Review based on the absorber plate coating for solar air heater applications

Rahul Kumar, Sujit Kumar Verma
Department of Mechanical Engineering GLA University, Mathura, India
rahul.aero001@gmail.com

Abstract. The critical review presents the development of the solar selective coating on the absorber plate used for solar air heater. Absorber plate coatings directly convert the solar energy into heat. Different type of solar selective coating is therefore developed with high solar absorptance ($\alpha$) and low emittance ($\varepsilon$). A critical investigation is done on the absorber plate metal multi-layers and nanomaterial based coating and resulting performance enhancement. This review reports the similarities in the result through in depth discussion on different type of parameters which can affect the solar air heater performance. Analysis was performed and reviewed here to rationalize and eventually explain the complex behaviors of spectrally selective coating. Based on a systematic review by many researches of published works, coating improves the heat absorbing characteristics for the absorber of SAH.

Keywords: Solar air heater, Absorber plate, performance parameter, Energy conversion.

1. Introduction

Solar air heater is a device to produce the green energy[1] by heating the air which can be used for the various household and industrial applications like building heating, crop drying and space heating etc. The low coefficient of heat transfer between air and absorber plate, the solar air heater always suffers from poor thermal efficiency. Researchers have been used different techniques and methods to improve heat energy transfer from the absorbers. The nanomaterial coating over the absorber plate is most commonly used approach of all these methods for improving the efficiency of the SAH. This review is focused on the absorber plate coating on absorber plate.

Solar thermal collectors will have an installed capacity of nearly 3,500 GW for heated water or space heating, representing approximately 8.9 EJ per year by 2050 hot water and heating space in the building sector. The International Energy Agency reports that warm water and space heating make up 14 percent of energy of space and water [2]. While the solar absorber market is growing rapidly, there is still a lack of a reliable and fairly qualified and long-term norm, especially for solar absorber coatings for high-temperature. Thermal stability and life of service are important high-temperature parameters for solar absorber applications [3]. The absorber coatings are exposed to extremely intense solar intensity and experience high thermal shocks during the day and night. This is one of the main factors of ageing, since the alternation between night and day and cloud spells may create sharp changes in solar intensity, leading to thermal heat shocks to the absorber coats.[4]

2. Presented review methodology

This section is dedicated to the early work that laid the foundation and led to the development of convective heat transfer through absorber plate coating. The following relevant historical points summarise the past results for heat transfer in the absorber coating. Figure 1 shows the description of performance improvement methods for the SAH,
Table 1 shows the comparative analysis based on the nanomaterial coating and Table 2 shows the metal multi-layer coating on the absorber plate for SAH applications.

Figure 1: Description of performance improvement methods

El-Sebaii and Al-Snani [5] investigate the mathematical model for single pass SAH with CuO, Cr-Cr2O3, Ni-Sn and CoO, black paint coated absorber plate. The result was also gives the higher annual average efficiency with Ni-Sn coated absorber by 19.23%. Figure 7: Variation of the absorptivity and daily efficiency for absorber plate coating [5]

Liu et al.[6] studied the effect of CrAlO nanocomposite coating on the absorber plate. The four-layers structured coating consists of a pure chromium layer, low Cr–Al–O (LOCL) content of oxygen, a central Cr–Al–O(MOCL) oxygen content and a high Cr–Al–O(HOCL) oxygen content. The results show that LOCL and MOCL had a relatively large absorptive value of 0.924 and a relative low emittance of 0.21 as well as an excellent thermal stability of 0.919/0.225 selectively even after annealing at 7000 C in the air during 2 hours.

Wäckelgård et al.[7] did comparative study for the W-SiO2 and Nb-TiO2 for the absorber coating. Results: W-SiO2 absorber gives higher emittance comparative to Nb-TiO2. The value of solar absorptance and emittance is 0.93 and 0.1 or less respectively at 350°C

Nady et al.[8] the comparative analysis consists of black paint and bright nickel combined with black paint for absorber coating. They found in result the bright nickel coating was give better performance compared to black paint in case of efficiency and the overall heat loss and optical gain of collector was decreases. The Figure 2 shows the SEM morphology of plain and cross-sectional view of the bright nickel.

Gao et al.[9] did study the high performance coating for absorber plate. Here a porous material SS/TiC-Y/Al2O3 was used for coating by the simple vacuum annealing process. The result shows the good thermal stability at 800°C in vacuum for 100h for SS/TiC-Y/Al2O3 porous material.

