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RESEARCH PAPER

Enhancing the Thermal Performance of Parabolic Trough Collectors Using Nano-Enhanced Absorber Coatings: A Comparative Study of Fe_3O_4, Al_2O_3 and Hybrid Fe_3O_4- Al_2O_3 Coating

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Abstract

Solar thermal systems use parabolic trough collectors (PTCs) to concentrate sunlight on an absorber tube to create heat for various applications. They are efficient but have optical losses, heat dissipation, and reduced performance owing to dust and high-emissivity coatings. Hence, nanomaterials can improve absorber coatings' heat retention and energy efficiency. This research paper is an examination of the impact of nano-enhanced coating on PTC thermal characteristics. The various types of coating were a hybrid coating of Fe_3O_4-Al_2O_3 nano-enhanced coating, Fe_3O_4 nano-enhanced coating, Al_2O_3 nano-enhanced coating and black matte tested in their effects on energy and exergy efficiency, heat absorption, and fluid outlet temperature. It was found that the hybrid Fe_3O_4-Al_2O_3 coating recorded the highest of 81.5 ^{o}C fluid outlet temperature, maximum of 3186.4 W heat absorption, thermal efficiency of 79.38% or exergy efficiency of 42.88%. Fe_3O_4 was selected because it has a high optical absorption, and Al_2O_3 was selected because it has a high thermal conductivity, which allows heat transfer to be efficient and losses to be reduced. The most ineffective one was black matte coating because the highest 59.4 ^{o}C fluid temperature and 42.57% thermal efficiency. Therefore, the nanomaterials enhance the power of PTC, and this indicates that the materials have the possibility of maximizing the utilization of solar energy. The researchers established that solar thermal collector performance can be increased with the use of advanced nano-coatings, including the Fe_3O_4-Al_2O_3 hybrid and facilitation of the renewable, efficient, and sustainable renewable energy systems.

Keywords: Sustainable; Solar; Energy; Exergy; Efficiency; Nanoparticles.

1. Introduction

One of the widely used solar thermal technologies is the Parabolic Trough Collectors (PTCs) [1]. The focal line

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is implicated with a parabolic reflective surface that diffracts the sunlight to a receiver tube [2]. A heat transfer fluid in the receiving tube transforms concentrated solar energy to thermal energy. PTCs are capable of generating power, desalinating water and heating industrial processes up to 150 °C -400 °C [3]. They are designed to utilize energy efficiently by following the sun on one axis. The radiative and convective losses are minimized by selective coatings on the absorber tube to enhance thermal performance [4]. Nano-enhancing the heat transfer fluids and coating are under investigation to enhance efficiency [5]. PTC technology can be used in sustainable energy systems to transition to cleaner, renewable energy [6].

PTC absorbers with nano-coatings increase the sun absorption and thermal efficiency [7]. Nanoparticles reduce heat losses, enhance thermal conductivity and enhance optical properties [8]. Convective and radiative losses are minimized by temperature retention, enhancing conversion of energy and such coatings [9]. Through the study of stainless steel TiB_2 coatings on collector absorbers, it was observed that the stainless steel possessed 0.93 absorptivity, 0.11 emissivity, and high thermal stability [10]. On the same note, the nickel-aluminum exhibits a peak absorptivity of approximately 0.75 [11]. In addition, C/NiO spray coating increased the absorptivity of the aluminum receiver by approximately 90% [12]. Vasudevan et al. [13] compared black nickel-coated aluminum PTCs. They found the effects of temperature on the thermal properties of materials that resulted in an increase in the absorptivity and a reduction in the emissivity. Table 1 presents the coating material, in addition to the values of its absorptivity and emissivity.

Table 1: The coating method employed and the absorptivity and emissivity of the material are reported in previous studies

References	Material	Coating method	Absorptivity	Emissivity
[14]	W	Laser sintering	0.90	0.49
[15]	SiO_2/Al_2O_3	Spray coating	0.985	0.901
[16]	SnO_2	AI	0.91	0.16
[17]	MoO_3	Wet chemical etching	0.89	-
[18]	Al_2O_3	PVD	0.93	0.12
[19]	Cr_2O_3	Electroplating	0.96	0.35

Through the literature, the applications of the PTCs are very common in solar thermal energy systems, where a parabolic reflector focuses sunlight on an absorber tube. The absorber coating determines the efficiency of the PTCs since it reduces radiative and convective losses and maximizes the utilization of solar radiation. The latest developments on nano-enhanced coating have greatly enhanced thermal performance by improving optical and thermal properties. Different coating materials have been explored in terms of high absorptivity and low emissivity include TiB2, nickel-aluminum and C/NiO spray coating. Research indicates that the black nickel-coated aluminum absorbers exhibit temperature-related response in thermal properties to enhance efficiency. Also, other techniques of coating, such as Laser sintering, Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) have been considered in response to the best coating performance.

