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Preparation and characterization of nanographite- and CuO-based absorber and performance evaluation of solar air-heating collector

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Abstract Nanostructured absorbers and novel collectors are to be developed so as to reap the enhanced thermal performance of solar thermal gadgets. In this connection, the nanographite- and CuO-coated solar absorber was developed, and it was characterized through XRD, SEM, and EDAX. In addition novel collector with nanostructured and baffle-arranged absorber was developed, and it was tested. It was found that the maximum temperature attained on sample absorber (1 m × 2 m) was 48.5 °C in outdoor conditions. It was also found that the grains in the coating were in nanosizes with spherical structure. The results of thermal analyses revealed that the maximum temperature enhancement of the working fluid was 59.4 °C, and the maximum thermal performance of the collector was 68%. On the basis of the present research outcomes, it could be concluded that nanostructured and baffle-arranged solar absorbers would be used in solar collectors for reaping enhanced thermal performances.

Keywords Nanostructured absorber · Baffle fixed absorber · Solar air-heating collector · Thermal efficiency

Introduction

A solar thermal collector essentially forms the basic unit in a solar thermal gadget. It absorbs solar energy as heat and then transfers it to the heat transport fluid efficiently. The heat transport fluid delivers the heat to a heat exchanger or drying unit [1]. Solar air heaters are preferred nowadays, as they yield the benefits like controlled, hygienic, and effective dehydration of products [2]. Conventional flat plate collectors are widely used for heating applications, and it is reported that novel heating systems with enhanced thermal performances are necessitated so as to match the demand and supply of hot air in various energy-intensive sectors of India [3–6]. The major component in all air-heating collectors is blackened absorber, and it is reported that the coating, material, and size of absorber determine the optical characteristics and thermal performances of the flat plate collectors [7–10]. In this connection, it is essential to prepare and characterize nanostructured solar absorbers and to conduct structural analysis on the solar absorbers [11, 12]. It is also essential to estimate the thermal performances of solar heating collectors with nanostructured absorbers so as to utilize these solar thermal devices in the application sectors [13]. In these perspectives, the present investigation has been devoted for the (1) preparation of nanographite- and CuO-coated solar absorber (2) characterization of deposited coating on solar absorber (3) measurement of thermal enhancement on solar absorber and (4) development of solar air-heating collector with nanostructured and baffle-arranged absorber and (5) estimation of thermal performance of solar air-heating collector. In this research work, the nanosized materials in powder forms were obtained, and the solar absorptive solution was prepared by mixing these nanosized powders. The prepared solution was coated on solar absorber by spray-coating method. The characterization with reference to XRD, SEM, and EDAX was carried out. The increase in temperature on the nanostructured absorber in the outdoor atmosphere was measured. The thermal performance of solar air-heating collector was estimated by adhering to the standard

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specifications. The generated results of the present investigation have been documented in this research paper for the benefits of manufacturers, researchers, and end users worldwide.

Materials and methods

Preparation of absorptive coating

Graphite blocks were commercially procured. By adopting ball milling method, the graphite blocks were made into nanographite powder. The prepared powder was mixed with nanosized CuO in varied compositions. In the meanwhile, conventional absorptive solution that is commonly used for coating on absorbers in solar air-heating collectors was procured from a solar industry. The mixed powder of graphite and CuO was stirred thoroughly in the conventional absorptive solution by using a mechanical stirrer. The developed absorptive solution was used for coating on solar absorbers.

Deposition of absorptive coating

The prepared absorptive solution was sprayed at a spray rate of 10 mL min^{-1} onto the clean metal absorber using compressed air as carrier gas [14]. The distance between the spray head and the absorber was ~ 15 cm. The coating was checked by naked eyes, and the uniformity in coating was confirmed.

Thermal durability

The prepared solar absorbers were kept in a hot air oven at 175° C for 4 hours. The samples were taken out and it was cooled as per Bureau of Indian Standards (BIS) specifications. The peeling off and fading of coating, if any, was inspected [15].

Characterization

As the XRD is an ideal technique for the assessment of the structural characteristics of the material [16, 17], the structural characterization with reference to XRD was carried out on the developed sample. The diffractogram that contained 2θ, d values, net intensity, and relative intensity was obtained through XRD characterization. The crystallite size in the coating was calculated by using the Debye–Scherrer formula [18] that has been presented in Eq. (1)

$$D = K\lambda/\beta\cos\theta \quad (1)$$

where D is crystallite size, K is correction factor, λ is wavelength of X-ray used, and β is the FWHM of the observed peaks and θ is the diffraction angle.

