Optical and Thermal Investigation of Selective Coatings for Solar Absorber Tube

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Abstract - In this paper, three kinds of common coatings in solar systems including the matt black painting, the black chrome and the black nickel-chrome coating were used on the absorber tube of a parabolic trough collector (PTC). These coatings are compared in aspects of optical absorptance and thermal conductivity. Plating chrome and nickel-chrome coatings were carried out at the optimal conditions of operating temperature, time coverage and cathodic current density. After coating, the inside and outside temperatures were measured and the thermal conductivity was studied by applying uniform heat flux to the coated absorber tube. The results showed that the black chrome coating with 98% purity had the highest absorption in the ultraviolet and visible range and the matt black paint had the lowest thermal conductivity. The SEM images in the result section show the pore spaces in black chrome cover and prove the high thermal conductivity.

Keywords: coating; solar systems; uniform heat flux; thermal conductivity.

1. Introduction

In the industries, such coatings of solar thermal systems have wide range of uses. The coatings that have been applied to the systems must have a low emissivity at long wavelengths, high absorption at short wavelengths, and high thermal conductivity. Black chrome coating is one of the common coatings in parabolic trough collectors. Also, the matt black painting is widely used on the commercial evacuated tube flat plate and on some parabolic trough collectors such as the Mexican prototype (IIE[1]) [1]. The black nickel coating, due to its high potential, is considered for using in optical, electronic components and solar energy conversion [2]. In 2005, the researchers of the National Laboratory of Renewable Energies (NREL) simulated a selective coating with a high thermal stability with a computer [3]. In 2011, Ghasempour et al. studied the optical properties of black nickel on copper, steel and brass [4]. Shawki and Michael studied the performance of black nickel coating for solar system applications. According to their work, by changing the composition of plating solution, the absorptance coefficient was 93% at the best coating

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conditions [5]. In 2011, Toghdori et al. studied the performance of black cobalt with a sub-layer of nickel for using in the solar system applications. In this research, the effect of thermal processes on the optical absorption properties and the surface morphology of black cobalt had been studied. The results showed that the thermal processes would lead to a reduced optical absorption in the near infrared wavelength range [6].

The coating section has a significant effect on the performance of the solar collectors. Bahrami et al. investigated GaAs solar cells by utilizing the cell with single and double layer antireflecting Al_2O_3/TiO_2 coating and a sensational growth in the cell`s performance was seen [7]. Ibrahim and El-Amin presented a low cost antireflection coating (silicon oxide and titanium oxide) and improvement in the cell's performance and reduction in reflection loss was observed [8]. For the low and medium temperature applications, a black chrome coating was used on selective absorber by PVD technologies [9]. A selective coating (AlmecoTiNOX Energy Cu – a copper-based TiNOx sheet) in a micro solar thermal collector for methanol reforming was presented by Gu et al. which had an absorptance of 94% [10]. Zettl studied an antireflective coating and his calculations reveals solar absorptance over 94.5% and thermal emittance below 5% [11]. July et al. investigated a novel black Cu–Co–Mn–Si–O coating on stainless steel tube made by sol-gel coating; they achieved a high solar absorptance over 95% [12].

The black painting was coated by spraying method and the nickel and the black chrome coating was carried out through plating. Control of the electrolyte temperature during the process, uniform deposition of coating and the percentage of additives to the electrolyte solution are the main and difficult circumstances to be done in the plating processes. On the other hand, the black chrome has some environmental limitations. All the studies on the particular coatings with different sub-layers or changes in the components of coatings were on the optical point for improving the absorption properties. According to the aforementioned studies, a comparative study of three different coatings in solar systems has been done in the cases of thermal conductivity and optical absorption.

2. Plating process of absorber tube

For choosing the appropriate coating among the common coatings in solar systems, black chrome coating on a copper tube and matt black paint were taken into account for the process. The reason of choosing these coatings was their good thermal conductivity and optical properties. In this case, before deposition, the metal tube should be polished for plating process and washed with distilled water for removing the impurities. Degreasing and pickling must be done in several steps. In the black chrome plating, the electrolyte plays the anode rule which contains chrome metal and 25 percent chromium oxide. The dissolved positive ions migrating to the cathode were deposited on the metal plate by applying an electric current. The operational terms such as the pH of solution, the electrolyte temperature, the coverage time and the density of cathodic current have a great influence on the uniformity and adhesion level of the coating. The German Schlotter standard reports an acceptable range for the above terms [13]. After several tests, the optimal status for the plating process is reported in Table 1.