The coating materials, which include SiO_2, Al_2O_3 and Cr_2O_3, are highly absorptive and thermally stable, and thus could be good potential PTC coating material. On the whole, the development of the coating technology helps to increase the efficiency of PTC, encourage the shift to green energy projects. Other materials that have been investigated before as a coating include TiB_2, nickel-aluminum and SiO_2/Al_2O_3 with regard to their absorptivity and emissivity. Nevertheless, very minimal research has been done on Fe_3O_4 and Al_2O_3 nanoparticles as a hybrid coating to PTC absorbers. Current literature mainly analyzes the performance of individual nanoparticle-based coatings, and the synergetic effect of the optical properties of Fe_3O_4 and the thermal conductivity of Al_2O_3 is not well-investigated. Furthermore, most research focuses on coating characterization rather than its direct influence on fluid temperature profiles, heat energy absorption, and exergy efficiency in real-time PTC applications.

The PTC performance was investigated in this research using the nano-enhanced coating on the absorber surface. Black matt material was taken as the base material, and Fe_3O_4 and Al_2O_3 nanoparticles were used to make the nano-enhanced coating. In the case of a hybrid nano-enhanced coating, the two nanoparticles were considered in a 50:50 proportion. Based on experimentation, fluid temperature profile, heat energy absorption, and thermal and exergy efficiency were examined and compared to black matt material. Finally, the hybrid Fe_3O_4-Al_2O_3 nano-enhanced coating gives a positive outcome as opposed to the other coatings.

2. Materials and Methods

1.1 Preparation of nano-enhanced Coating

The base material of the cover was selected to be black matt material because of its high absorptivity and low reflectivity, making it better in thermal performance. A 50:50 blend of Fe_3O_4 and Al_2O_3 nanoparticles was used to enhance thermal conductivity and stability. The two kinds of nanoparticles were purchased online (India Mart). Two 0.5vol.% nanoparticles were picked. At 0.5 vol.%, the hybrid nanoparticles were best balanced in terms of thermal enhancement and viscosity control.

