cu, Al, and stainless steel, respectively). The area under these two curves were calculated using numerical integration to calculate the total absorptance in the UV visible range, which is equal to the ratio between the two areas. As a result of reducing reflectance after coating by the Cr_2O_3, more reduce after doping with carbon NPs, and more decrement for sample coated by the composite

CuO:C:PVP, for all substrates, so the area under the green curves increased as compared with that of the black coloured curves.

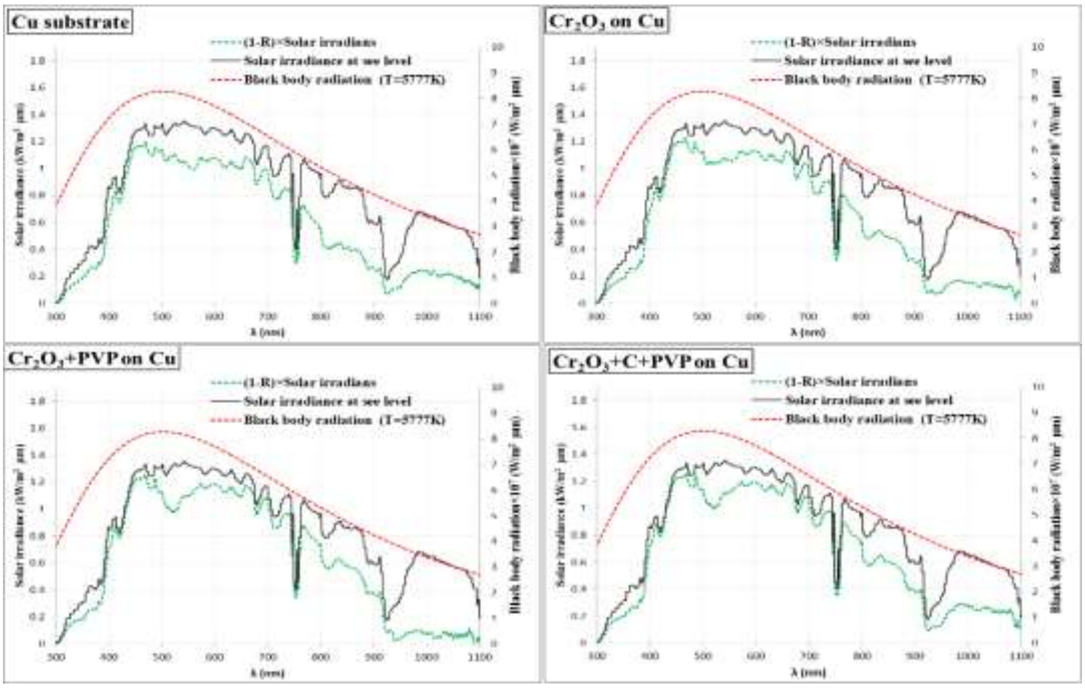

Figure 4: Comparison between solar irradiance curve and (1-R)×solar irradiance for bare copper substrate, and coated with Cr_2O_3 particles, Cr_2O_3 mixed with PVP and Cr_2O_3:C mixed with PVP.

