Karbala International Journal of Modern Science

Volume 6 | Issue 1 Article 4

Effect of Chromium Trioxide Coating on the Thermal Performance of Solar Thermal Collector

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Recommended Citation

Alaskaree, Èkram Hadi; Skheel Alkhafaji, Osamah Raad; and Al-Muhsen, Nizar F. O. (2020) "Effect of Chromium Trioxide Coating on the Thermal Performance of Solar Thermal Collector," *Karbala International Journal of Modern Science*: Vol. 6 : Iss. 1 , Article 4.
Available at: https://doi.org/10.33640/2405-609X.1311

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Abstract

This paper compared the thermal performance of two solar collectors. The first collector is coated by a dark black absorbent solar collector, and the second one coated by the chromium trioxide. The results of the second collector show a better selectivity in terms of greater radiation absorption, and less emission compared to the first collector. At the minimum solar irradiance time, the absorbed energy is increased from 908.28J to 1221.5J, and the thermal efficiency is improved from 37.3% to 50.1% when the chromium trioxide coating is used. Besides, at the maximum solar irradiance time, the absorbed energy is increased from 1340.5J to 1528.4J, and the thermal efficiency is improved from 63.9% to 78.9%. After three months exposing the collectors to outdoor conditions, the chromium trioxide coated collector show superior thermal performance over dark black coated collector. At the minimum solar irradiance time, the absorbed energy is increased by 877J and the thermal efficiency is improved by about 34% when the chromium trioxide coating is used. In addition, the absorbed energy and thermal efficiency are also increased from 501.1J and 20% to 1440.7J and 62.2% respectively when the solar irradiance is at its maximum value

Keywords

Absorption energy; Chromium Trioxide Coating; Efficiency; Selectivity; Solar Collector; emission.

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1. Introduction

The use of the common energy sources such as coal and petroleum produces large amount of greenhouse gases such as carbon dioxide (CO_2), carbon monoxide (CO) and nitric oxide (NO). This can severely enlarge the global warming crisis over the time increasing the temperature of the earth planet and consequently rising the climate change effects [1]. The solar energy presented the most promising, clean and available source of energy in the world. Therefore, searching for new methods, devices and fabrications which can assist to capture the maximum amount of solar energy is necessary [2].

The coating process on the solar collectors developed a promising way to enhance their overall thermal performance. Therefore, the utilization of the mixture of vanadium and aluminum oxides ($VO_2/V_nO_{2n}\pm1/A_{12}O_3/SiO_2$) developed the emissivity of the collector from about 6% to 48% [3]. The coated material could be fabricated for solar absorber enhancing the heat transfer activity. So that it was found an enhancement in the absorbing of the Evacuated Tube Collector (ETC) system when the $Ni-A_{12}O_3$ layer was used. The increase in the thermal efficiency of the collector was noticed when the thickness of the Ni−Al2O3 layer was increased [4]. The coating materials were used not only to improve the solar absorbance properties of the collectors but also to provide an addition external protection. This statement was found in different types of coating materials such as C/NiO, TiO2 and CuFeMnO4 [5]. Moreover, the authors reported that the use of solar paint materials as an absorber coating reduced the peak absorber temperature from 175 °C to 135 °C. This one was also numerically investigated by simulating the relationship between the thermochromics properties of the black chrome and solar paint coating materials, and their effect on the thermal performance of the used solar collector [6].

Thermal performance enhancement by 89% in the solar collector absorbance was attained when a Cr2O3 coating was used [7]. Besides, recently a Cr2O3−TiO2 (Cardio) composite powders have been synthesized through the high-temperature solid−state reaction method. The achieved results by the X-ray diffraction analysis (XRD) showed that the main composition of the CrTiO composites were TiO_2 and $Cr_{0.12}Ti_{0.78}O_{1.34}$. The complex permittivity permeability of coating increased by the increase of Cr_2O_3 content [8]. Moreover, the numerical simulation for the Cr_2O_3 layers were dielectric in nature, while the Cr layer was semi-transparent due to its low thickness. Therefore, the experimental reflectance spectrum of the $SS/Cr_2O_3/Cr/Cr_2O_3$ solar absorber was successfully simulated using CODE software. It was found that this coating exhibited a good spectral selectivity of 0.82/0.21 at 300 °C [9]. It was well known that the Nanomaterials were also used in different fields of engineering and particularly in heat transfer applications. The use of 0.3% by volume of the carbon-based Nanofluid on multi types of solar collectors could develop an effective improvement. It was found that the carbon-based Nano-fluid material could enhance the thermal efficiency of the flat plate solar collector by about 95.12% compared to the conventional one [10].