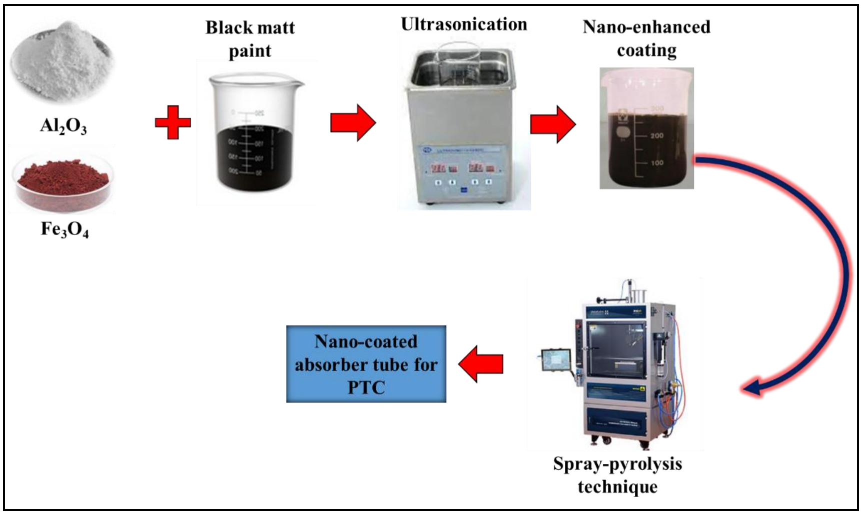

Fig 1: Hybrid Fe_3O_4-Al_2O_3 nano-enhanced coating making

This concentration was also used to ensure homogenous dispersion of the black matt material so that sedimentation was not observed. Fe_3O_4 was added to provide magnetic characteristics, which helped in the transfer of heat, whereas Al_2O_3 enhanced thermal conductivity and stability. The process of blending guaranteed a high thermal efficiency and long life of the coating. The blends and mixtures were ultrasonicated (Ultrasonic Cleaner made by Phoenix 4.5 L Digital with Heating-100W Basket PH-UC-120) at 80 °C for 60 minutes, to obtain a homogeneous suspension of nanoparticles in the black matte material. The coating was subsequently carried out by using the spray pyrolysis procedure after the ultrasonication. The reason behind the selection of the spray pyrolysis technique with MSK-USP-04C equipment is that it allows the creation of uniform and controlled thin films. Working at 300 °C is sufficient to provide enough thermal energy that can be used to decompose precursors and generate a film without degradation. A required portion of precursor that would produce the same thickness of the films was carefully added to the injector volume of 5 ml.

. The method is very versatile in the production of films with tailored properties. Table 2 indicates the thermal characteristics of the coating material. In the same way, Fig 1 illustrates the preparation procedures of the hybrid Fe_3O_4 -Al_2O_3 nano-enhanced coating.

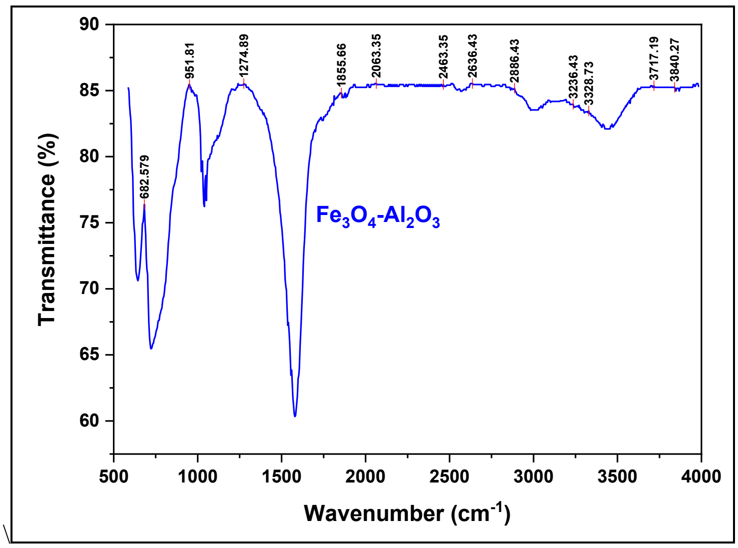

Fig 2: The result of FTIR for Fe_3O_4-Al_2O_3 hybrid nanoparticles

Table 2: Properties of Fe_3O_4, Al_2O_3 and black coating materials

Description of the property	Unit	Fe3O4	Al2O3	Black Coating
Size	nm	45	40	-
Thermal Conductivity	W/m·K	8.5	30	0.8
Density	g/cm3	5.17	3.96	2.6
Specific Heat	J/kg· K	836.8	915.3	518.3
Thermal Stability	°C	Decomposes >600°C in inert conditions	Melting point ~2072°C	withstands high temperatures
Operating temperature	°C	800	1900	500–700

The Fourier transform infrared (FTIR) spectrum of Fe_3O_4-Al_2O_3 hybrid nanoparticles reveals characteristic peaks corresponding to different functional groups and chemical bonds, and it is depicted in Fig 2. The high peak at 692.57 cm^{-1} identifies the presence of Fe-O vibration, indicating that there was the presence of Fe_3O_4, and the presence of Al_2O_3 is confirmed by the presence of peaks at 951.81 cm^{-1} and 727.89 cm^{-1}. The wide absorption between 3200-3400 cm^{-1}, especially at 3283.73 cm^{-1}, can also be attributed to the O-H stretching, which implies the existence of the surface hydroxyl groups or adsorbent water molecules. Also, the maximum at 1655.66 cm-one is at C=O stretching, which can be attributed to the presence of surface organic residues from the process of making them. The presence of these characteristic peaks confirms the successful formation of Fe_3O_4- Al_2O_3 hybrid nanoparticles without significant impurities. The transmittance is above 70% in most locations, indicating a well-dispersed nanoparticle system with low agglomeration. These hybrid nanoparticles are useful for solar thermal coatings and heat transfer enhancement because structural confirmation improves thermal and optical properties.

