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A comparative study for selecting more efficient black selective coating in solar water heating system

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Abstract

Solar thermal collector represents a common system for efficient solar energy conversion. In the field of solar panels, there are numerous types of coatings; their absorptivity is almost more than 90%. The challenge now is to lower the heat loss through emissivity as it predicts the ultimate efficiency (i.e. performance). The solar selective coating is showing higher solar absorption efficiency compared to the commercial black paint, that are applied in most usual solar water heating systems. The present research is devoted to test two types of coatings: second anodized aluminium and traditional matte black paint. Two prototypes of solar water heating system were designed, one having aluminium solar panel coated by matte black paint and the other including solar panel of anodized aluminium electrolytically coloured by tin metal ions after two steps of anodization. The second anodized was found to be superior. The calculated performance or efficiency was about 62%. The efficiency of matte black paint was less than the second anodized type. Moreover, the performance without collector glass cover is lowered drastically.

Keywords: solar panel coatings; solar collector efficiency; solar heating system performance; selectivity; absorptivity; emissivity.

1. Introduction

Solar energy is one of the most popular renewable energy resources that can be used in thermal and photovoltaic systems [1, 2]. Conversion of solar energy into heat is the easiest, cheapest and more efficient way to provide domestic hot water, industrial processes heating and water desalination [3]. These applications require collector panels having high value of absorbance in solar spectrum region (0.3-2.5µm) and minimum heat loss within infrared region ($\lambda >$ 2.5µm). So, the coating for solar collectors should absorb incident radiation as much as possible and preserve thermal energy from re-radiation [4].

This is known as selectivity of coatings, which has been studied since 1950[5]. Consequently, the selected coating should maintain these properties during long term exposure to weathering conditions [6]. Currently, the commercial coatings available on the market with appropriate thermal stability are TiNOX Classic and TiNOX Energy Cu or Al (absorptivity: 0.95, emissivity: 0,04) [7]. Also, the surface called Sunselect & Mirotherm [8], deposited on copper surfaces, has (absorptivity: 0,95 and thermal emittance: 0.05). Hence, the coating type has a significant impact on the performance of the solar collectors.

The most recommended surfaces for heating panels are black paint, black chrome, black nickel, sol-chrome and black anodized aluminum. However, some of these are costly in production and not friendly environmental such as chrome coating [**6**] .Others are expensive and strong emitters for thermal infrared radiation at high temperature like black paints [**9**, 1**0**]. Daviran et al. [11], studied three kinds

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of black coating used in solar systems. The coatings were matt black paint, black chrome and the black nickel-chrome coating used for the absorber surface.

The results showed that black chrome coating (98% purity) had the highest absorption in the ultraviolet and visible range but the matt black paint had the lowest thermal conductivity. Toghdori et al. [1**2**] studied the performance of black cobalt with a sub-layer of nickel to be used for the solar system applications. The results showed a reduced thermal radiation within the near infrared wavelength range. Madhukeshwara et al [**9**], stated that adding of one or more filters or putting a reflector on the absorber surface may decrease the radiant energy loss. Other researchers [1**3**] suggested improving the collector efficiency through using glass cover of three layers. However; this may be high in cost.

Actually, there was a previous interest in Al_2O_3 matrices incorporated with metals to prepare black films [1**4**-1**7**]. Girginov et al. [1**8**], stated that electrodeposition of metal ions within porous alumina, results more efficient coating. The formed anodic aluminum oxide layer (AAO) is characterized by specific structure having self-organized and more-ordered nano-pores [19].

Also, Bwana [20] prepared highly ordered nano-porous AAO via double anodization process and found that longer anodizing period resulted widening of pores. Shaffei et al studied the electro-deposition of Sn, Ni, Cu on anodized aluminum [21-24]. Moreover, in literature, the researchers had investigated [25, 26]the nano-porous AAO film after one and two steps of anodization .The results revealed that, after first anodization, a thick and nonordered layer of AAO film was formed.