In the present study, the effect of the Cr_2O_3 coating on the performance of the flat plate solar collector regarding with the black color coating was investigated. Where the coating process augmented the solar collector properties [11]. It was also found that the tendency to use the coating process was due to its ability to improve the thermal performance of collectors [12]. Furthermore, it was conducted that the use of Cr_2O_3 coating material could have the potential for improving the thermal performance of the solar absorption process in solar collectors [13]. As a result, Cr_2O_3 tincture was used in the surface coating of the used solar water collector in this study. The obtained results were compared with a normal black coating of another solar collector. A standardized procedure for calculation of the annual collector energy output based on the performance parameters resulting from efficiency tests according to EN 12975 and reference climates that were developed in the Solar Key mark II project. The procedure was coded into an Excel spreadsheet that will be available for laboratories' tests. It was also planned to be an informative annex to EN 12975 in the future [14].

1.1. *Theoretical part*

In 1838 via a secret process, Parisians [15] first prepared the transparent hydrated form of Cr_2O_3, then the sold form as a pigment [16] by using Eq. (1). In this process, the Chromite was converted to chromium proceeds via $Na_2Cr_2O_7$ from a derived from the mineral chromite (Fe, Mg) Cr_2O_4. $Na_2Cr_2O_7$ which was reduced with sulfur at high temperatures [17]. In fact,

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this reaction had a low ignition temperature of less than 200 °C, and it was frequently used in “volcano” demonstrations [18,19].

Cr_2O_3 Chromium (III) oxide (or chromium) is an inorganic compound. It is one of the principal oxides of chromium, and it is used as a pigment. Because of its considerable stability and its resistance to the high temperature and wet reactions, chromium is commonly used a pigment. It was originally named viridian. Now Cr_2O_3 is used in inks, paints and glasses. It is the colorant in “chrome green" and “institutional green". The Cr_2O_3 is a forerunner to the magnetic pigment chromium dioxide, this following the reaction shown in Eq. (1) [20−22].

$$Cr_2O_3 + 3CrO_3 \rightarrow 5CrO_2 + O_2 \ldots\ldots\ldots\ldots\ldots\ldots \qquad (1)$$

1.2. Research methodology

This research compares two flat plate of the solar collectors where the coating of the solar absorber with a certain material in which it has the perfect solar properties. The deposition of the black oxide material layer on the absorber surface tends to enhance the absorption of the solar energy. The metal of the absorber is coated with black color which has an absorption rate of a solar beam of about 98% [8]. However, the absorbent surface of the solar collector tended to lose the heat energy when the heat of the absorbent surface is increased more than the ambient temperature. This one tended to make an increase in the emission rate by about 90% and consequently a reduction in the absorption efficiency with a range of 8−10% [9]. Generally, the dark coatings have high solar absorption rates while the bright and shiny colors are low because of being that the dark surfaces absorb all the wavy lengths.

Two identical flat plate solar collectors are designed and fabricated. The first collector is coated with the black color as shown in Fig. 1.The second one is coated with a chromium trioxide material which its properties are shown in Table 1 and Fig. 3 [9]. Each collector is formed by a metallic rectangular parallel box that is provided with an insulating material layer. The top side of the collector is covered by a 4.5 mm glass layer in order to allow for the sunlight to pass through with a minimum amount of solar reflectance. Besides, a water tube bank is used inside each box in order to collect the heated water. The end of the water tube bank was connected to an insulated storage tank to keep the hot water temperature as long as possible.

