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Optimization Study of Collector's Absorber Coating Parameters for Solar Thermal Heat Collection Applications

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The ability of a solar collector to transform (absorb) as much of the solar energy it receives into useful heat, minimizing loses of the converted energy to the environment, determines the effectiveness of the collector. These capabilities are functions of the absorber plate parameters, design and ambient conditions. This study experimentally examined the effect of absorber coating vis-a-vis coating thickness on the overall performance of flat-plate solar collectors. The samples consist of three mild steel absorber plates of 50mm by 10 mm and 1mm of thickness each, named Samples A, B and C. Sample A was uncoated, a thin film (less than 1mm thickness) of acrylic resin is deposited on Sample B, while Sample C was thickly coated with the same resin at a thickness of approximately 1mm. It was discovered that acrylic resin actually increases the solar absorbance of the thin (lightly) coated absorber plate sample by 21%, over the uncoated sample. It was noted that when the layers of coatings were increased (thick coating), the absorbance dropped sharply by

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about 50% lower than that of thin coating (lightly coated). Thick coating reduced the absorbance of solar energy of uncoated sample by about 32%.
It is therefore evident that lightly coated metal sample have a far better absorbance value than that with thick coating. In order to validate the result, the samples were subjected to an on-site solar thermal investigation under the same atmospheric conditions. The Samples A, B and C recorded average plate temperatures of 68^{o}C, 92^{o}C and 85^{o}C respectively. Therefore, the thinner the coating of a substrate, the higher the absorptivity.

Keywords: Collector; absorber plate; acrylic resin; coating; spectral selectivity; thin film.

NOMENCLATURES

Q_o	:	*Rate of heat loss*
Q_u	:	*Rate of useful energy extracted by the collector*
U_L	:	*Overall heat transfer coefficient*
T_{plate}	:	*Collector Plate temperature*
T_a	:	*Ambient temperature*
ρ	:	*Reflectivity of a surface,*
τ	:	*Transmittance*
α	:	*Absorption*
$\alpha_{\lambda,T}$	:	*The monochromatic absorptance of a surface*
$\varepsilon_{\lambda,T}$	:	*The monochromatic emittance of a surface.*
$\rho_{\lambda T}$	:	*The monochromatic reflectance of a surface*
n	:	*Refraction index of the substance*
v_o	:	*Speed of light in vacuum*
c	:	*Complex speed of electromagnetic wave in the substance*
n_r	:	*The real part refraction index of The substance,*
k	:	*The imaginary part constant of absorption of substance*
j	:	*Imaginary unit.*
r	:	*Specific resistance*
α_c	:	*The absorption coefficient ,*
A	:	*Absorbance*
k	:	*Thickness of the sample*
θ	:	*Electrical conductivity*
E, E_o	:	*Permittivity*
μ, μ_o	:	*Permeability*
f	:	*Frequency of radiation*

1. INTRODUCTION

Interests in solar energy as a competitive contributor to the world energy mix have risen again primarily on the basis of high cost of fossil fuel energy, its associated environmental problems and also in adherence to world campaign on the use of renewable energy. The search for alternative and new energy sources have risen due to long term over-reliance on fossil fuels with its attendant cost and its negative environmental impact. [1-3]. Implementation of Passive, hybrid and low/medium energy for water heating and ventilation techniques are being undertaken in a number of countries of the world. Hot water is a necessity in order to maintain proper sanitation, health, comfort air-conditioning and for domestic / industrial production processes [4-6]. The capacity to maximize absorption of solar radiation into useful heat with minimal loses of the absorbed energy to the environment is the determinant for thermal efficiency of a solar collector. This quality of a good solar collector; that is, its capacity to maximize absorption of solar energy into useful heat is dependent majorly on the transmittance (τ) of the solar collector's cover and the absorptance (α) of the absorber (coatings and substrate) and also the efficiency factor (F) of the collector . The Collector heat losses are basically dependent on the nature / type of insulation material and the emittance ε of the used absorber coating [7-8].