The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from electron sample interactions reveal information about the sample including external morphology (texture), chemical composition, crystalline structure and orientation of materials that makes the sample [17, 19, 20]. In the present study, to know the morphology of the coating, the developed sample was subjected to SEM analysis. Energy-dispersive X-ray spectroscopy (EDS, EDX, or EDXRF) is an analytical technique used for the elemental analysis or chemical characterization of a sample. The EDS makes use of the X-ray spectrum emitted by a solid sample bombarded with a focused beam of electrons to obtain a localized chemical analysis [21, 22]. In the present study, the developed sample was subjected to EDAX analysis not only to identify the elements but also to estimate their relative proportions.

Temperature measurement on solar absorber

The prepared absorber was kept in outdoors for the measurement of temperature on absorber in varied meteorological conditions. During experimentation, the temperature of absorber plate along with the influencing parameters such as incident solar radiation, ambient temperature, and wind speed were measured [15]. It should be noted that the sample was free from fall of dusts, shadows, and other influencing materials during the experimental period.

Development of solar air heater

An aluminum plate of size 2 m^2 was commercially procured. It was found that the procured plate had homogeneous surface with same thickness and suitable roughness. The baffles of length 800 mm, breadth 40 mm, and thickness 0.56 mm were prepared separately. These aluminum baffles were fixed on both sides of the aluminum plate at equi-distances of 200 mm. The plate with baffles was coated with graphite and CuO mixed solution by spray-coating technique. The prepared absorber plate was integrated subsequently in the solar air-heating collector. It should be noted that solar air-heating collector had the other integral components such as toughened glass cover, rock wool insulation, and aluminum channel sections in suitable dimensions.

Estimation of thermal performance of solar air heater

The developed solar air heater was kept in open atmosphere and the temperature rise of the working fluid was periodically recorded during sunshine hours. The major meteorological parameters were also recorded during the experimental period so as to know their degree of influence on the thermal performance of solar air heater [23].

Thermal efficiency (η) of the solar air heater is defined as the ratio of the useful energy gain to the solar radiation incoming to the solar air heater [24].

$$\eta = Q_u / I A_c \tag{2}$$

where Q_u is the collector useful energy gain (W), I is the solar radiation (W m^{-2}) on the heater surface, and A_c is the surface area of the collector (m^2). The useful energy gain (Q_u) can be calculated by equation [25],

$$Q_u = \dot{m} C_p \left[T_{a,out} - T_{a,in} \right] \tag{3}$$

where $\dot{m}$ is the mass flow rate (kg s^{-1}), C_p is the specific heat of air at constant pressure (kJ kg^{-1} K^{-1}), $T_{a,out}$ is the temperature of air at outlet and $T_{a,in}$ is the temperature of air at inlet. Putting Q_u from Eq. (3) in Eq. (2), it becomes

$$\eta = \dot{m} C_p \left[T_{a,out} - T_{a,in} \right] / I A_c \tag{4}$$

The mass flow rate ($\dot{m}$) can be calculated by equation

$$\dot{m} = \rho A V \tag{5}$$

where ρ is the density of air (kg m^{-3}), A is the cross-sectional area of pipe at exit (m^2) and V is the velocity of air at exit (m s^{-1}) [3].