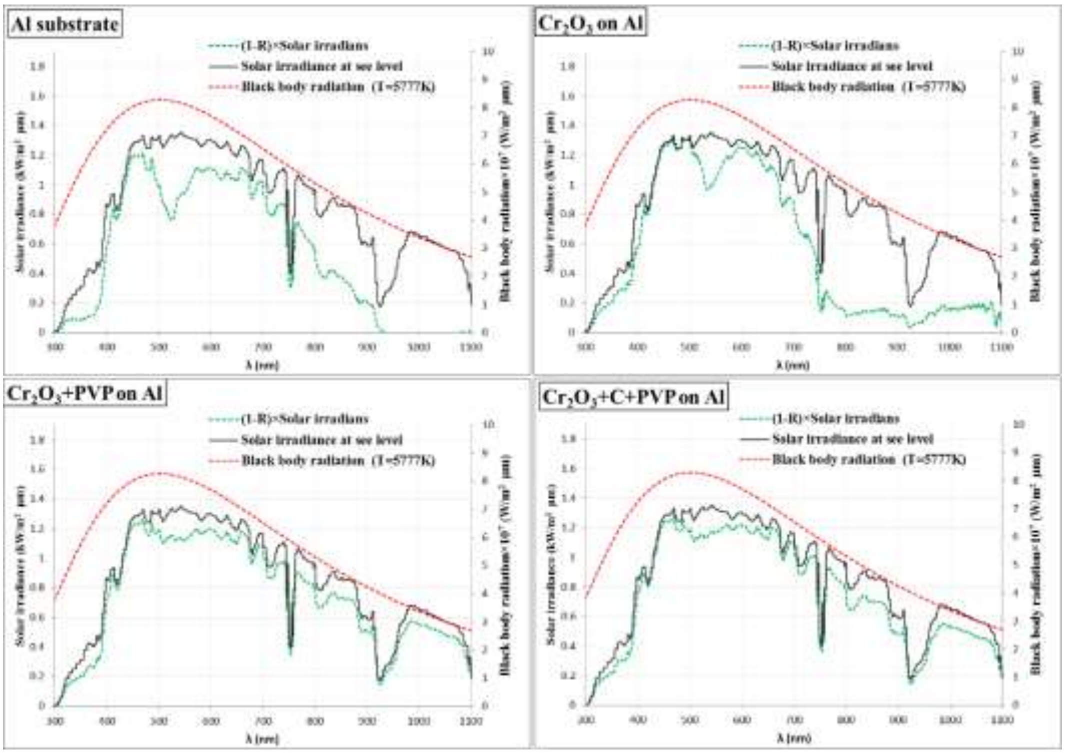

Figure 5: Comparison between solar irradiance curve and (1-R)×solar irradiance for bare aluminium substrate, and coated with Cr_2O_3 particles, Cr_2O_3 mixed with PVP and Cr_2O_3:C mixed with PVP.