Fig. 1 shows the solar spectrum which is the distribution of the emitted electromagnetic radiation by the sun. This distribution is a function of the wavelength incident from the top of the atmosphere to the surface of the earth. Considering the total electromagnetic radiation emitted from the sun, over 50% occupies wavelengths longer than the visible region (From the Infrared region), approximately 44% in the visible region (0.4~0.7 μm), while about 3% in wavelengths shorter than the visible region (From the Ultraviolet region). Most of the electromagnetic energy from the sun, reaching the earth emanates from the photosphere, that is, sun's surface [7-8].

Ramalingam et al. [10] reported the effect of different ratios of grapheme on black paint as a selective coating on a mild steel absorber plate of a flat plate solar collector. is investigated experimentally. Three samples, made up of different ratios of black paint to graphene as 1:1, 1:2, and 1:3. The average absorptivity of the

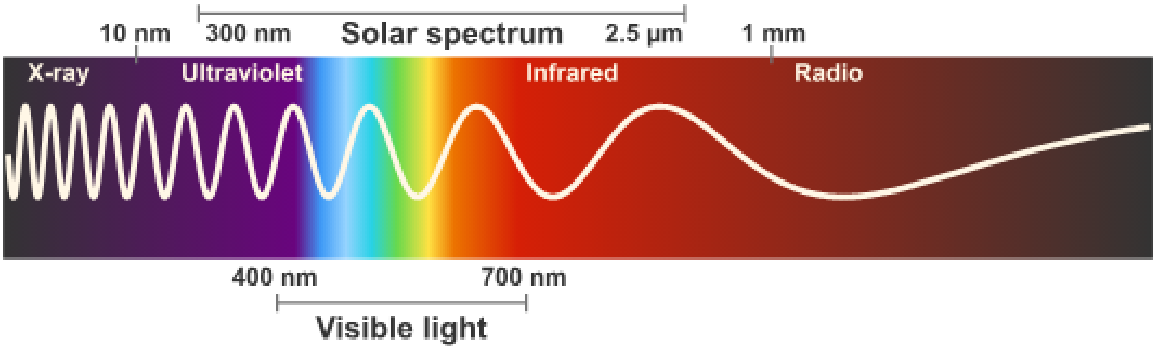

Fig. 1. Solar radiation spectrum [9]

graphene and black paint coated samples are determined to be about 0.87 and 0.82, respectively. The absorber surface with 1:3 ratio of black paint and graphene coating had the best performance, It is observed to have an average 6.25% more than that of the standard black paint coating because of higher thermal conductivity of graphene particles.

Mong et al. [2] experimentally studied a hybrid flat-plate solar collector/nocturnal radiator for water heating and cooling in Owerri, Nigeria. They deployed a single mild steel absorber plate, film-coated with a spectrally selective acrylic resin. The work recorded a peak water temperature of 60ºC at a plate temperature of about 80ºC, under solar heating phase, at a heat collection efficiency of 31%. The peak insolation was about 900W/m^2, at ambient temperature fluctuating between 27ºC and 32ºC all through the diurnal phase. The work recommended an improved coating parameters on the substrate for better efficiency.

Nwaji et al. [11] presented a parametric analysis of the dynamic performance of a hybrid flat-plate solar collector/nocturnal radiator, using Titanium PolyethyleneTerephthalate composite coating, for water heating and cooling. The work recorded a maximum water temperature of 88 °C (average value), under diurnal phase.

Roro et al. [5] undertook a selective coating of the absorber at South Africa, using a spray coating technique in order to deposit C/NiO coatings on the substrates, mainly aluminum. Their result showed an impressive 90 % absorptance.

Grangvist [12] reviewed works done by researchers on selective coatings, and described three applications of spectral selective coatings with respect to heating and cooling applications. They are selective transmission to achieve energy efficient windows; selective absorption of solar energy in order to produce useful heat; and radiative cooling by selective infrared emission towards the clear sky.

Other works reviewed, are those that adopted spectrally selectivity single surface to achieve both heating and cooling.