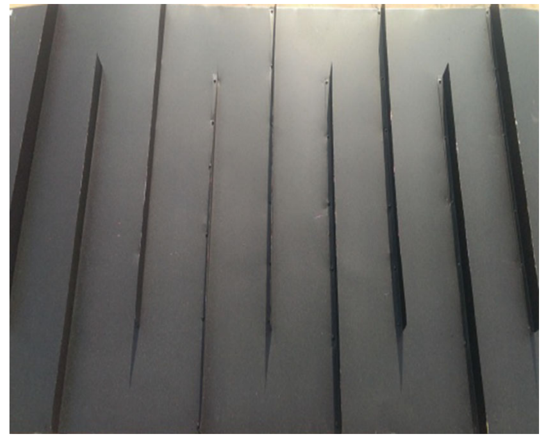

Fig. 1 Nanostructured and baffle-arranged absorber

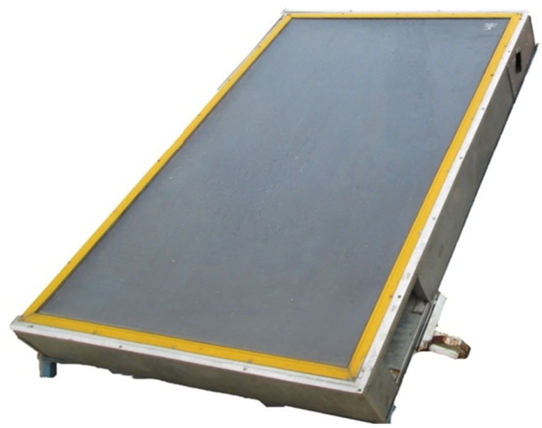

Fig. 2 Solar Collector

Results and discussion

In the present study, a nanostructured absorber was developed. In addition, a solar collector integrated with the nanostructured and baffle-arranged absorber was developed. The photographs of the developed absorber and collector have been presented in Figs. 1 and 2 respectively. The technical specifications of the developed collector have been presented in Table 1. The coated substrate (5 cm × 10 cm) and coated absorber plate (1 m × 2 m) were kept in the open atmosphere during sunshine hours. Measurements were taken, and the dataset of temperature on substrate and absorber plate for the period of 10.00 a.m–14.00 p.m have been presented in Table 2 and 3, respectively. The developed absorber was characterized, and the outcomes of XRD, SEM, and EDAX are presented in Figs. 3–6 respectively. The developed solar air-heating collector was also kept in outdoors and the increases in the temperature of working fluid at a flow rate 60 m^3 h^{-1} were noted. The increases in temperature of working fluid along with related meteorological parameters and the efficiency of the developed solar air-heating collector are presented in Table 4.

The temperature enhancement of the conventional coating-based substrate was noted. In addition the temperature enhancement on the substrates with different composition (20:80, 40:60, 60:40, 80:20) of nanosized graphite and cupric oxide was noted. It was found that the temperature enhancement on nanocomposite-coated substrate was higher than that of the conventional coating-based substrate. It was also found that the substrate with 60:40 ratio (of nanosize graphite and cupric oxide) coating on absorber had higher enhancement of temperature than those of absorbers with all other ratios of coating of nanocomposite. On conventional coating-based substrate, the temperature varied from 36.3 to 43.8° C during the experimental period. At the same time, the temperature ranged between 41.7 and 46.2 °C on 60:40 ratios of

Table 1 Technical specifications of solar collector

Component	Specifications
Glass cover	
Material	Toughened
Thickness	4.00 mm
Transmittance	82%
Surface area	2 m^2
Absorber plate	
Material	Aluminum
Thickness	0.56 mm
Coating	Nanocomposite
Surface area	2 m^2
Insulation material	
Material	Rock wool
Thickness (side)	25 mm
Thickness (bottom)	50 mm
Surface area	2 m^2
Solar collector	
Length	2000 mm
Breadth	1000 mm
Height	225 mm

graphite- and cupric oxide-coated substrate during the experimental tenure. The enhancement in the minimum and maximum values of temperature of graphite- and cupric oxide-coated substrate could be correlated with the enhanced absorption of radiation by the nanocomposite coating on the aluminum substrate in the present investigation.

As it is already mentioned, the sample absorber of solar collector was characterized. In Fig. 3, which shows the X–ray diffraction pattern of the coating on aluminum substrate, five peaks could be observed. The intense sharp peak at $2\theta = 26.68°$ indexed as [002] plane with d value of 3.34 Å could be associated with the graphite nanopowder. The other two intense peaks (at 65.21 and 78.35) could be associated with the aluminum substrate structure. The remaining broad and intense peaks at $2\theta = 35.6°$ and $2\theta = 38.8°$ indexed as [002] and [111] plane with d values 2.52 and 2.32 Å were found to be the characteristic peaks of CuO. The diffractogram clearly established the composite nature of the coating that was composed of graphite and cupric oxide particles. By using Scherrer's formula, the crystallite sizes were calculated and they were observed to be in nanosizes. While the crystallite sizes of graphite were calculated to be 31.58 nm, the crystal sizes of cupric oxide were calculated to be 45.82 nm. At the same time, the mixed crystallite sizes of graphite and cupric oxide were found to be 37.32 nm. The morphology of the present nanocomposite coating was analyzed using the scanning electron micrograph. The SEM micrographs of the coating shown in Fig. 4 indicated the narrow size distribution of spherical shape particles. It was obvious that the coating was found to be extremely smooth, compact and uniform. The qualitative elemental analysis of the coating was carried out using energy-dispersive X-ray spectroscopy (EDAX), and Fig. 5 represents EDAX spectra of the coating. The EDAX analysis revealed that the coating contains C, O and Cu elements with 65.39, 19.15 and 3.26 at.%, respectively. Neither there was blistering and rupture nor peeling of the coated surfaces on the absorber plates of collectors during the temperature test on the absorber plates. It would be worth mentioning here that the presence of large number of graphite and cupric oxide particles due to their nanosizes in the surface area of the absorber would have caused the improved absorption of solar radiation and enhanced heat transfer to the working fluid. The temperature measurements on the substrates revealed that the maximum temperature that could be obtained was 43.8 °C on the non-coated absorber and