Table 1. Operating conditions for plating black chrome and black nickel-chrome

Cathodic current density ($\frac{A}{m^2}$)	~25
Temperature (℃)	18
pH	4<
Coating time(minute)	10
Cathode	Copper
Anode	Nickel/Chrome

3. Thermal and optical properties measurement

The absorptance and reflectance coefficients, the overall optical properties of the absorber tube coating and the reflector measurements were achieved by the Avaspec machine, manufactured by the Spanish Avantes company, with an accuracy of 0.08 nm. Also for studying the thermal conductivity of black chrome, black nickel-chrome and matt black plaint coating on the steel tube and copper tube, a constant heat flux was applied to both ends of the tube by an element. The inside and the outside temperatures of the tube in the coated and uncoated parts were measured by K-type sensor. The K-type thermocouple temperature sensor works in the range of -270 to 1600 °Cand it has an error of 0.5% in this temperature range. The data of the K-type sensor is recorded by a four-channel Lutorn thermometer, TM-946 model. Also an infrared thermometer camera, ITIP-240, was used which functioned in the temperature range of -20 to 250 °Cwith an accuracy of 2%. The method of the inside and outside temperature measurement for computing the thermal conductivity of coatings is shown in Fig. 1.

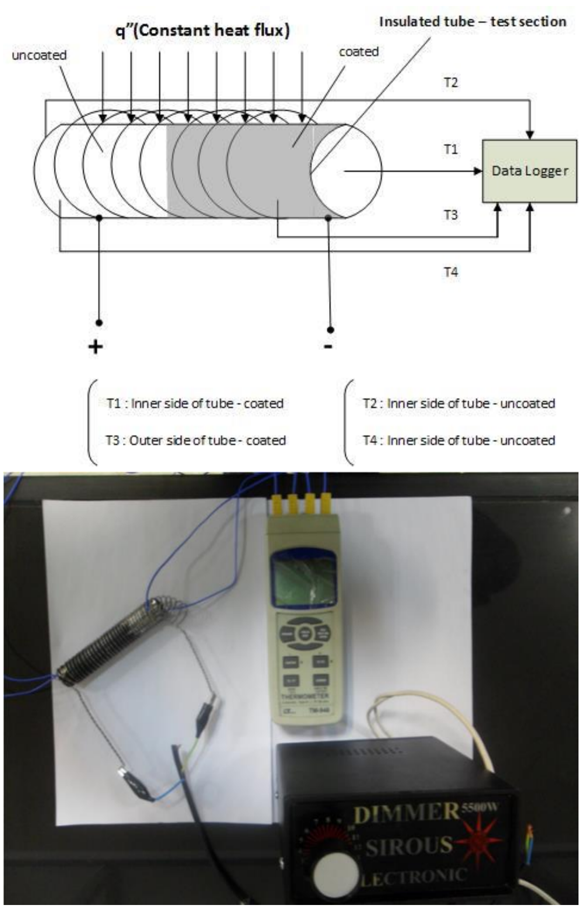

Fig.1. Measurement of thermal conductivity of absorber tuber coating

4. Result and discussion

The SEM analysis images for two kinds of coatings on the copper tube are represented in Figs. 2 and 3. As can be seen, the black nickel-chrome coating has a relatively smooth surface. So, as expected, the absorption amount of black chrome has been increased by trapping the projected light to the surface and preventing the reflection of that light. Trapping and preventing the reflection are the consequence of higher porosity.