Yiping et al. [13] in Tiajin, China, combined solar heating and night radiative cooling, using single collector to produce a novel heating and cooling system. They adopted a composite coatings , comprising two different types of acrylic resins on the substrates. The work recorded a satisfactory results both in heating and cooling phases respectively. The daily average heat-collecting efficiency are respectively about 32% and 20% with the maximum points of 50% and 30%, in November. It equally 20 W/m^2 and 40W/m^2 cooling capacity for nocturnal cooling applications. Mingke et al. [14] studied a spectral selectivity surface for both solar heating and radiative cooling in their experimental and theoretical study. In the course of their work, they did a trial-manufacturing of a selective surface with a Titanium substrate, coated with polyethylene terephthalate (PET powder) called TPET, which recorded an average plate(Titanium) temperature of 90°C at maximum solar radiation in the range of 710W/m^2 and 925W/m^2 during heating with peak value at around 12:30PM in Hefei, China, using TPET as coating material. Cooling recorded 13^{0}C temperature depression at optimum weather and design conditions.

A surface is said to be spectrally selective if it has a high absorptance for solar radiation, as well as a low emittance for the temperature range in which such surface emit radiation. A good selective surface is one which allows for absorption of large solar radiation, such that a small amount of energy is reflected and radiated. However, this capability can be enhanced by designing optimal coating parameters. Therefore, this work undertook absorber plate selective coatings of various coating thickness, optical characterization of coated plates of different thickness and recommend coating with optimum performance for solar thermal heat collection. The aim is to increase the solar absorptance α of collectors, vis-à-vis the performance the collector. Thus, this study seeks to experimentally expand the study in the development of surfaces for solar heat collections through coatings.

2. MATERIALS AND METHODS

2.1 Experimental RIG (Substrates) Materials

In a bid to maximally evaluate the effectiveness of the coating, three mild steel plates (substrates) were used and presented as samples A,B and C. Sample A was uncoated, Sample B was light (thin) coated with acrylic resin, in micrometer coating thickness while Sample C was heavy (thick) coated with same resin. This was in order to evaluate the effects of substrate coating thickness in the performance operation of a flat plate collector. The choice of materials was based on usage, cost and availability in order to encourage further experimentation in the future.

2.2 Absorber Coatings / Samples Preparation

The basic essence of the selective coating is to maximize the absorptance of solar within the radiation band.Acrylic resin and black paint are used, having proved to be spectrally selective [3,13].

Acrylic resins are derived from acrylic acid, methacrylic acid or other related compounds. They belong to family of related thermoplastic or thermosetting plastic substances. Acrylic resins are primarily monomers of acrylate and methacrylate and are water / weather resistance, it is glossy provides good color retention when coated in exterior surfaces [15]. Acrylic resin as used by Yipping et al. [13] had the following optical properties as used in the research work; 0.4~ 0.7 Absorptivity, 0.92~0.96 emissivity and 0.3~ 0.6 reflectivity.

The Samples, A, B and C were 50mm by 10mm each and 1mm thickness. The choice of the dimensions was based on the dimension of the testing space in Spectrophotometer machine.

The absorber coating technique as adopted was spraying technique, using a 5hp compressor powered sprayer owing to the viscosity of the acrylic resin. The coating thickness was varied by varying the number of sprays.

2.3 Theoretical Assessement of Spectrally Selective Surfaces

Solar radiation shown in Fig. 1, is found to concentrate within 0.2-3μm spectral region of the solar radiation band.

As the collector absorbs heat, its temperature starts getting higher than that of the surrounding and heat is lost to the atmosphere via the surrounding, by convection and radiation. The rate at which heat is lost (Qo) depends on the collector overall heat transfer coefficient (U_L) and the collector temperature.

$$Q_o = U_L A(T_{plate} - T_a) \quad (1)$$

Fig. 2. Acrylic res

Fig. 3. Labeled metal samples

"Thus, the rate of useful energy extracted by the collector (Qu), expressed as a rate of extraction under steady state conditions, is proportional to the rate of useful energy absorbed by the collector, less the amount lost by the collector to its surroundings" [18].

Therefore, selecting the right surface for solar thermal collection is critical to efficiency of flat plate collectors. Spectral selective materials coated on the absorber ensures that heat exchange is allowed within certain wavelengths.

2.3.1 Kirchhoff's law

The solar radiation falling from the upper atmosphere strikes on surfaces on the earth, where it is partly reflected, partly transmitted and the surface absorbs part of it. The optical characterization of reflectivity of a surface ρ, transmittance τ and absorption α, as captured by [16-18] is shown.