While, after second anodization step, highly ordered AAO nanotubes with regular distribution was built over aluminum surface. In addition, the optical results proved that the structure of nano-porous AAO is suitable for deep black color and more efficient solar panels. In this work, a comparison between two types of black coatings was studied. The tested coatings were black anodized aluminum colored by tin electrode-deposition after double anodization and aluminum strips coated with commercial black paint. Two prototypes of solar water heating system were designed. In addition, the effect of existence of glass cover on solar collector surface was investigated.

2. Experimental

2.1 Materials

Aluminium sheet of alloy 99.5 % was cut into similar samples of dimension 40 x 25 cm; aluminium samples were cut with middle flange as shown in Fig.1. Lead and stainless steel were used as counter electrodes in 1st anodization, 2nd anodization and colouring steps, respectively. Some chemical materials were used and prepared in the appropriate concentrations for the preliminary treatment such as acetone, sodium hydroxide, nitric acid and distilled water. Then sulfuric acid was used as the electrolytic solution for first and second anodization. A mixture of phosphoric acid, sulfuric acid and water was used for electropolishing step. Salt solution of 25 g/l tin (II) sulphate was prepared as colouring solution.

Figure 1 A groove with middle flange in the aluminium sheet absorber for fixing the copper tube in tight contact

2.2 Apparatus

- Cooling system was designed for cooling the electrolytic solution during first and second anodization steps. It consists of thermostat, electric engine, copper serpentine immersed in water for circulation of Freon.
- GW Lab DC Power Supply GPR-3030 was used as a source of DC current during first and second anodization steps.
- AC power supply MIO-523/RI Contact voltage 1000 VA output 0-250 V, single phase 50 Hz was used as a source of AC current during electrodeposition and colouring step.
- Thermometers for measuring temperature of heated water
- Solar meter model 776 for recording the intensity of solar radiation
- Thermocouples

2.3 Procedures

2.3.1 Preliminary step

- Aluminum samples were firstly degreased by rinsing with acetone for the disposal of grease or oils.
- Rinsing by tap water and distilled water.
- Etching by immersion in a solution of sodium hydroxide 12 % for 10 min.
- Rinsing by tap water and distilled water.
- De-smutting by immersion of samples in a solution of nitric acid 20% for 30 sec.
- Rinsing by tap water and distilled water for a few minutes.

2.3.2 First anodization

First anodization was carried out by using electrolytic cell of DC power supply connected to working electrode and lead as counter electrode in electrolytic solution of 170 g/l H_2SO_4, where the solution was cooled to 15 ˚C before starting first anodization for 15min. Rinsing by distilled water for a few minutes. Electropolishing step for elimination of the outer irregular layer of anodic coating for 2 min. and rinsing by distilled water.

2.3.3 Second anodization

Second anodization was carried out at 40 min. for rebuilding up of new regular anodic film with diameter in nano size, followed by rinsing of distilled water for few minutes. Finally, electrolytic coloring step using electrolytic cell of AC power supply connected to working electrode and stainless steel and tin sulfate solution.

2.3.4 Preparation of high scale area

A scaling up was done using a larger area 40 x 15 cm, subjected to first and second anodization steps, then electrolytic coloring were frequently applied and consequently, a uniform black color was produced by tin deposition as shown in Figure (2)

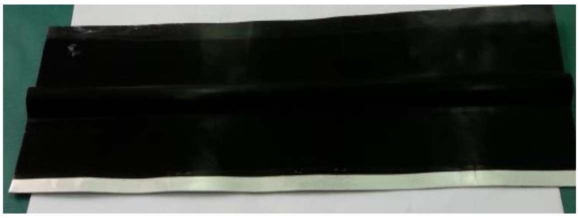

Figure 2 Sample of dimensions 40 x 15 cm after second anodization and electrolytic colouring

Multi samples of second anodized and electrolytically coloured were prepared with the same area and operating conditions for using into the setup of primary model of solar water heater as shown in Figure (3).