L and S [10] did solar absorber coating study in CuO-PANI nanostructure. They was examine the SEM morphology and XRD diffraction analysis for nanostructure and find the solar absorptance, emittance and selectivity was optimized to 0.94, 0.01 and 94 respectively. Results: CuO-optimized PANI solar absorber coating is highly promising for its selective optical properties.

Chen and Boström [11] investigate the comparative study of three type of N-CNT, P-CNT and T-CNT for the spectral selective coating for absorber. They found in result, the P-CNT absorber achieve better spectral selectivity.

Jeong et al.[12] investigated the CuO nanostructure as a absorber coating for solar absorption. The experiment was examined by both indoor and outdoor condition for the performance of solar absorber. Results showed that the sharp morphology and a random distribution of the CuO structure permit enhanced optical broadband absorption, with the corresponding results calculated at about 95% and 97% of the existing state-of-the-art TiNOX absorber for both single-and two-glazing situations. The Figure 3 shows SEM morphology of CuO absorber plate.
Šest et al.[13] the experimental study improves the corrosion behaviour to understand the functionality of graphene nanomaterial spectral selective coating. They found in result “In order to significantly improve the corrosion inhibition behaviour of the coating, a small quantity(0.05 % wt) of graphene platelets was required for paint dispersion.”

Abdelkader et al.[14] investigated the effect of absorber coating on flat plate SAH and examined the exergy and energy analysis. The coating was fabricated by the carbon nanotubes (CNTs) and cupric oxide nanoparticle (CuO) embedded in black paint. They found in result the exergy efficiency is increased by 24.4% and the difference in output and input temperature is rises to 22% for 4% CNTs/CuO embedded in black paint. Figure 4 shows the SEM image of 4% CNT nanoparticle embedded in black paint. Figure 8 shows the day time vs. absorber plate and ambient temperature and solar radiation with and without 4% CNT/CuO- black paint.

Sivakumar et al.[15] did experimental study on the flat SAH for the drying applications. They was done comparative study between the black paint and different percentage of CuO nanoparticle for improving heat transfer between absorber plate to air. It was identified the efficiency of the system got improved by 4% , drying time is reduced by 6% and higher temperature is recorded while using 0.04 % of CuO nanoparticle with black paint coated absorber plate.

Madhu et al.[16] studied the effect of CNT-black paint coating on absorber plate for passive type SAH and Experiments have been carried out continuously and the air flow rates through the duct are different. The results showed that the coating effect increased the plate temperature to a maximum of 102 degrees celsius while the modified SAH coated with ordinary black paint and staggered fin was found to 95 degrees celsius for m= 0.03 kg/s. Figure 5 shows the SEM morphology of CNT nanoparticle.

Kumar et al.[17] the experimental study was carried out on the triangular shape SAH with graphene nanomaterial embedded in black paint coating on absorber plate. The result improves the thermal efficiency is about 4.9% for 1% graphene nano material and it was found the maximum glass and absorber plate temperature at the solar intensity 930-980 W/m². Figure 6 SEM image of the graphene embedded in black paint.

| Authors                  | Coating Material | Absorption/Emittance | Design Modification | Results | Remark (Analysis) |
|--------------------------|------------------|-----------------------|---------------------|---------|-------------------|
| El-Sebaii and Al-Snani, 2010[5] | CuO, Cr–Cr₂O₃, Ni–Sn and CoO, Black Paint | Flat Plate | Ni–Sn as an average daily coating material efficiency of 0.46 was obtained the best output due to reduced heat losses rate and improved usable energy rates. | Solar air heater's performance compared to the CuO, Cr–Cr₂O₃, Ni–Sn and CoO and black layer. |
| Liu et al., 2014[6]      | CrAlO            | 0.924                 | Absorber coating    | The surface coating demonstrated greater thermal stability in air for 2 h up to around 700 C. | These findings recommend that the coating can be used for highest-temperature solar photo thermal conversion. |
| Wäckelgärd et al., 2015[7] | W–SiO₂ and Nb–TiO₂ | 0.91/0.08            | Flat Plate          | Results show that both perform as well as 0.91/0.08 and 0.93/0.09 as-prepared solar absorptance/emittance at (350°C) respectively. | The W–SiO₂ coating on absorber could also be generated with grater absorption and emission. |
| Nady et al., 2016[8]     | Ni electroplating and black paint | Absorber plate coating | The optical collector gain F₉ of the commercial paint was reduced by 24.7% and for paint combined with bright nickel by 19.3%. | - The total F₉(UL) heat loss for commercial paint was increased by 3.3%. - Increased by 2.7% for commercial paint mixed with light nickel after temperature ageing test. |
Table 1: Various Solar Absorptive Coating and Their Performance