Table 2 Temperature enhancements on sample (5 cm × 10 cm)

Time/h	Solar radiation/W m^{-2}	Ambient temperature/°C	Wind speed/m s^{-1}	Temperature/°C	
				On conventional coating-based substrate	On graphite- and CuO-coated substrate
10.00	490.2	29.4	0.4	37.6	44.0
10.30	655.4	30.0	0.6	37.6	44.8
11.00	696.7	30.2	0.3	40.9	45.6
11.30	706.8	31.3	0.5	43.8	45.2
12.00	713.4	31.9	0.6	39.7	46.2
12.30	712.8	30.1	0.4	40.4	45.2
13.00	712.5	31.0	0.5	40.7	42.5
13.30	692.7	30.5	0.9	36.3	44.0
14.00	637.4	30.7	0.4	37.9	41.7

Table 3 Temperature enhancements on sample (1 m × 2 m)

Time/h	Solar radiation/ W m^{-2}	Ambient temperature/°C	Wind speed/m s^{-1}	Temperature/°C		
				Top	Middle	Bottom
10.00	478.3	28.7	0.6	36.6	36.5	36.5
10.30	518.0	29.7	0.7	37.8	37.8	37.7
11.00	768.4	30.1	0.7	38.9	38.8	38.9
11.30	786.5	30.4	0.9	40.3	40.2	40.2
12.00	793.2	31.1	0.7	41.0	41.0	41.0
12.30	785.1	32.5	0.8	46.0	45.9	46.1
13.00	773.2	30.4	0.9	48.4	48.5	48.5
13.30	674.0	30.6	1.2	45.5	45.4	45.4
14.00	678.4	31.5	0.5	46.4	46.5	46.4