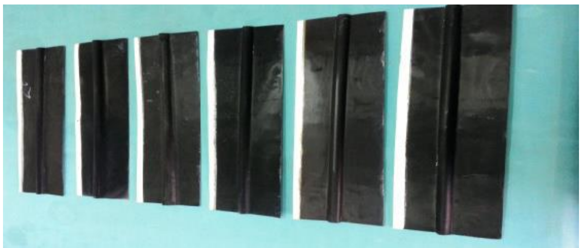

Figure 3 Preparation of multi samples by 2nd anodization and colouring for installation of primarily model solar water heater

2.3.5 Design of prototype of solar water heater

Set up of primary model of solar water heater of the black surface absorber prepared of nano porous anodized aluminium solar panel that electrolytically coloured by tin deposition and another one having aluminium strips coated by matte black paint using brush hand. To assess the performance efficiency of the prepared nano porous anodic black absorber for photo thermal conversion, both systems were exposed to the same conditions of solar radiation in the same situ and the surface temperature of both absorbers were measured and recorded. Then, the temperature of water flow through both absorbers was measured at the same time, photo of the both prototypes are seen in Figure (4).

(a) (b)

Figure 4 Set up of a prototype of solar water heating system. (a) Prepared of black colored nano porous anodized aluminum, (b) matte black paint absorber

The performance of the solar water heating system tested through collector solar panel efficiency evaluation. It is the ratio between the rates of useful heat (Q) transferred to a fluid and the solar radiation intensity falling on the collector surface. It was expressed previously as follows [12]:

$$\eta = \frac{Q}{\text{Ac Gt}} \qquad (1)$$

Where: η is collector efficiency, Q is the gained energy by water (W), A_c is the collector area (m^2) and Gt is incident solar radiation W/m^2

$$\eta = m\, cp\, \frac{(To - Ti)}{Gt * Ac} \qquad (2)$$

Where:
η is collector efficiency,
m: mass of water, C_p = 4180 J/Kg ^oC,
Ac area of collector 0.168 m^2, Gt W/m^2 intensity of incident light,
Ti inlet temperature, To outlet temperature.

3. Results and Disscusion

The paper results are concerned with performance testing of two solar collector panels in two similar heating systems. The first system dedicated secondly anodized black panels. The other is having black aluminium solar panel coloured by matte black paint. The systems were investigated in presence of glass cover and without cover. Then, we have two prototypes of solar water heater, with two different solar panels. The solar panel temperature is (T_p), the inlet water temperature to the collector is (T_i) and the outlet temperature from the collector is (T_o). Figure 5 shows temperature measurements and also the relation of solar radiation intensity in the time range of measurements.

There is high rate of heating initially according to the solar intensity that reached maximum value at 12.30 pm. The temperature increased continuously until 1.30 pm, after that we noticed there is steady state with the decline of solar intensity. Hence, we can observe that, maximum temperature was attained by solar panel of second anodized type (Tp_1= 92ºC). However, for matte black paint Tp_2 is decreased by ten degrees (Tp_2 = 82 ºC) .Moreover, outlet water temperature was 80ºC and 67 ºC respectively, that was the maximum temperatures attained. So, it can be concluded that aluminium anodized panels having higher temperatures than matte black paint solar panel.

The outlet water temperature was lower as a result of heat losses of convection currents between the solar panel and the surroundings. Consequently, the convection currents in the space between the panel, water tubes and glass cover, have a principle role in the process of heating. As shown in case of testing the removing of glass cover from the solar collector, the solar panels were in direct with ambient air and the temperature decreased.