| Authors               | Coating Type                  | Solar Absorption | Solar Emission | RemarksABBREVIATIONS | Remarks |
|-----------------------|-------------------------------|------------------|----------------|------------------------|---------|
| Gao et al., 2016[9]   | SS/TiC-Y/Al2O3                | 0.9              | 0.11           | Absorber coating       | A simple vacuum annealing method was developed to produce a high-performance, spectrally selective solar absorber coating. |
| L. and S, 2016[10]    | CuO-PANI(Polyaniline)         | 0.94             | 0.01           | Flat Plate solar air heater | The PANI and CuO-PANI optical characteristics increase the value of the os while the desired texture of the combinations reduces the et value which makes their use in solar thermal systems extremely impressive. |
| Chen and Boström, 2016[11] | CNT Nanotube                  | 0.90             | 0.14           | Solar air heater absorber plate | The best result was a 0.90 and a solar absorption thermal emission 0.13. |
| Jeong et al., 2017[12] | CuO nanostructures            | 0.876 to 0.946   | 0.85 to 0.94   | Absorber coating       | It improves the performance of absorber plate by using CuO nanostructures. |
| Sest et al., 2018[13] | Graphe ne nanoplatelets       | Solar absorber coating | Compared to Al substrates, these coatings have shown higher corrosion inhibition behaviour and have improved significantly with regard to normal TSSS coatings. |
| Abdelkader et al., 2020[14] | cupric oxide nanoparticles embeded in black paint | 0.954-0.979     | 0.15 to 0.22    | Flat Plate solar air heater | The conclusions made indicate a 24.4 percent improvement in energy efficiency. |
| Sivakumar et al., 2020[15] | CuO nanoparticle in black paint | Solar absorber coating | Collector performance increased by 4.0 percent using black paint with 0.04 vol. percent of CuO nanoparticle for absorber plate coating. |
| Madhu et al., 2020[16] | CNT-black paint               | Solar air heater | The effect of absorber coating improves the temperature of absorber and maximum temperature achieved 102 °C. |
| Kumar et al., 2020[17] | Graphene nanomaterial in black paint | Solar air heater | By using graphene-nanomaterial coating on the absorber plate, the average thermal efficiency is improved by 4.9 percent in daylight hours. |
Schüler et al. [18] investigated the optical properties of C: H/Ti for solar selective absorber coating with the help of PVD/PECVD process for vacuum deposition of titanium containing amorphous hydrogenated carbon film. The experimental result gives the absorptance and emittance value is 0.876 and 0.061 respectively for the service life of more than 25 years.

Cao and Hu [19] studied the coating of NiCrOx stainless steel substrate on the absorber plate and calculate the optical constant for the film thickness. They found in result the zero reflectance at 8 micro metre and high reflectance at the infrared.

Xiao et al. [20] investigated the CuO thin film coating on the absorber plate by using chemical conversion method. SEM, XRD and FTIR spectra were used to find optical properties of thin film and composition of material characterization. The results show that thin film composition structures and optical properties have been greatly affected by NaOH reaction temperature, time and concentration.

Khamlich et al. [21] studied the annealing effect of Cr/alpha-Cr2O3 monodispersed material coating on absorber plate. The result was gives better performance of rough tantalum substrate at lower temperature 600°C. Céspedes et al. [22] investigated the effect of Mo–Si3N4 based solar selective coating on the solar applications. It has a high solar absorptivity 0.926 and low emissivity 0.017 on silver film. It gives the high thermal energy conversion efficiency.

Valleti et al. [23] Investigate the high temperature multi-layered coating for stainless steel and copper substrates using physical vapour deposition technique. In the temperature range 27–700°C the open air high temperature output of the optimised multi-layer structure was also investigated and the stability of the coaters in terms of optical properties was defined at high temperatures.