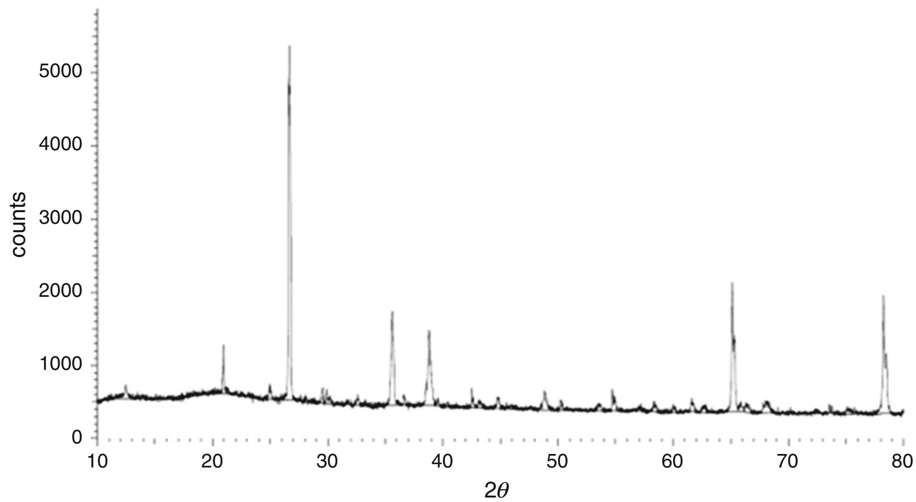

Fig. 3 XRD spectrum of nanosize graphite- and cupric oxide-coated Al substrate

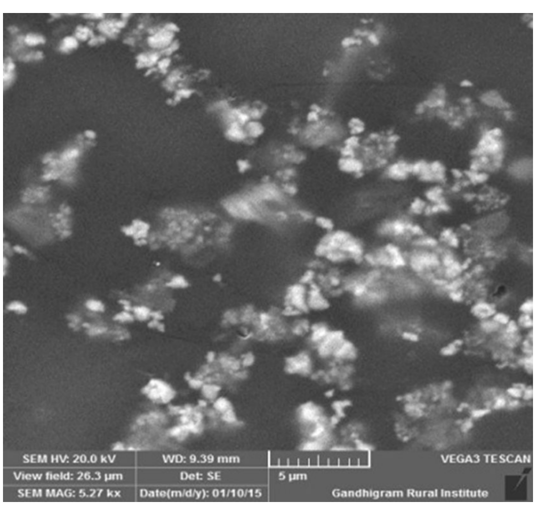

Fig. 4 SEM image of nanographite and CuO coated Al substrate

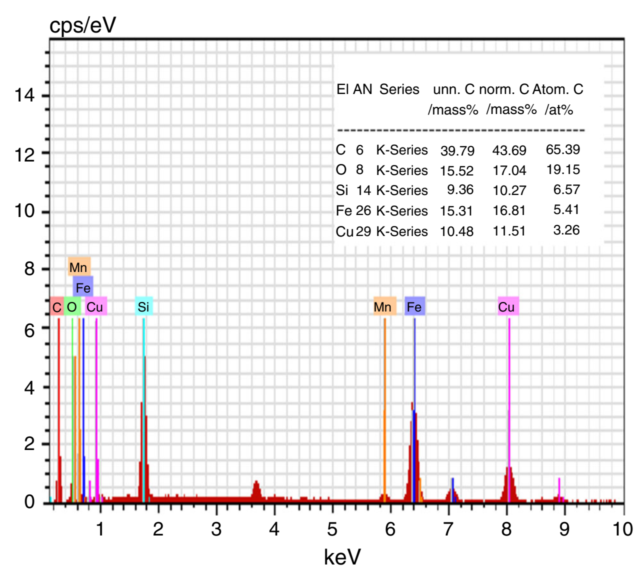

Fig. 5 EDAX spectrum of nanographite- and CuO-coated Al substrate

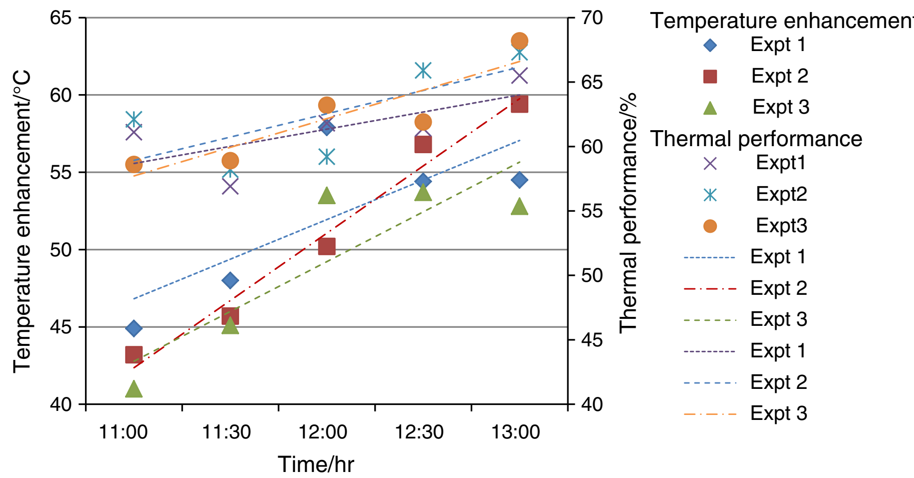

Fig. 6 Thermal characteristics of solar collector

Table 4 Thermal performance of solar air heater

Expt	Time/h	Solar radiation/ W m^{-2}	Ambient temperature/°C	Wind speed/m s^{-1}	Temperature of working fluid/°C	
					Initial	Final
1	11:00	615.3	32.0	1.8	29.8	74.7
	11:30.	705.7	32.2	0.9	30.0	78.0
	12:00	785.2	32.9	0.8	30.2	88.1
	12:30	742.0	33.1	0.9	30.3	84.7
	13:00	696.6	32.6	1.0	30.0	84.5
2	11:00	582.5	30.4	0.5	29.3	72.5
	11:30.	657.9	30.6	0.6	29.4	75.1
	12:00	710.2	30.9	0.2	29.6	79.8
	12:30	722.3	31.0	0.3	29.6	86.4
	13:00	739.7	31.2	0.6	29.7	89.1
3	11:00	586.0	33.7	1.1	29.2	70.2
	11:30.	641.7	34.8	1.6	30.9	76.0
	12:00	708.6	35.8	1.2	31.2	84.7
	12:30	726.2	36.9	1.3	31.8	85.5
	13:00	647.6	35.7	1.2	31.5	84.3

46.2 °C on the coated absorber. As the coating comprised graphite and CuO, the absorption of incident solar radiation would have caused the increase in the temperature of about 2.4 °C. On the whole, the enhancement in temperature could be directly correlated with the enhanced absorption of radiation by nanocomposite-based coating on the substrate.