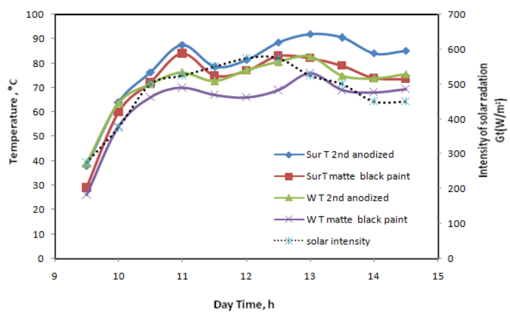

Figure 5 Variation of recorded temperatures (panel & outlet water) with intensity of solar radiation for both second anodized and matte black paint solar collectors with glass cover within day time.

As shown in Fig.6, the temperature behaviour of the two tested solar panels was illustrated. There is obvious decrease in the temperature than that attained before. The lowering of temperatures is approximately from 40 to 50 %. Hence, the curve behaviour in Figure 6 was similar as in Figure 5. The second anodized panel is still higher than the other.

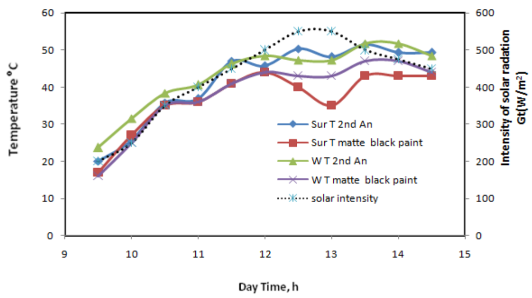

Figure 6 Variation of recorded temperatures (panel & outlet water) with intensity of solar radiation for both second anodized and matte black paint solar collectors without glass cover within day time.

The results of efficiency calculations were listed in Table 1. Moreover, the average efficiency is calculated and collected in Table 2. It illustrates the results of performance for all the systems that were tested for both prototypes of solar water heaters. Tests were repeated at different climatic conditions. From these data, we can conclude that; the higher performance of solar water heater is for second anodized solar panel type (≈ 62%), the calculated increment percent of efficiency than the matte black paint is approximately 17%.

Table (1) Comparison of maximum solar panel (second anodized) temperatures and outlet water with average efficiency values

Intensity of light, W/m²	Max TP_1, ºC	Max TP_2, ºC	Max. TW_1, ºC	Max. TW_2, ºC	$\eta_{1\%}$	$\eta_{2\%}$
575	103	89	92	77	61.7	49.5
500	104	81	85.6	78	55.7	46.4
550	96	87	83	78	54.4	51.4
500	91.6	76	79	76	53.4	45.8
400	45.9	42	46.5	39	26.3	22.4
450	44.7	42	41	38	25.3	23.1
500	51.5	43	51.8	47	28.8	22.6

Table (2) Comparison between increases in efficiency of the anodized panels over the traditional one

Parameter	Average intensity of light, W/m²	$\Delta\eta_1$	$\Delta\eta_2$	Increasing* %
Second anodized with cover	497	56.3	48.2	16.8
Second anodized without cover	397	26.8	22.7	18.1

$$\text{Increasing* \%} = \frac{\Delta\eta 1 - \Delta\eta 2}{\Delta\eta 2} \qquad (3)$$

From these results, we can summarize that second anodized solar panel is more efficient than matte black paint type. This finding agrees with the values of maximum solar panel temperatures listed in Table2. Higher values are recorded for the second anodized panel.

4 Conclusions

Performance of two solar panels is subjected to comparison. Two panels are second anodized and the traditional black painted panel (they have been tested in two prototypes solar heating collectors). Experimental data have been recorded in presence of glass cover and without cover. The data involve temperatures of panel, inlet and outlet water. Also, solar intensity at day time range is recorded. It can be concluded that the performance is judged by controlling the heat loss from the coating of panel that absorbs the solar energy.

The collector loses about 50% of its efficiency when the glass cover is removed. The second anodized coating is more efficient than the black paint coating.

Conflicts of interest

The authors declare no conflicts of interest.

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