Ding et al. [24] investigated the Fe–Cr–Ni alloy coating on the absorber surface. Detailed surface-structure and chemical composition details were examined using AFM & Raman spectroscopy. The CrO3 and NiFe2O4 surface structure shows the good stability at 300°C in air. It gives better temperature for photo thermal conversion applications.

Zheng et al. [25] investigate the Mo–SiO2 double cermate solar selective coating for absorber applications. It was found in result Mo–SiO2 coating with angular absorptance 0.945 from 0–600 is a wide angle for absorptance coating.

| Authors | Coating Material | Absorptance | Emittance | Design Modification | Results | Remark (Analysis) |
|---------|------------------|-------------|-----------|---------------------|---------|------------------|
| Schüler et al., 2000 [18] | C: H/Ti | 0.876 | 0.061 | Solar absorber coating | This coating gives the better performance at 0.876 absorptance and 0.061 emittance. | The life-span of these coatings on aluminum substrates is expected to be over 25 years. |
| Cao and Hu, 2000 [19] | NiCrOx/SS | 0.8 | 0.14 | Solar absorber surface | The measured optical constants of the NiCrOx absorbing layer were necessary to obtain zero reflectance, and at a wavelength of 0.8 mm, the spectral reflectance of the NiCrOx tandem exhibited near zero reflectance. | It gives better solar optical properties for the NiCrOx stainless steel substrate as absorber coating. |
| Xiao et al., 2011 [20] | copper oxide | 0.94 | 0.08 | solar selective absorbers | • The thin film was prepared at 40°C pure Cu2O coating. • It gives the maximum thermal efficiency is 0.68 at 15 min. | The film thickness increases the reaction time, temperature and concentration also. |
| Khamlich et al., 2013 [21] | Cr/Cr2O3 | 0.9 | 0.28 | Monodispersed particles based solar absorbers | • This technique has shown that it can render reproducible, low-cost coatings of high quality. • This type of rough tantalum substrate coatings are good for applications with solar absorbers at temperatures below 600°C. | The optical measurements indicate that samples annealed at 400 and 500°C are heavily absorbed. |
| Céspedes et al., 2014 [22] | Mo–Si3N4 | 0.926 | 0.017 | Parabolic concentrating | The high absorptivity and low emissivity gives the higher | With the full optical and thermal analysis of the |
Valleti et al., 2014[23] Cu/TiAl CrN/TiAlN/AlSiN 0.91 0.007 Solar absorber coating Here Cr/AL multilayer gives the good absorptivity and emissivity value. The multi-layer structure of TiAlCrN / TiAlN/ AlSiN has shown promise of high-temperature thermal stability.

Ding et al., 2015[24] NiFeCrOs 0.9 0.1 Selective absorber coating • This material coating improves the thermal stability and optical performance.
• The needle-like structure was found to have unique anti-reflection and selective absorption advantages.

Zheng et al., 2015[25] Mo-SiO2 0.945 solar selective absorber coating Over a large range of incidence angles from 0 to 60, Mo-SiO2 double cermet selective solar absorber absorption remains almost constant. The experiment was investigated as a function incidence angle of from 0-75 degree for measuring spectral reflectance.

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**Figure 2**: SEM image of bright Nickel (a) Plain view (b) Cross-sectional view [8]
Figure 3: Using focused ion beam technique, CuO absorber SEM images and cross-sectional images of the CuO generated by varying process time from 1 min to 4 minutes. [12]

Figure 4: SEM image of 4% (CNTs and CuO) -black paint [14]

Figure 5: SEM image of CNT nanoparticle[16]
Figure 6: FE-SEM image of graphene embedded with black paint

Figure 7: Variation of the absorptivity and daily efficiency for absorber plate coating[5]

Figure 8: Day time vs. absorber plate and ambient temperature and solar radiation with and without 4% CNT/CuO–black
3. Mathematical relations for Solar air heater