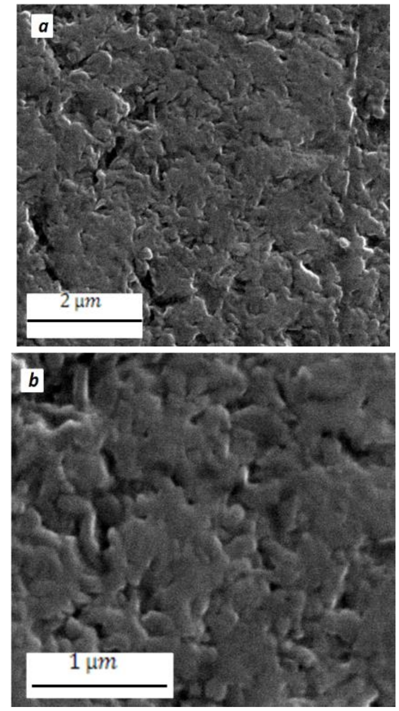

Fig. 2.SEM images of black chrome coating on copper tube in two zoom modes

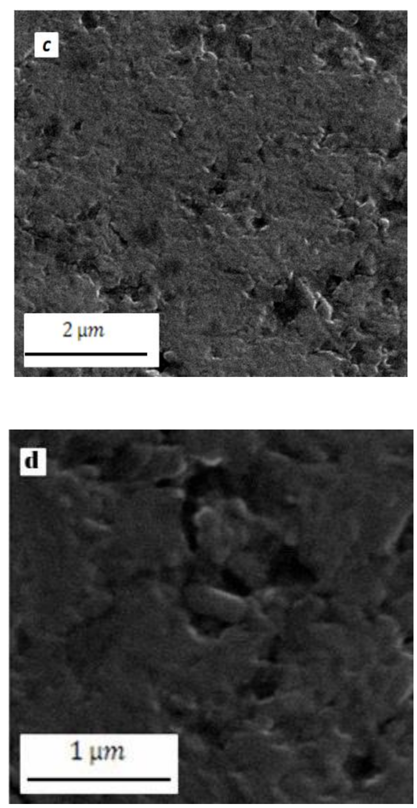

Fig. 3. SEM images of black nickel-chrome coating on copper tube in two zoom mode

The thermal and optical properties of the applied coating on the copper and steel absorber tube have been studied. The comparison between the properties is shown in Table 2. The absorptance coefficient of matt black paint on the steel tube, black chrome coating on the copper tube and black nickel-chrome on the copper tube are shown in Fig. 4. According to figure, in the wavelength of 300-1000 nm (ultraviolet and visible range), the absorptance amount of black chrome and nickel-chrome coating were constant and had the absorptance amount of 97.4% and 98%, respectively. The absorption percentage of the matt black paint was decreased by increasing wavelength and the amount of the matt black paint absorption was 6% lower than the black chrome coating.

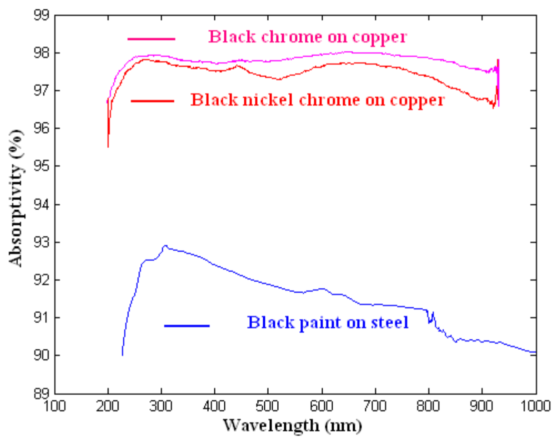

Fig. 4. Optical absorptance coefficient of studied coatings in the UV-Visible-range

According to the explained method, for studying the thermal conductivity of the matt black paint, the black chrome and the black nickel-chrome coating, a constant voltage-based heat flux was applied to both ends of the tube with the mentioned coatings. The temperature profile on the tube under the constant heat flux in the coated and uncoated parts is shown in Fig. 5. Fig. 6 shows the temperature difference between the inside and outside temperatures with the three mentioned coatings under the uniform-constant heat flux applied to the tube. There is no temperature difference between the inside and outside of the black chrome and black nickel-chrome coatings according to Fig. 6. On the other hand, for the matt black painted tube, the temperature difference between the inside and outside of the tube was increased by increasing the heat flux. Using this coating in solar systems especially in concentrating system which has heat flux more than that applied to the system, leads to a higher temperature difference.