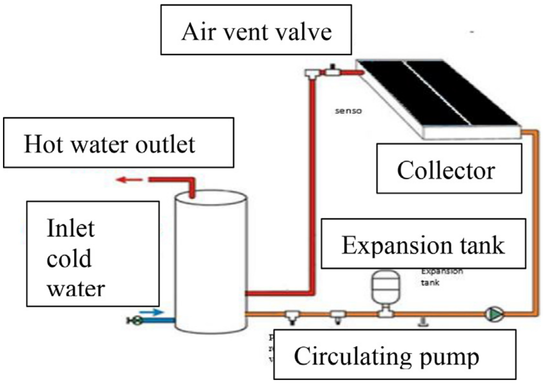

Fig. 1. Solar collector with dark black pickup painted.

The collector box includes a flat plate is made from aluminum and copper alloy and coated by a black color in order to receive the maximum available amount of the solar energy. The use of this type of alloy is to satisfy the maximum thermal conductivity and provide more anti corrosion factors.

A water pump is provided to system in order to circulate the water from the solar collector to the storage tank where the used specifications of that pump are observed as shown in Table 2. Moreover, This system is provided with multi valves to prevent any water leakage when the water pump is switched off/on. It is well known that the increase of the water temperature tends to increase the pressure of water inside the system. Therefore, a pressure relive valve used to work in the emergency situations to reduce the pressure of pumped water throughout the solar collector system as shown in Figs. 1 and 2.

Experiments are conducted to these two solar collectors at the same time and for a specified period of time (9/1/2018 to 27/2/2018). It is also that the periodic daily time is from 9:30 AM to 4:00 PM. The two solar hot water systems are left without cleaning or

Table 1
Cr_2O_3 properties.

Item	Specification
Chemical formula	Cr_2O_3
Molar mass	151.9904 g/mol
Appearance	light to dark green, fine crystals
Density	5.22 g/cm^3
Melting point	2435 °C (4415 °F; 2708 K)
Boiling point	4000 °C (7230 °F; 4270 K)
Solubility in water	insoluble
Solubility in alcohol	insoluble in alcohol, acetone, acids
Magnetic susceptibility (χ)	$+1960.0 \times 10^{-6}$ cm^3/mol

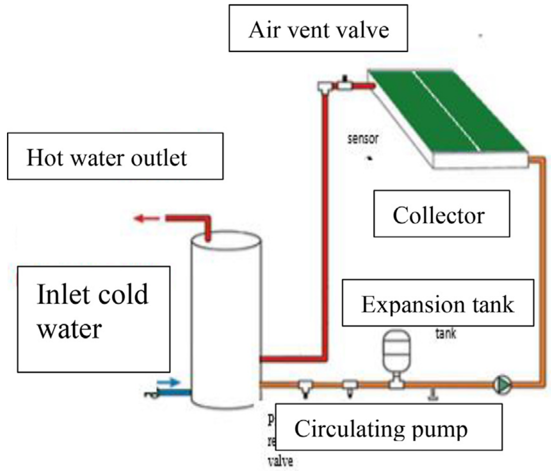

Fig. 2. Solar collector with chromium trioxide pickup painted.

maintenance exposed to dust and rain until 17/3/2018 and then, new readings are taken from 9:30 AM to 4:00 PM.

2. Data reduction

The processing of the extracted data by the instruments are carried out by using the following equations:

Efficiency computation:

$$\zeta\% = \frac{\O u}{A*I}*100\% \tag{2}$$

Thermal energy equation:

$$\dot{Q} = \dot{m}*C*\Delta T \tag{3}$$

3-Solar Intensity equation

$$I_d = \frac{\dot{Q}}{A} \tag{4}$$

3. Results and discussionresults

3.1. Results and the discussion of the first experiment

Fig. 4 shows the behavior of efficiency for the used solar collectors under the same of solar depending on Table 3. It compares between pickup 1 and pickup 2 in term of the thermal efficiency at the same day time. Fig. 4 shows that the thermal efficiency of the solar 2-shot, which is dyed with chromium triglyceride, where it is significantly greater during the day hours from 9:30 AM to 4:00 PM. This is indicating that the chromium trioxide dye made Solar pickup is a selective absorbent of the solar radiation heat, making the solar collector more efficient. After that readings are taken at the first pick up and get results for the following days starting from 10/1/2019 to 27/2/2019. It can be noticed that the top of the solar heat flux at 12:30 PM could cause a greater amount of the absorbed heat at that hour. On the other side, they can often have higher efficiency at 4:00 due to the storage of energy in hot water. At the same time, second readings are taken for the second pick up (see Table 4).