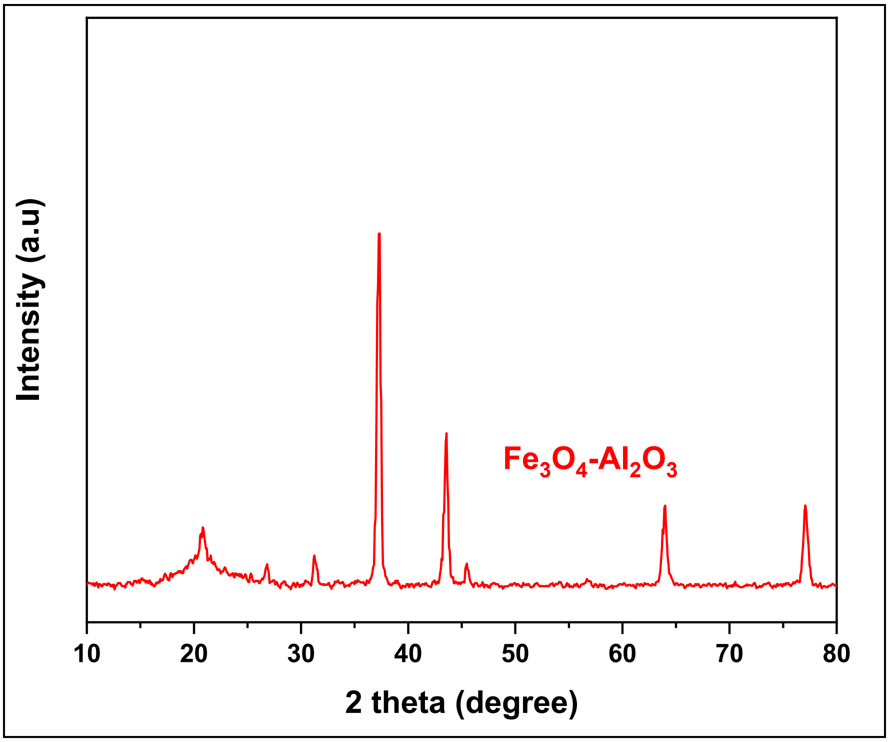

Fig 3: XRD pattern of Fe_3O_4-Al_2O_3 hybrid nanoparticles

Similarly, Fig 3 illustrates the X-ray diffraction (XRD) pattern of Fe_3O_4-Al_2O_3 hybrid nanoparticles, and it confirms their crystalline content with typical peaks. The 2θ values represent crystallographic planes for Fe_3O_4 and Al_2O_3 phases. Sharp and powerful peaks imply high crystallinity, indicating well-formed nanoparticles with little amorphous content. The peak at 35-40° indicates the presence of the Fe_3O_4 phase in the hybrid structure. Al_2O_3 peaks at higher 2θ values, particularly between 50° and 75°, indicate good integration of both metal oxides. Nanoparticle size and crystal lattice strain effects are suggested by peak broadness and intensity fluctuations. The absence of any unwanted mountains means that synthesis did not generate any contaminants or later stages. The

XRD pattern has validated the structural soundness and phase distribution of Fe_3O_4-Al_2O_3, which is suitable for thermal and optical applications. It is also estimated by the Scherrer equation to determine the size of the crystallites, which shows the nanostructure of the material. The results indicate the possibilities of using the Fe_3O_4-Al_2O_3 hybrid nanoparticles in heat transmission and solar thermal applications. The peaks of diffraction are in accordance with JCPDS reference data of Fe_3O_4 and Al_2O_3, which proves the purity of the phases. Thermal conductivity and structural stability, which are offered by the hybrid composition, are needed for high-temperature applications. Well-defined peaks indicate homogeneous nanoparticle distribution, reducing agglomeration. The incorporation of Al_2O_3 improves the mechanical and chemical stability of the hybrid, making it more durable for long-term applications. Such structural validation by the XRD analysis plays a vital role in the determination of the efficiency and reliability of Fe3O4-Al2O3 in the high-tech thermal energy and coating systems. The UV-Vis-NIR spectrophotometer was used to measure the coating absorptivity, which is approximately and the emissivity was approximately 0.42.