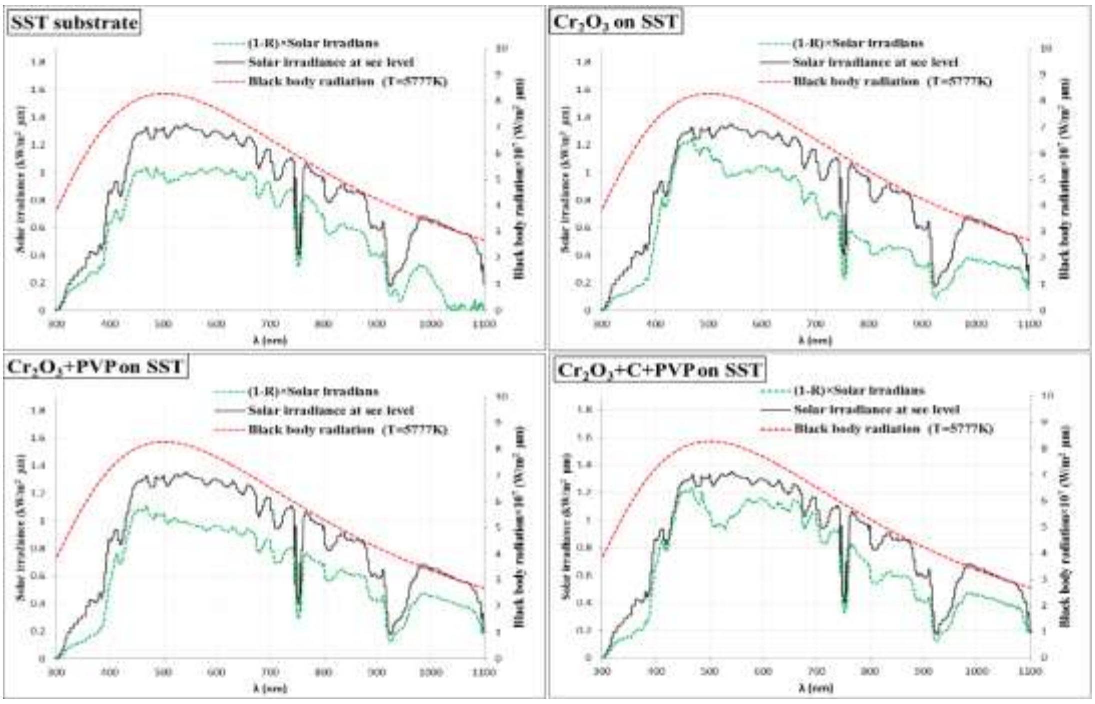

Figure 6: Comparison between solar irradiance curve and (1-R)×solar irradiance for bare stainless steel substrate, and coated with Cr_2O_3 particles, Cr_2O_3 mixed with PVP and Cr_2O_3:C mixed with PVP.

Figures 7 to 9 show the normal blackbody radiation curves at 373 K and the emittance curves calculated from the reflectance curve for the different substrates (Cu, Al, and stainless steel) respectively. These figures show the emittance curves of bare substrates, and coated with Cr_2O_3 NPs, Cr_2O_3 mixed with PVP and Cr_2O_3:C mixed with PVP. The area under the curves were calculated to measure the total thermal emittance for the samples. It seems that the emittance varied according to the samples ‘material.

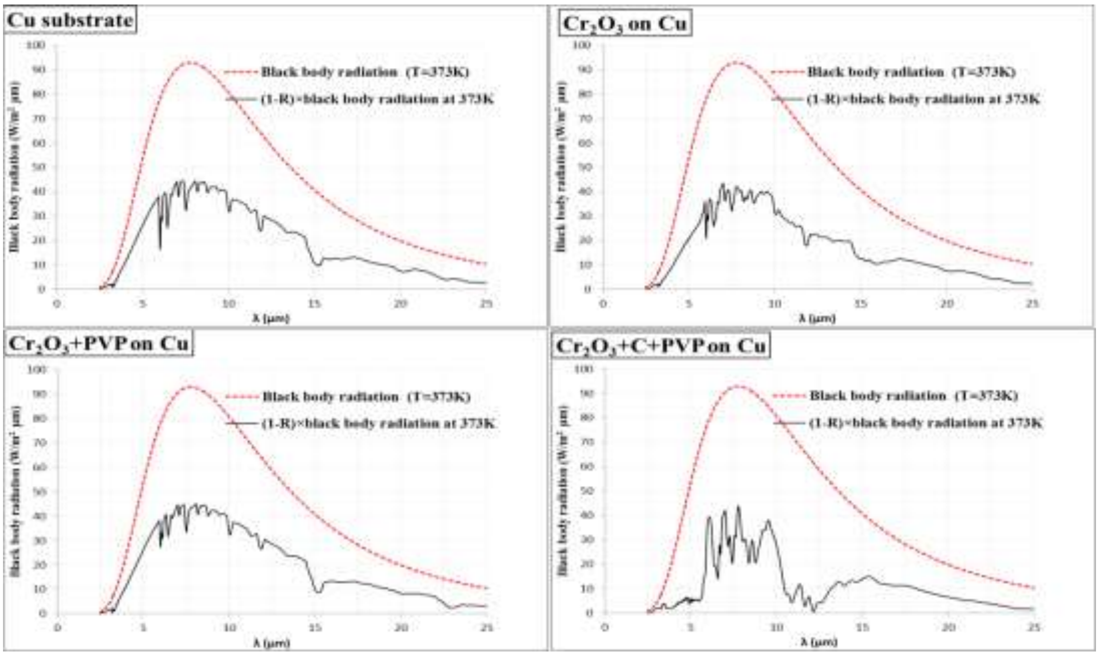

Figure 7: Comparison between black body radiation curve at 373 K and (1-R)× black body radiation for copper substrate, and coated with Cr_2O_3 particles, Cr_2O_3 mixed with PVP and Cr_2O_3:carbon mixed with PVP.