The achieved results for the following days starting from 10/1/2019 to 27/2/2019 refer that the top of the

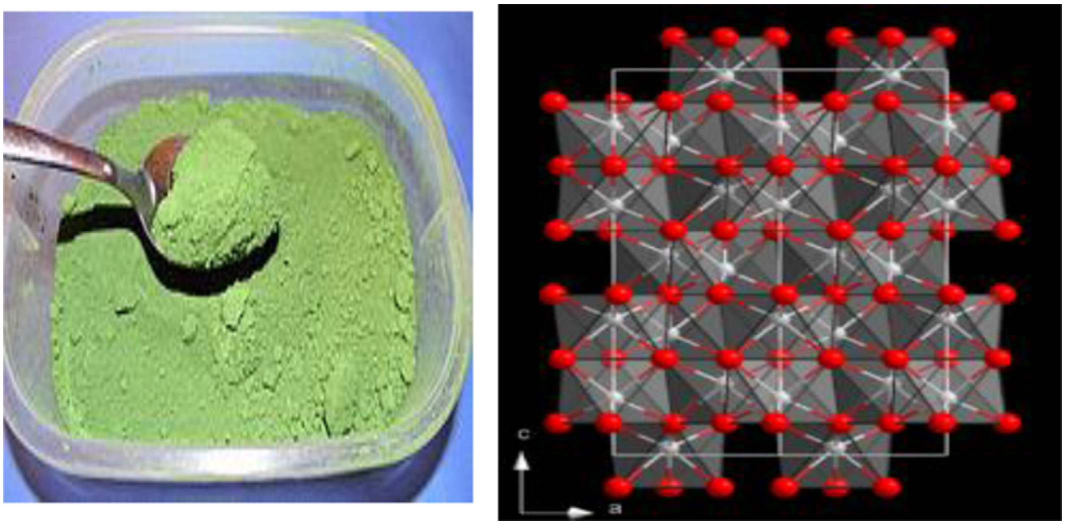

Fig. 3. Chromium(III) oxide properties [9].

Table 2
Pump specifications.

Item	Specifications
Head	30 m
Quantity	5 m^3/hr
Revolution	1500 r.p.m
Type	Centrifugal

solar heat flux at 12:30 PM causes a greater amount of the heat absorbed at that hour always greater than the first pickup.

Furthermore, the thermal efficiency are often greater at 4:00 PM due to the storage of energy in hot water, and it is also greater than the thermal efficiency of the first pickup which could be mainly attributed to the chromium oxide paint.

3.2. *Results and discussion of the second experiment*

Added CrxOx as second compound with a black absorber plate painted with an added coating CrxOx. In March on 17/3/2017 at 9:15 AM to 4:00 PM, readings for the temperature and the solar radiation intensity as shown in Fig. 5 have concluded the amount of energy transferred from the complex and the achieved thermal efficiency for the adopted systems.

4. Comparison of the two solar collectors in the second experiment

The two solar collectors are exposed to the weather conditions for 24 h/day as shown in Fig. 6 Consequently, the corrosion to the pigment of the first collector surface (which was dyed with normal black dye) is observed due to the exposure to dust and acid rain.

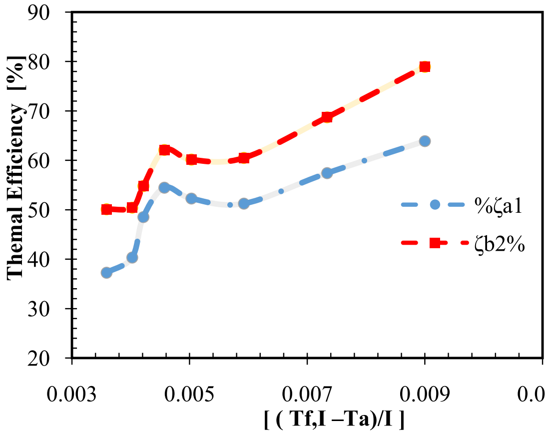

Fig. 4. Comparison between thermal efficiency of pick up 1 and pick up 2 at the same day time in 9/1/2018.