1.2 PTC experimental setup

The experiment was carried out with the PTC with a tracking mechanism system (ET 203) set up. The PTC system area measures 1.7m^2 with a focal length of 0.4m. The absorber tube was then placed in the middle of the two-walled glass shell in order to minimize the amount of heat that was lost to the atmosphere. The mirror used in PTC was a 0.9-absorptivity reflectivity mirror. A 5L water storage capacity was installed to supply operating fluid. Thus, the control valve and flow meter provided the absorber with working fluids. The 0.5hp water pumps provided water pressure. J-type thermocouples operate from -300°C to 1500°C. Inlet and outlet thermocouples sensed fluids and temperatures for thermal data. Solar rays and wind speed were monitored by a pyranometer and an anemometer. The Keysight 34970A data gathering system logs temperature. With 2 bars of pressure, fluid flows 50 LPH. Table 3 lists ETC specifications details.

Table 3: Description of the PTC system

Description of Parameters	Unit	Quantity
Absorber diameter	m	0.3
Aperture area	m2	1.7
Absorptivity of glass	-	0.91
Coating material	-	Black matt
Coating thickness	μμ	30
Hybrid nano-enhanced coating	-	Fe3O4-Al2O3
Length of the tube	m	0.6
Material of the absorber	-	Copper
Transmissivity of glass	-	0.92

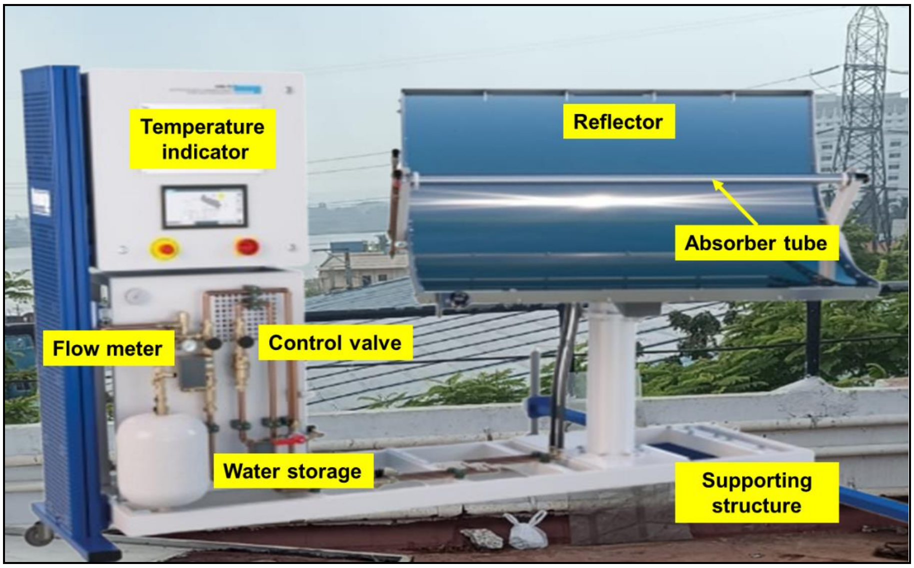

Fig 4: Actual view of the PTC setup

The tests were run across four days, in September, starting at 09:00 and going until 15:00, whereby measurements were taken on an hourly basis and analyzed, calculated, and plotted on graphs. The experiment was conducted in Chennai, Saveetha University at the latitude of 13.0802 ºN and the longitude of 80.2011 ºE. The solar radiation on the site was between 50 W/m^2 and 950 W/m^2, and the ambient temperature was 30 ºC and 38 ºC. The experiment was carried out on a PTC under different circumstances of the absorber coating, which comprised the non-coated absorber, the black matte coated absorber and the hybrid nano-enhanced coating with 1 mm and 2 mm thickness. Fluid outlet temperature, heat energy absorption, thermal efficiency and exergy efficiency were the indices of key performance that were investigated. The parameters proved convenient in establishing the impact of the coating on the thermal performance of the system. Fig 4 explains the experimental system, the system installed and the test conditions. Their results showed the effect of the hybrid nano-enhanced coating in the determination of the characteristics of heat transfers and revealed that they can play a role in enhancing a high thermal efficiency to facilitate increased use of solar energy.