Generally;

$$\rho + \tau + \alpha = 1 \quad (2)$$

For opaque body is τ = 0, so absorption of substance is α = 1− ρ. In assumption that radiation of body is during thermodynamic balance with surroundings, then in accordance with the Kirchhoff's law for spectral emissivity $\varepsilon_{\lambda,T}$ of body equals;

$$\varepsilon_{\lambda,T} = \alpha_{\lambda,T} = 1 - \rho_{\lambda T} \quad (3)$$

$$\varepsilon_{\lambda,T} = \alpha_{\lambda,T} \quad (4)$$

Where;

$\alpha_{\lambda,T}$ = The monochromatic absorptance of a surface
$\varepsilon_{\lambda,T}$ = The monochromatic emittance of a surface.

$\rho_{\lambda T}$ = The monochromatic reflectance of a surface [16].

Refraction index, n, of the substance is in general complex quantity.

$$n = \frac{v_o}{c} \quad (5)$$

Where n is in general complex quantity, where v_o = speed of light in vacuum , c is complex speed of electromagnetic wave in the substance. That means that complex refraction index $\boldsymbol{n}$ is,

$$n = n_r - jk \quad (6)$$

Where;

n_r = The real part refraction index of the substance,

k = The imaginary part constant of absorption of substance and $j = -1$ is imaginary unit.

Among optical quantities n_o and k, there are other electromagnetic quantities that characterize quality of substance, like, electrical conductivity θ, permittivity E and permeability μ and they relate by the equation;

$$n_r{}^2 - k^2 = \frac{E \cdot \mu}{E_o \cdot \mu_o} \quad (7)$$

Also,

$$n_r \cdot k = \frac{\theta \cdot \mu}{\omega \cdot E_o \cdot \mu_o} \quad (8)$$

Where $\omega = 2 \cdot \pi \cdot f$

and f is frequency of radiation, $E_o and\, \mu_o$ are permittivity and permeability of vacuum respectively.

Considering Fresnel's formulas for perpendicular incidence radiation to interface air-conduction area reflectivity, we can deduce that;

$$\rho = \frac{(n_r - 1)^2 + k^2}{(n_r + 1)^2 + k^2} \quad (9)$$

Where $\rho = Refectance$

Also substituting other optical properties, we can have;

$$\rho \approx 1 - \frac{2}{v_o}\sqrt{\frac{4 \cdot \pi \cdot f}{\mu \cdot \theta}} = 1 - 4\sqrt{\frac{\pi}{v_o \cdot \mu \cdot \lambda}} \quad (10)$$

Noting the relationship between Frequency, speed of light and wavelength as;

$$f = \frac{v_o}{\lambda} \quad (11)$$

We can then write that;

$$\varepsilon_{\lambda,T} = 4\sqrt{\frac{\pi \cdot r}{v_o \cdot \mu \cdot \lambda}} \quad (12)$$

Where from Equation 3.2;

$$\varepsilon_{\lambda,T} = \alpha_{\lambda,T} = 1 - \rho_{\lambda T}$$

Where $\boldsymbol{\varepsilon}_{\lambda,\mathbf{T}} = \text{Spectral Emissivity}$

$$r = \frac{1}{\theta} = \text{specific resistance} \quad (13)$$

Also required for optical characterization is absorption coefficient. Thus, absorption coefficient is a parameter that describes the amount of light of a given color that is absorbed by a material of a given thickness. The absorption coefficient , α_c *,* has units of 1/cm (1/length), because it depicts the amount of light absorbed per unit thickness of material. The more light a material absorbs, the higher its absorption coefficient will be. Because materials often absorb some colors better than others, the absorption coefficient is a function of color.

$$\alpha_c = \frac{2.303 \cdot A}{k} \quad (14)$$

Where;

A = Absorbance

k = Thickness of the sample [16-18]

3. EXPERIMENTATION

3.1 Sample Testing

Spectrophotometry is a technique that uses the absorbance of light by the substance to be characterized at a certain wavelength to determine the substance optical properties. The instrument used was UV-Vis-NIR spectrophotometer.

On starting the sample test, there were three major modes of measuring in which the UV-Vis-NIR spectrophotometer measures and the spectrum mode was selected as it is concerned with wavelength scanning over a continuous wide range, others were photometric mode which is for quantitative analysis, measuring absorbance at single wavelengths and kinetics mode which collects absorbance data at a particular wavelength versus time.