Table 3
The results that Comparison between pickup1 and 2 in efficiency at the same day time and same solar flux. In 9/1/2018.

Solar flux	Pickup 2		Pickup 1		Day time
I w/m²	*(Tf,I−Ta)/I*	*ζ2%*	*(Tf,I−Ta)/I*	*ζ1%*	*Hr*
975.25	0.003	50.09	0.003	37.2	9:30
993.7	0.004	50.427	0.004	40.3	10:30
996.57	0.004	54.81	0.004	48.529	11:30
984.38	0.004	62.103	0.004	54.4	12:30
953.8	0.0055	60.15	0.005	52.273	13:30
894.7	0.0059	60.48	0.005	51.24	14:30
776.6	0.007	68.711	0.007	57.246	15:30
666.7	0.008	78.92	0.008	63.886	16:00

Table 4
The comparison between pickup1 and 2 in efficiency at the same day time.

Solar flux	Pickup 2		Pickup 1		Time
I w/m²	*(Tf,I−Ta)/I*	*ζ2%*	*(Tf,I−Ta)/I*	*ζ1%*	*Hr*
969.56	0.0020	56.85	0.003	20.67	9:30
999.89	0.0020	57.63	0.0030	20.04	10:30
1012.57	0.0029	54.43	0.0036	18.06	11:30
1011.05	0.0049	49.56	0.0049	17.34	12:30
994.94	0.005	50.36	0.005	16.36	13:30
959.73	0.0052	52.21	0.0052	15.66	14:30
892.62	0.0056	56.13	0.0056	16.84	15:30
837.24	0.0059	62.84	0.0059	17.95	16:00

However, the Chromium pigment resisted weather conditions and it does not corrode. The thermal efficiency of the solar collector is larger than the first type. It is increased after 12:30, because the solar flux is decreasing according Eq. (4).

4.1. *Comparison between the collector 1 and 2 in temperatures of water in, water out and ambient air at the same day time*

In Table 5 daytime starting from 9:30 AM to 4:00 PM in the first experimemt in 9/1/2018 the temperature

Table 5
First experiment the results of temperatures of water in, water out and air ambient of collector 1 and 2 at the same day time.

Day time	pickup2			Day time	pickup1		
Hr	T_{e2}	$T_{f,i}$	T_a	Hr	T_{e1}	$T_{f,i}$	T_a
9:30	30	10.5	7	9:30	25	10.5	7
10:30	32	12	8	10:30	28	12	8
11:30	35	13.2	9	11:30	32.5	13.2	9
12:30	38	13.6	9.1	12:30	35	13.6	9.1
13:30	37	14.1	9.3	13:30	34	14.1	9.3
14:30	36.3	14.7	9.4	14:30	33	14.7	9.4
15:30	35.5	14.2	8.5	15:30	32	14.2	8.5
16:00	35	14	8	16:00	31	14	8

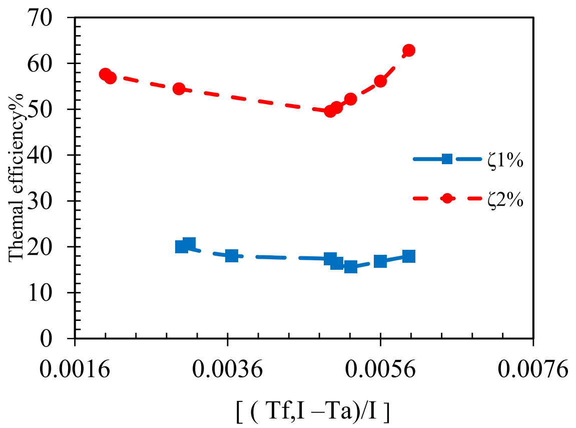

Fig. 5. Comparison between thermal efficiency of pick up 1 and pick up 2 at the same day time in 17/3/2018.

water enters to the collectors and ambient air for both collectores are the same. However, the exit water temperature of collector two is higher than that of collector one. The maximum temperature of water out of collectore 2 is 38 °C at 12:30 PM while the peak temperature of water out of collectore 1 is 35 °C (see Table 6).