1.3 Thermal modelling

The heat energy absorption by equation (1) [4].

$$Q_u = mC_p(T_o - T_i) \quad (1)$$

Heat input is calculated by equation (2).

$$Q_{in} = AcI_T \quad (2)$$

The thermal efficiency by equation (3) [3].

$$\eta_{th} = \frac{Q_u}{AcI_T} \quad (3)$$

Similarly, exergy efficiency by equation (4).

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} = \frac{mC_p\left[(T_o - T_i) - T_a\left(\ln\frac{T_o}{T_i}\right)\right]}{AI\left[1 - \frac{T_a}{T_{sun}}\right]} \quad (4)$$

1.4 Uncertainty analysis

Equation (5)is used to determine the uncertainty value.

$$\omega_x = \sqrt{\left(\frac{\partial x}{\partial x_1}\right)^2 \omega_{x1}{}^2 + \left(\frac{\partial x}{\partial x_2}\right)^2 \omega_{x2}{}^2 + \cdots + \left(\frac{\partial x}{\partial x_n}\right)^2 \omega_{xn}{}^2} \quad (5)$$

The uncertainty information of the parameters as described in Table 4. In addition, Fig 5 demonstrates the graphical flow of the present research.

3. Result and Discussions

1.5 Analysis of Outlet Temperature of Heat Transfer Fluid

The temperature of the outlet of the fluid is highly dependent on the absorption of the coated layer on the tube of the absorber of PTC. Fig 6 shows the temperature profile of the fluid as exiting PTC during the daytime. The maximum solar radiation was used to determine the maximum temperature and minimum temperature. The fluid that was covered with the black matte coating recorded the highest temperature of 59.4 ºC as the absorptivity and emissivity were very high. While black matte coatings effectively absorb solar radiation, they also emit a significant portion of the absorbed heat as infrared radiation, leading to heat losses. In contrast, the Fe_3O_4 nano-enhanced coating resulted in a higher maximum fluid temperature of 70.7°C. A PTC was subjected to various kinds of absorber coating conditions, such as the non-coated absorber, the black matt coated absorber, and the hybrid nano-enhanced coating of 1 mm and 2 mm. The analyzed key performance parameters were fluid outlet temperature, heat energy absorption, thermal efficiency and exergy efficiency. These parameters were useful in determining the impact of coatings on the thermal performance of the system. The experimental setup (including installed system and test conditions) is presented in Fig 4. The findings illuminated the impact of hybrid nano-enhanced coating on thermal transfer properties, which suggest its use in promoting thermal efficiency in better solar energy use.

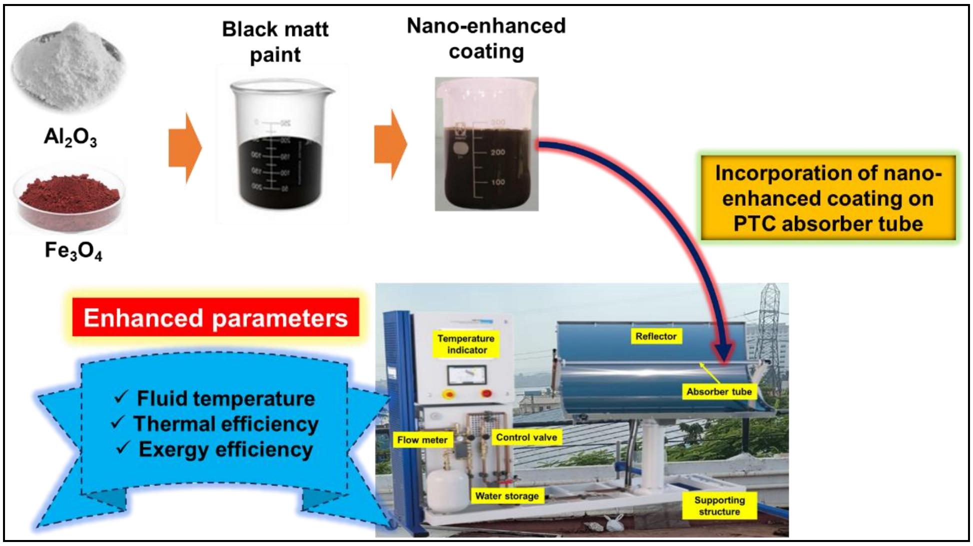

Fig 5: Graphical flow of the PTC study

Table 4: List of Instruments employed for measurement and their Uncertainty

Description of the measuring Instrument	Specified Range	Uncertainty
Anemometer	0.4-45 m/s	±2%
Data logger	-400 to 1400°C	±0.3%
Pyranometer	0-1800W/m2	±5%
Thermocouples	-0 to 400°C	±0.2%