After choosing the spectrum mode of operation, we clicked on the “M” button to set up your acquisition parameters. We entered the wavelength range and scan speed (usually fast), and click on OK. The maximum allowable wavelength range is 1100 nm to 200 nm.

After setting-up the system, the samples were inserted into the sample compartment and the start button was clicked to begin the spectrum scan. The scan was carried out three times to avoid discrepancies and errors. After the scan, the spectrum was displaced on the monitor screen. This scan was done for sample A, B and C.

4. RESULTS AND DISCUSSION

The performance of uncoated, lightly coated and thick coated absorber plates is presented.

The result for Sample A (uncoated) is shown in Fig. 4 and Fig. 5.

The result for Sample B (lightly coated) is shown in Fig. 6 and Fig. 7.

It was discovered from Fig. 6 and Fig. 7 that acrylic resin actually increases the solar absorbance of the metal samples as shown by the graphical increase of absorbance from a maximum value of 3.182 to 4.000 (based on the scale used by the spectrophotometer) for the uncoated and coated samples respectively. This is 21% increase in the absorptance of solar energy as a result of thin coating. This affirms the assertion of [13] in their research that acrylic resin is spectral selective.

The result for Sample A (uncoated) is shown in Fig. 8 and Fig. 9.

From the results obtained for thick coating, shown in Fig. 8 and Fig. 9, it could be seen that when the layers of coatings were increased (thick coating) , the absorbance dropped sharply by about 50% lower than that of thin coating (lightly coated). The result showed that uncoated surface performed better than thick (multi-layered) coated plate, in terms of energy collection, vis-à-vis efficiency. It is therefore evident that the lightly coated metal sample have a better absorbance value than the absorber with thick coatings. There is drop in absorbance as can be seen in the graph, corresponds with the position of [10,13,19], that the thinner the coating of a substrate, the higher the absorptance.

In order to validate this results, the respective samples (A,B and C) were subjected to solar heating, under same atmospheric condition and their plate temperatures over the period of test are tabulated in Table 1.

The on-site assessment of the samples confirms the better performance of thin film coated absorber plate over non-coated and thickly coated plates in flat plate solar collectors.