Fig. 6 represents the repeated for the exit water temperatures from 9/1/2018 to 27/2/2018 (Te2 >> Te1). This is because of the paint of the trioxide chromium could give collector 2 more absorbed and less emitted solar energy. This difference is repeated in the temperature of the water out of the compilers for the same testing dates. These results of all belong to the first experiment and after leaving the solar collectors from 28/2/2018 until 17/3/2018 to expose to the

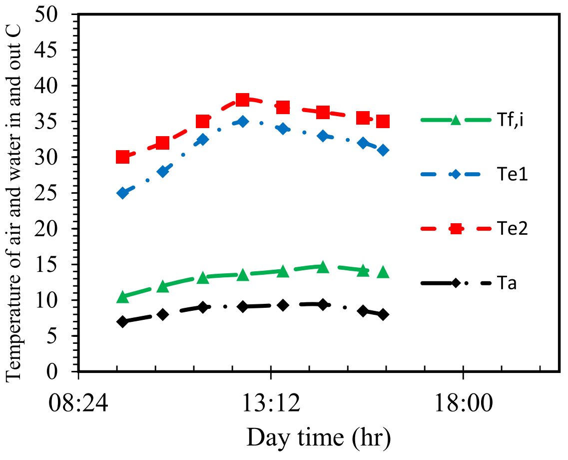

Fig. 6. The comparison between the collector 1 and 2 in temperature of water out (T_{e1} and T_{e2}) in 9/1/2018.

Table 6
Second experiment the results of temperatures of water in, water out and air ambient of collector 1 and 2 at the same day time.

Day time	pickup2			day time	pickup1		
Hr	T_{e2}	$T_{f,i}$	T_a	Hr	T_{e1}	$T_{f,i}$	T_a
9:30	50	31	28	9:30	44	31	28
10:30	52	33	30	10:30	45	33	30
11:30	55	34.7	31	11:30	48	34.7	31
12:30	61	37	32	12:30	50	37	32
13:30	60	38	33	13:30	49	38	33
14:30	58	37	32	14:30	46	37	32
15:30	57	36	31	15:30	45	36	31
16:00	54	35	30	16:00	44	35	30

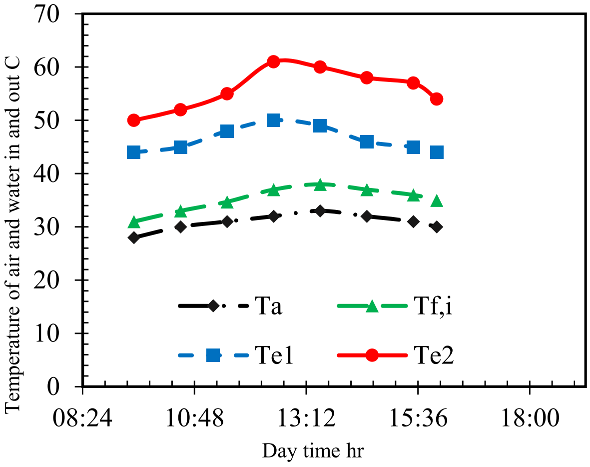

Fig. 7. Second experiment the results of temperatures of water in, water out and air ambient of collector 1 and 2 at the same day time.

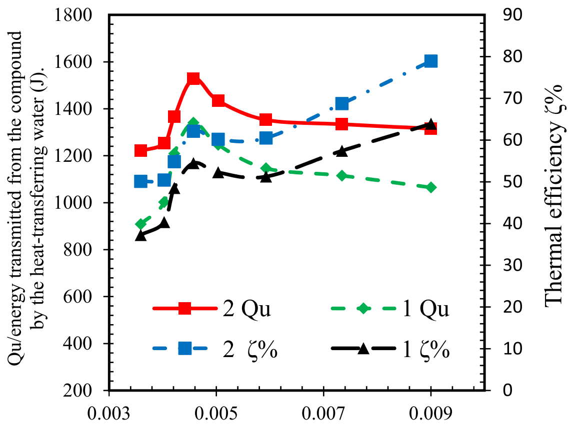

Fig. 8. Comparison of the efficiency curve and the power curve in both collectors in 9/1/20.

weather conditions without maintenance or cleaning. The second experiment is conducted on 17/3/2018. The temperature results of the compilers are presented in.