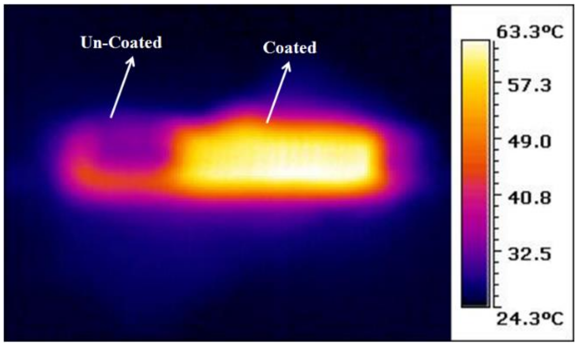

Fig. 5. Temperature profile of coated and uncoated tubes under a uniform heat flux

Table 2. Comparison between the specifications of black chrome and nickel-chrome

Specification	**Nickel-Chrome**	**Chrome**
Density (Mg/m^3)	8.65	7.19
Hardness (MPa)	6000	1060
Maximum Temperature Service (K)	1473	1754
Melting Point (K)	1710	2180
Specific Heat (J/kg.K)	448	460
Thermal Conductivity (W/m.K)	60.4	93.9
Resistivity(10^{-8} ohm.m)	240	125

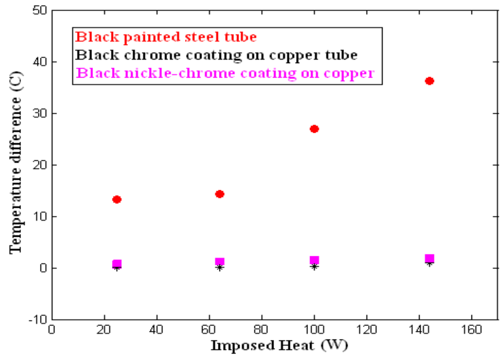

Fig. 6. Temperature difference between the inside and outside of the coated absorber tube under different heat fluxes

The thermal conductivity coefficient of coated and uncoated steel 304 tube was calculated by the Fourier law. The thermal conductivity coefficient values obtained for steel tube have consistency with the one in the reference [14], as shown in Fig. 7. Applying matt black paint with a very thin thickness leads to a reduction of 0.2 $\frac{W}{mK}$ in the thermal conductivity coefficient of the absorber tube.

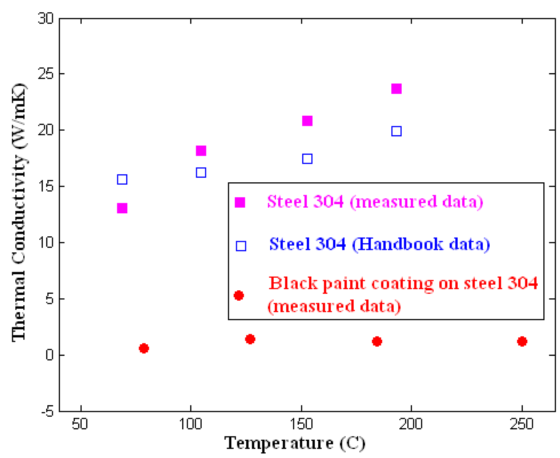

Fig. 7. Thermal conductivity of coated and uncoated absorber tube and comparing with the results of reference 14

5. Conclusion

In this work, three types of coating systems including matt black painting, black chrome coating and black nickel-chrome coating are investigated on the absorber tube of a parabolic trough collector. The optical absorptance and thermal conductivity comparison is carried out under uniform heat flux. The results show that, in the absorber tube with matt black paint, the temperature difference between the inside and outside of the tube is increased by increasing the heat flux. Applying matt black paint with a thin thickness causes a reduction in the thermal conductivity of absorber tube.

The absorption of the coatings are compared and it is found that the chrome coating has the most absorption in the range of ultraviolet-visible with 98% absorptivity. The high porosity of black chrome coating leads to a growth in the absorption amount of this coating. So, for this trough system and considering the morphologies, the chrome coating is preferred. Although the nickel-chrome can have better corrosion resistance and lower environmental concerns.

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