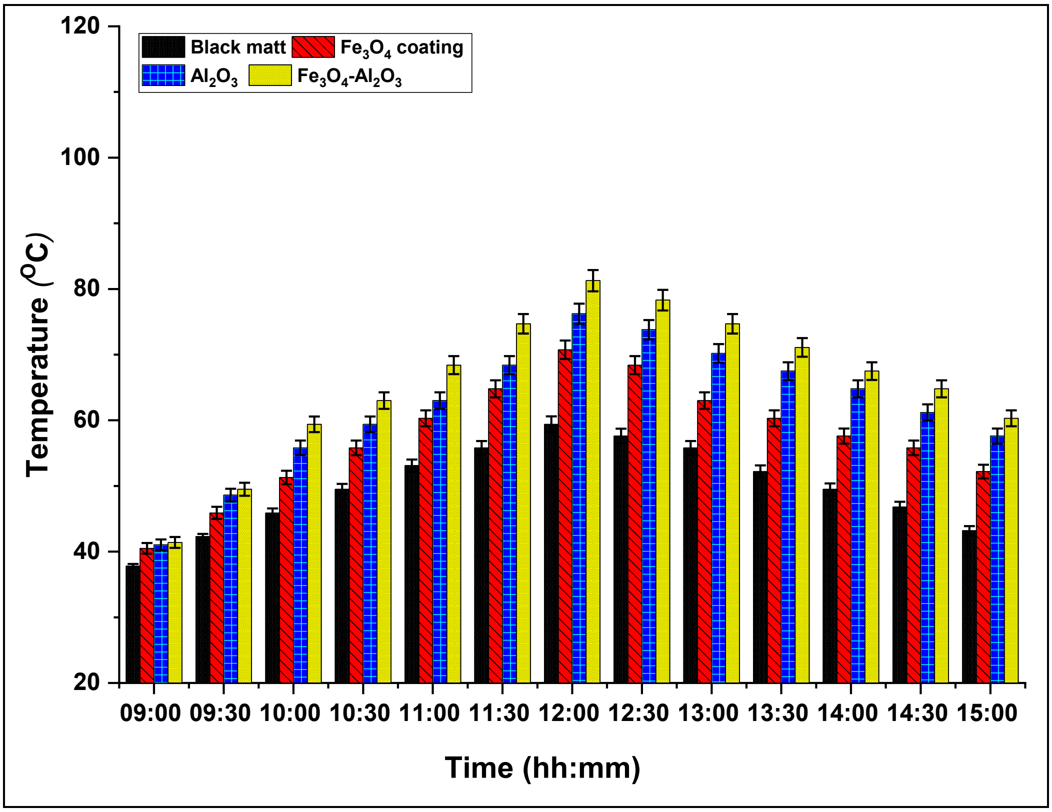

Fig 6: Heat Transfer Fluid outlet temperature performance with different coatings over the daytime

Nevertheless, the hybridized Fe_3O_4-Al_2O_3 nano-enhanced coating had the maximum fluid temperature recorded at 81.5 °C. This is attributed to the synergistic effect of Fe_3O_4-Al_2O_3 nanoparticles, which combine high thermal conductivity, good solar absorbance and stability in the absorber surface. The hybrid coating is effective in the maximization of thermal performance by reducing the convective and radiative losses and maximizing the solar energy absorption and the heat transfer. Fe_3O_4 is present to improve the optical absorption that is associated with magnetic properties as well as conductive properties, whereas Al_2O_3 increases the thermal conductivity of the coating, which offers efficiency in the heat distribution throughout the absorber. Besides, the hybrid nanoparticle coating can have superior surface wettability and low contact resistance, which also adds to the observed enhancement of the highest temperature of the fluid in the PTC circuit with the absorber.