The energy and efficiency curves of the second pickup, which are painted with a triple chromium oxide coating, are higher than the energy and efficiency curves of the first pickup except for some points of intersection between the power curve and efficiency. However, as shown in Fig. 7 which is for the second experiment, it can be noted that the power curve and efficiency of the pickup 2 are very clear from the curve of the pickup 1. This is another indication of the tolerance of the triple chromium oxide pigment for atmospheric conditions compared to the black dye of the first pickup.

Fig. 8 shows that the thermal energy absorbed by the second solar complex (pigment chromium trioxide) is higher than the first complex. Consequently, the system thermal efficiency of the second complex is greater than the first complex as well. Although both of collectors are exposed to the same weather conditions of acid rain and dust, the second collector proves better resistance to the weather conditions, and more efficient in absorbing a large amount of solar energy and lower emission from the surface of the complex. This superior absorber performance can mainly attributed to the pigment of chromium trioxide coating.

5. Conclusions

The presented study compared the thermal performance of two solar thermal collectors. The first solar collector was coated by a dark black absorbent solar collector, and the second collector was coated by the chromium trioxide material. It is concluded that the triple chromium oxide pigment gives the solar receiver selective absorption of the largest amount of solar heat and emission of the least quantity possible, bearing this dye for the weather conditions of rain, dust, and wind. This made the chromic trioxide pigment worthy of the attention. The best-added quantity of the chromium trioxide to the black bag was experimentally investigated and determined. The determined quantity led to better selectivity and higher thermal efficiency. The paper experimental results showed adding more quantity of triple chromium oxide material resulted in decreasing the selective absorption and reducing the coated solar collector withstand to weather conditions.

Determining the best and worst amount of the triple chromium oxide material in terms of the thermal performance to reach the best selectivity and endurance to.

The extreme weather conditions is another attained contribution in this study. This is conducted by adding a small amount of triple chromium oxide material to exceed 1:5 any five units of black Dye that was added one unit of green chromium trioxide powder.

6. Uncertainty analysis

The uncertainty of water mass flow rate ($\dot{m}$)

$$\frac{\partial \dot{m}}{\dot{m}} = \sqrt{\left(\frac{\partial \dot{m}}{\dot{m}}\right)^2} = \sqrt{\left(\frac{0.015}{10}\right)^2} = 0.0015$$

The uncertainty of water temperature of at the entrance of the collector ($T_{f,\,i}$)

$$\frac{\partial T_{f,i}}{T_{f,i}} = \sqrt{\left(\frac{10}{35}\right)^2} = 0.0816$$

The uncertainty of water temperature exit Collector (T_e)

$$\frac{\partial T_e}{T_e} = \sqrt{\left(\frac{30}{54}\right)^2} = 0.74$$

The uncertainty of ambient air temperature (T_{am})

$$\frac{\partial T_{am}}{T_{am}} = \sqrt{\left(\frac{7}{30}\right)^2} = 0.142$$

The uncertainty of specific heat of water(C)

$$\frac{\partial C}{C} = \sqrt{\left(\frac{1}{1.16}\right)^2} = 0.862$$

The uncertainty of water transfer temperature difference between the inlet and outlet of the collector (T).

$$\frac{\partial T}{T} = \sqrt{\left(\frac{0.6584}{4.5}\right)^2} = 0.146$$

T The uncertainty of heat energy (Qu)

$$\frac{\partial \dot{\mathrm{Q}}\mathrm{u}}{\mathrm{Qu}} = \sqrt{\left(\frac{\partial \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\partial C}{C}\right)^2 + \left(\frac{\partial T}{T}\right)^2}$$

$$= \sqrt{(0.0015)^2 + (0.862)^2 + (0.146)^2} = 0.8742$$

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