The developed solar air-heating collector had the integral components such as glass cover, absorber plate, baffle arrangements, insulation material, and bottom sheet in optimum dimensions. The glass cover was experimentally tested, and it was found that the transmittance of the glass cover was 82%. The aluminum was selected as absorber plate due to its features like light weight, ductile, durability, non-magnetic characteristics, and corrosion resistance. It was also selected due to its good thermal conductivity with the value of 237 W m^{-1} K^{-1}. The rock wool was used as insulation material and it was reported that it comprised fine and lengthy sized inorganic fibers that were bonded together by high-temperature binder. It was also reported that these fibers were uniformly distributed to trap millions of tiny pockets of air in the insulation material, and so the rock wool could serve as good thermal and acoustic insulation [26]. The chemical constituents of the insulation material were studied in the present investigation and it was found that there were minimum quantities of sulfur and chloride with moisture. It was found to be chemically inert and the thermal insulation of the material was 0.98 m^2 °C W^{-1}. It was also found that the rock wool had good thermal characteristics, low weight, high tensile strength and also good resilience. As per the specification of Bureau of Indian Standards, the thermal resistance and conductance of the present insulating material were found to be satisfactory [27].

The dimensions of all these components and also flat plate collectors were measured by using calibrated instruments. The thickness of the glass cover, absorber sheet and insulation material were found to adhere the standard specifications. The thickness of cover foil, bottom sheet, support retaining the glass cover and the channel section were also found to adhere the same standard specifications [15]. It would be worth mentioning that the dimensions of the most of the components were fixed so as to have effective heat transfer, enhancement in the temperature of the working fluid and enhancement in the thermal performance of solar air-heating collector. The length, breadth, and height of the solar collector were optimized so as to have simplicity in design, easiness in fabrication, and elevated thermal performances. The length, breadth and height of the solar collector were also optimized so as to develop the enlarged version of the solar air-heating collector with multiples of the optimized collectors so that the demand and supply of hot air in the application sectors would be matched. The developed solar air-heating collector was tested at a flow rate 60 m^3 h^{-1} of working fluid. It was noticed that the aluminum absorber (with nanographite and cupric oxide in the ratio of 60 and 40) integrated solar air-heating collector had the temperature elevation that varied from 41.0 to 59.4 °C. The thermal efficiencies of the developed solar collector were calculated and they were found to be the minimum of 57% and maximum of 68%, respectively. The calculated thermal efficiencies of the present solar collector were relatively higher than those of the conventional air-heating collectors [3, 28].

The present collector had three special characteristics. While the first specialty was the nanocomposite coating on absorber for having enhanced absorption of incident radiation, the second specialty was the presence of baffles for having more heat transfer to the working fluid. The third specialty was the fabrication of the collector with opt materials in optimized dimensions. The recorded thermal enhancements of the working fluid and thermal performance of solar air-heating collector could be attributed with the first specialty of the collector that pertains to the nature of nanocoating, optical characteristics of nanocoating, and thermal characteristics of the absorber material. The elevations could be correlated with the second specialty of collector that pertains to the presence of enhanced contact between the absorber and working fluid due to the presence of baffles on absorber sheet. The elevations could also be correlated with third specialty of the collector that pertains to usage of opt materials such as toughened glass cover, nanostructured absorber and rock wool in optimized dimensions. On the whole, the enhanced thermal performances of the designed solar collector could be correlated with enhanced transmittance of the cover plate due to the usage of toughened glass cover [29], increased absorptance of the absorber sheets due to the utilization of nanostructured absorber [30], increased heat transfer to the working fluid due to the usage of metallic absorber, reduced heat losses due the presence of rock wool in suitable thicknesses, and reduced heat losses to the surroundings due to the presence of opt gaskets fixed between channel section and glass cover. On the basis of the present research outcomes, it could be concluded that nanostructured and baffle-arranged absorbers along with opt materials of components would be used in solar collector so as to reap its enhanced thermal performance.

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