3.1. Characterization of performance of solar absorber coating

Scanning electron microscopy (SEM) has shown the surface morphology of the best spectral absorber coating and X-ray diffraction (XRD) was used to demonstrate nanomaterials used. Optical properties of coatings are measured at the ambient temperature of room. The solar absorptance (α) and thermal emittance (ε) were calculated by the mathematical relation[6],

\[ \alpha = \frac{\int_{0.3 \mu m}^{2.5 \mu m} I_{sol}(\lambda)(1 - R(\lambda)) d\lambda}{\int_{0.3 \mu m}^{2.5 \mu m} I_{sol}(\lambda) d\lambda} \] 3.1.1

\[ \varepsilon = \frac{\int_{2.5 \mu m}^{25 \mu m} I_b(\lambda)(1 - R(\lambda)) d\lambda}{\int_{2.5 \mu m}^{25 \mu m} I_b(\lambda) d\lambda} \] 3.1.2

Where \( R(\lambda) \) is the spectral reflectance, \( I_{sol} \) the solar radiation power is at AM 1.5 and \( I_b \) at room temperature is the black body spectral emitting power.

\[ \text{Spectral Selectivity} = \alpha - 0.5\varepsilon \] 3.1.3

3.2. Performance Analysis of solar Air Heater

In solar heating, efficiency is the biggest component. This aspect affects the system’s productivity. The rate of usable heat \( Q_u \) determined by the solar air heater is expressed in terms the energy lost by the system,[26]

\[ Q_u = A_c E_c [I(\tau_\alpha) - U_l(T_a - T_{in})] \] 3.2.4

The sum of top loss coefficients and the losses from the bottom and heat loss from the edge are the total heat coefficients \( U_t \). Which is by the equation can be expressed,[26]

\[ U_t = U_t + U_b + U_e \] 3.2.5

The formula determines the top loss coefficients \( U_t \)[27],[28]

\[ U_t = \left( \frac{N}{C(T_p-T_{in})^{N+1}} + \frac{1}{h_a} \right)^{-1} + \sigma(T_p-T_a) \left( \frac{T_p^2 + T_a^2}{1 + \frac{T_p}{0.0896 + \beta}} \right) \] 3.2.6

\[ f = \left( 1 + 0.0896 + 0.01166 + 0.000051 \beta^2 \right) (1 + 0.0786\beta) \]

\[ e = 0.43 \left( 1 - \frac{100}{T_p} \right) \frac{2N + f - 1 + 0.133e_p}{\varepsilon_0} \]

\[ C = 520[1 - 0.000051 \beta^2] \text{ For } 0^\circ \beta < 70^\circ \]

The coefficients for heat loss from the bottom,[29]

\[ U_b = \frac{h_b}{h_a} \] 3.2.7

And coefficients for heat loss from the edges,

\[ U_e = U_b \left( \frac{A_e}{A_c} \right) \] 3.2.8

We can use the equation to calculate the heat removal factor,[30]
The air heat transfer coefficient can be obtained from the equation. [31]

\[ F_R = \frac{\dot{m} C_{\text{pair}}}{A_L U_L} \left[ 1 - \exp \left( -\frac{U_L A_p}{\dot{m} C_{\text{pair}}} \right) \right] \] 3.2. 9

The Dittus-Boelter equation finds the Nusselt number,

\[ N_u = 0.003 R e^{0.8} P r^{0.4} \] 3.2. 14

The coefficients of heat transfer obtained with the number of Nusselt and given by the relationship are,

\[ h = \frac{N_u k_a}{D_H} \] 3.2. 15

The efficiency factor of the absorber is defined by the equation,

\[ F' = \frac{h}{h + U_L} \] 3.2. 16

The solar heating system's efficiency is the ratio of useful heat gain and energy input from heat. [26],

\[ \eta_e = F_R \left[ \alpha U_L (T_a - T_{in}) \right] \] 3.2. 17

4. Conclusion

The present analysis aims to provide an overview of recent developments in solar air heater research with an emphasis on the absorber plate’s solar selective coating. The parameters solar absorptance (\( \alpha \)) and thermal emittance (\( \varepsilon \)) and design consideration such as significantly influence the efficiency of SAH. On the basis of the analytical evaluation of the absorber plate coating, the reviewer suggests the following important points:

- The experimental method has been more popular among researchers, but recent trends have shown that there is extensive use of nanomaterial coating on the absorber plate.
- The coating effect increased the plate temperature to a maximum value.
- Early work contributed several researchers to investigate a different form of coating material which gives the better heat absorbing characteristics for the absorber plate.
- The performance of the SAH improves by using coating material on the absorber plate.
- Most of the researcher uses large gain in solar absorptance and reduced thermal emittance for better improvement in solar absorber coating.