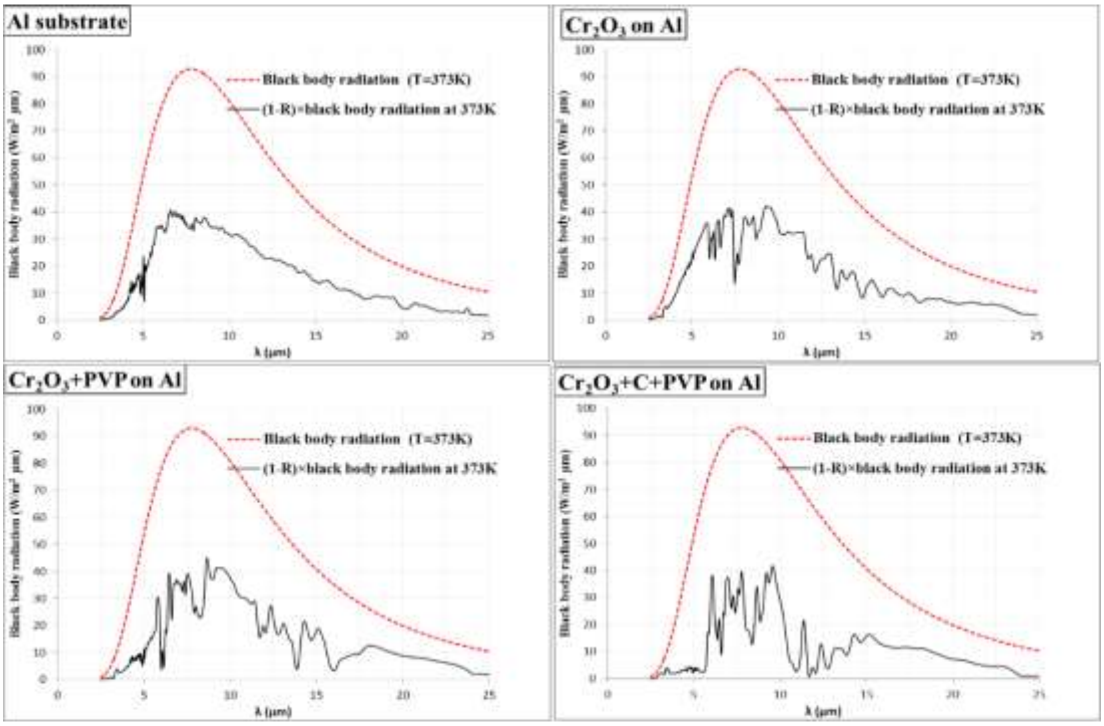

Figure 8: Comparison between black body radiation curve at 373 K and (1-R)× black body radiation for aluminium substrate, and coated with Cr_2O_3 particles, Cr_2O_3 mixed with PVP and Cr_2O_3:carbon mixed with PVP.