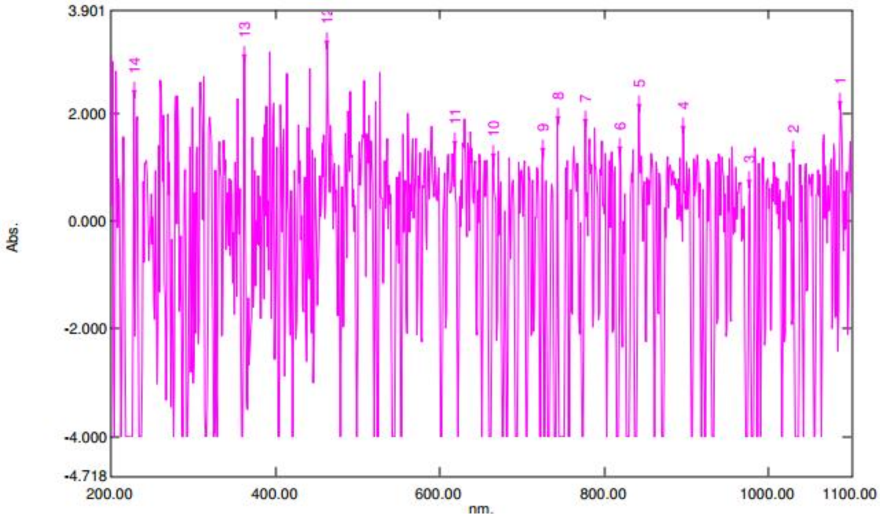

Fig. 4. Spectrum graph of Uncoated Mild steel sheet

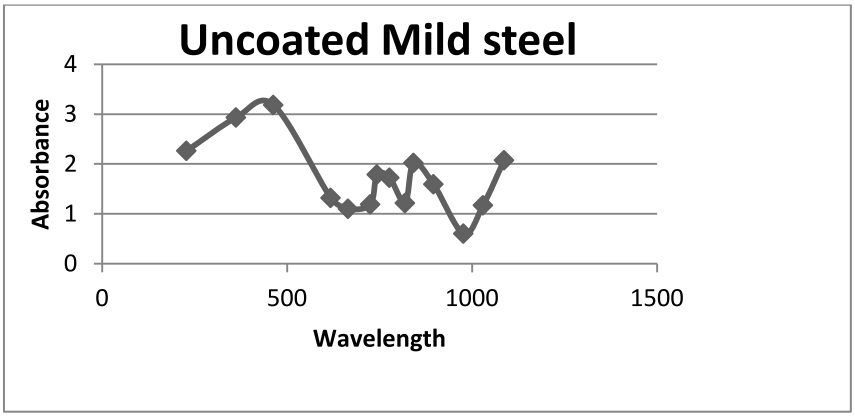

Fig. 5. Spectrum graph of Uncoated Mild steel sheet for peak values

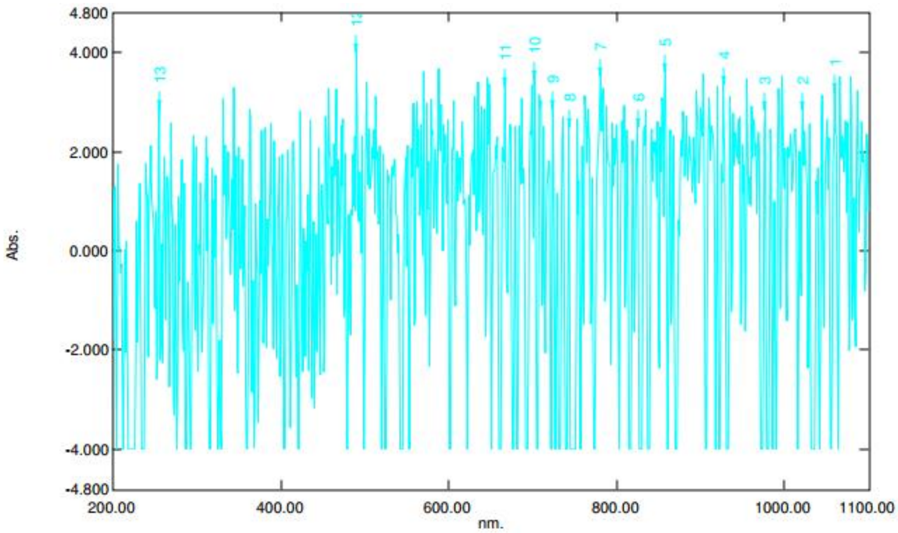

Fig. 6. Spectrum graph of lightly coated Mild steel sheet

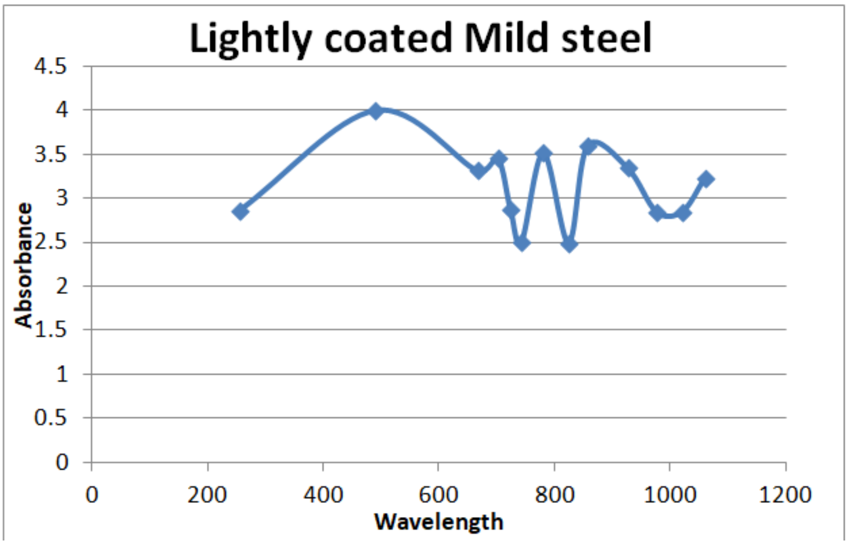

Fig. 7. Spectrum graph of lightly coated Mild steel sheet for peak value

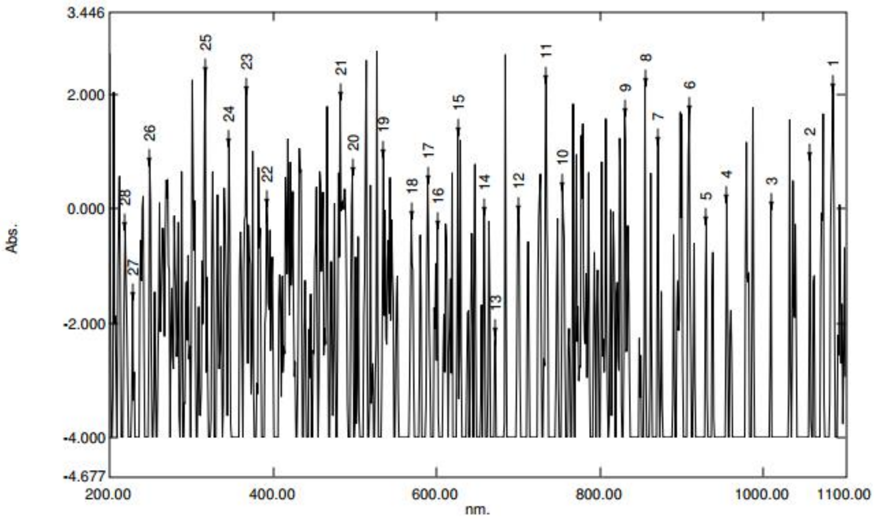

Fig. 8. Spectrum graph of thick coated Mild steel sheet

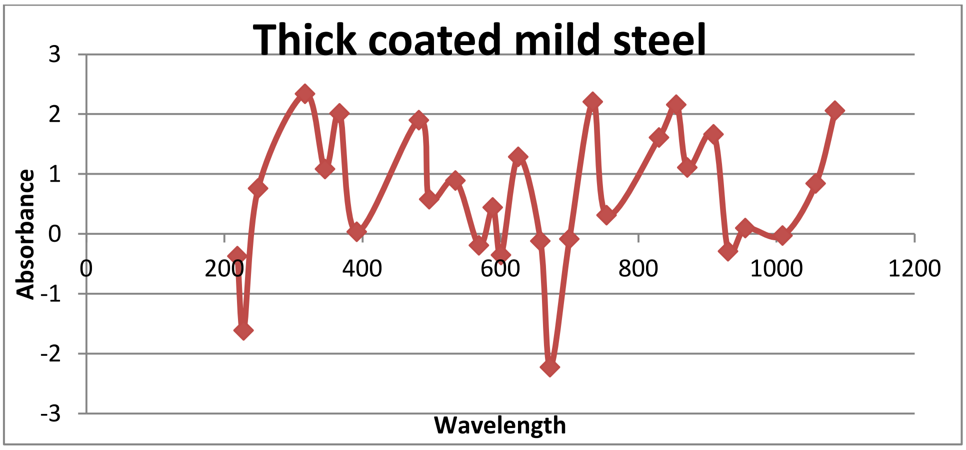

Fig. 9. Spectrum graph of thick coated Mild steel sheet for peak values

Table 1. Samples solar heating performance

	Sample A (Non- Coated) (°C)	Sample B (Lightly coated (°C)	Sample C Heavy coated (°C)	Ambient Temperature (°C)	Insolation (w/m^2)
11:00am	46	77	66	31	536.90
11:30am	48	82	69	32	550.30
12:00am	51	86	73	32	594.30
12:30pm	59	88	76	33	670.00
1:00pm	62	89	79	33	677.60
1:30pm	65	88	84	33	841.60
2:00pm	68	92	85	33	890.60

5. CONCLUSION

The application of selective coatings of varying coating thicknesses on absorber plates of a collector has been studied. Results show that acrylic resin increases the absorbance in the solar heating spectral region. The thin film coated absorber plate recorded the best absorbance at 21% increment in solar energy absorbance. Its plate temperature under solar radiation was greater than that of uncoated and thick coated absorbers by 24°C and 13°C respectively. Also, the thick coated plate (multi-layer coating) had the least absorbance, at about 50% lower than lightly coated absorber plate. Therefore, absorber coating thickness should be as thin as possible, preferably in nanometers, to achieving optimum absorptivity of solar radiation in solar thermal collectors.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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