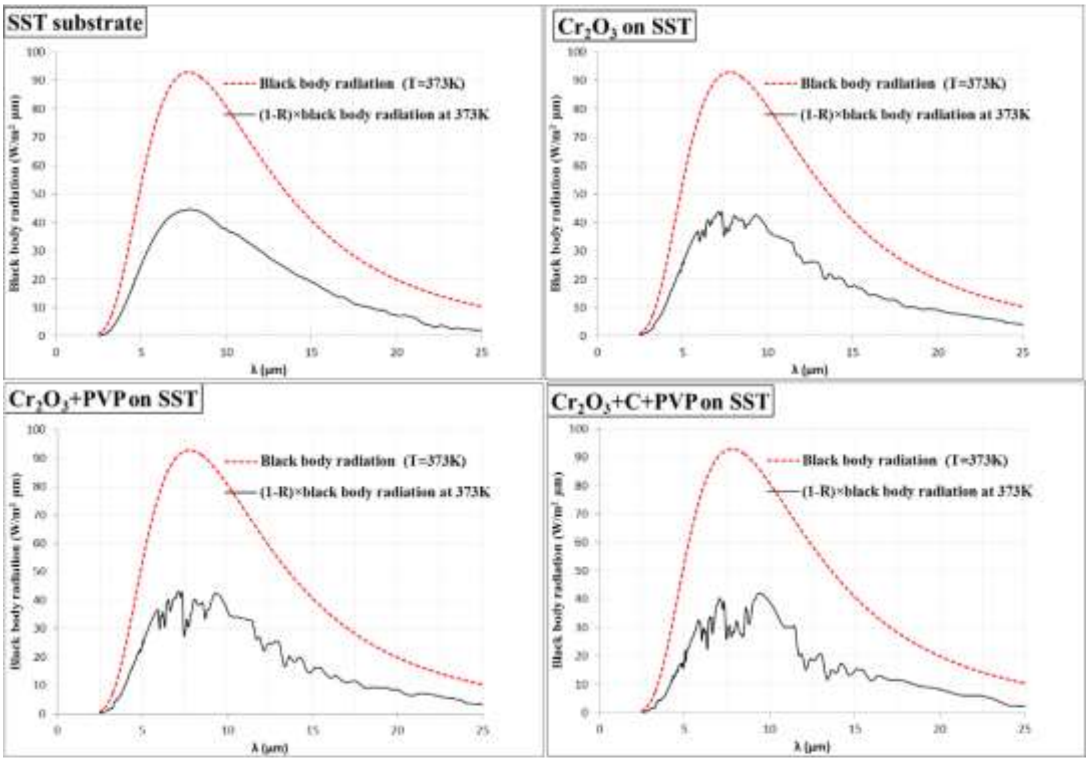

Figure 9: Comparison between black body radiation curve at 373 K and (1-R)× black body radiation for stainless-steel substrate, and coated with Cr_2O_3 particles, Cr_2O_3 mixed with PVP and Cr_2O_3:carbon mixed with PVP.

Table 2 shows a comparison between the UV- Visible absorptance and IR-emittance at 373 K for the different substrates and that coated by Cr_2O_3 nanoparticles, by Cr_2O_3 mixed with PVP, and Cr_2O_3 covered by carbon nanoparticles mixed with PVP. It appeared that the absorptance improved and the emittance reduced for all substrates that were coated by Cr_2O_3:C:PVP especially for Al substrates which showed an absorptance value of 0.886. This sample also has the lowest emittance at IR of 0.260, so it has the greatest ratio of α/ε equal to 3.4.

Table 2: The UV- absorptance and IR-emittance for the different substrates, and coated with Cr_2O_3 nanoparticles, Cr_2O_3 mixed with PVP and Cr_2O_3:C mixed with PVP.

Sample	**Cu substrate**		**Al substrate**		**SST substrate**	
	α	**ε**	**α**	**ε**	**α**	**ε**
Bare substrate	0.701	0.441	0.613	0.374	0.688	0.450
Cr_2O_3 coated	0.722	0.392	0.642	0.377	0.699	0.450
Cr_2O_3+PVP coated	0.742	0.448	0.881	0.348	0.729	0.424
Cr_2O_3:C+PVP coated	0.791	0.262	0.886	0.260	0.799	0.376

4. Conclusions

In this work, a new selective absorber coating was prepared simply and at low cost, using exploding wire technique to enhance the properties of the chromium oxide with carbon nanoparticles. This method was effective in achieving the goal of creating a new efficient coating material that could be used as a selective solar absorber in solar heater systems. The values of the absorbance within the solar spectrum were 0.791, 0.886 and 0.799 for the final coatings on copper, aluminium and stainless steel substrates, respectively. While the thermal emission values within the suggested operating temperature (373 K) were 0.262, 0.260 and 0.376 for the same substrates. The results showed that the best efficiency was obtained with aluminium substrate.

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