1.6 Analysis on Heat Absorption

Fig 7 illustrates the dependence of the heat energy absorption on time. The absorption of the heat energy was determined by the fluid temperature difference between the outlet and inlet. The black matte coating absorbs the lowest amount of heat energy, approximately 2138.4W, because it has the highest emissivity and therefore absorbs much heat energy, resulting in a limited ability to retain its heat. Conversely, the Fe_3O_4 nano-enhanced coating has a higher value of heat absorption, 2538.9 W, due to the great optical absorption and increased thermal conduction that can enable efficient transfer of heat to the working fluid. The Al_2O_3 nano-enhanced coating additionally increases the heat absorption up to 2740.2 W and has the advantage of Al_2O_3 with a better thermal conductivity and easy formation of a stable coating, decreasing radiative and convective losses.

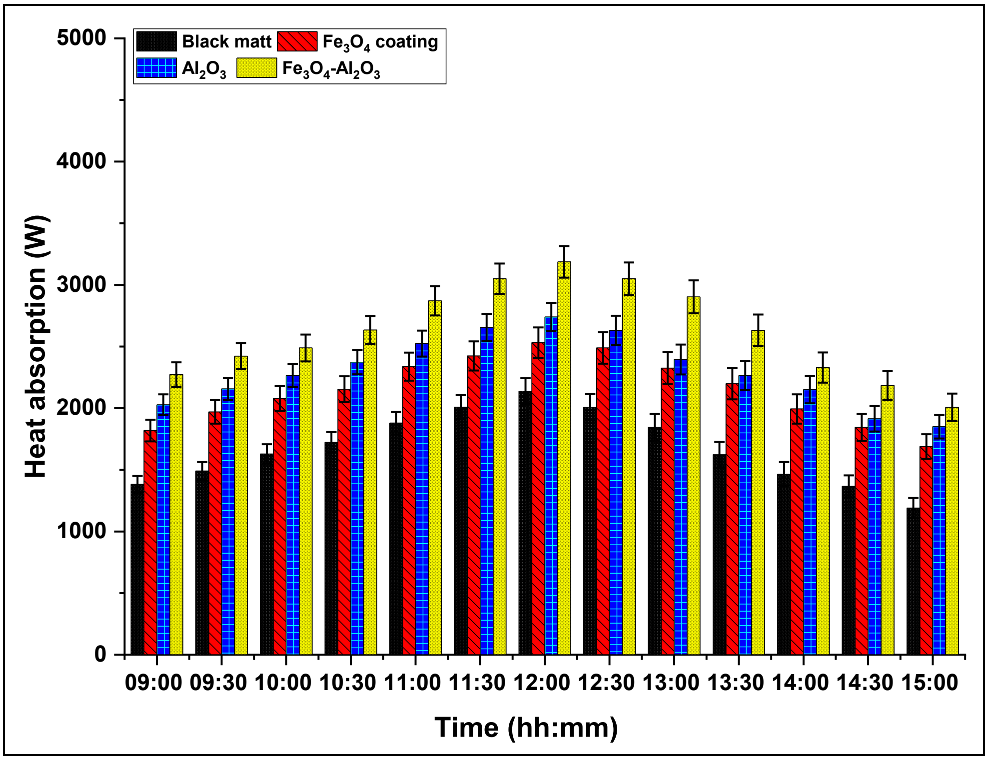

Fig 7: Heat absorption performance with different coatings over the daytime

The hybrid Fe_3O_4-Al_2O_3 nano-enhanced coating has the greatest heat energy absorption of 3186.4 W because it has the merits of the two nanoparticles. Fe_3O_4 increases optical absorption efficiency, and the efficiency of capturing solar radiation and Al_2O_3 increases heat transfer speed and efficiency, respectively. This synergy reduces radiative and convective losses, which means that more energy is held back in the system. Surface wettability and stability are also enhanced by the hybrid coating, thereby minimizing thermal resistance and increasing the total heat retention. Moreover, the presence of Fe_3O_4 nanoparticles gives the material a higher absorption of light because of its magnetic quality, and Al_2O_3 makes the distribution of heat even. This is a combination that maximizes the thermal performance of the absorber, and it is more efficient compared to the single nano-coatings. Consequently, the hybrid Fe_3O_4-Al_2O_3 coating enhances the total performance of the solar thermal collector to a large extent.

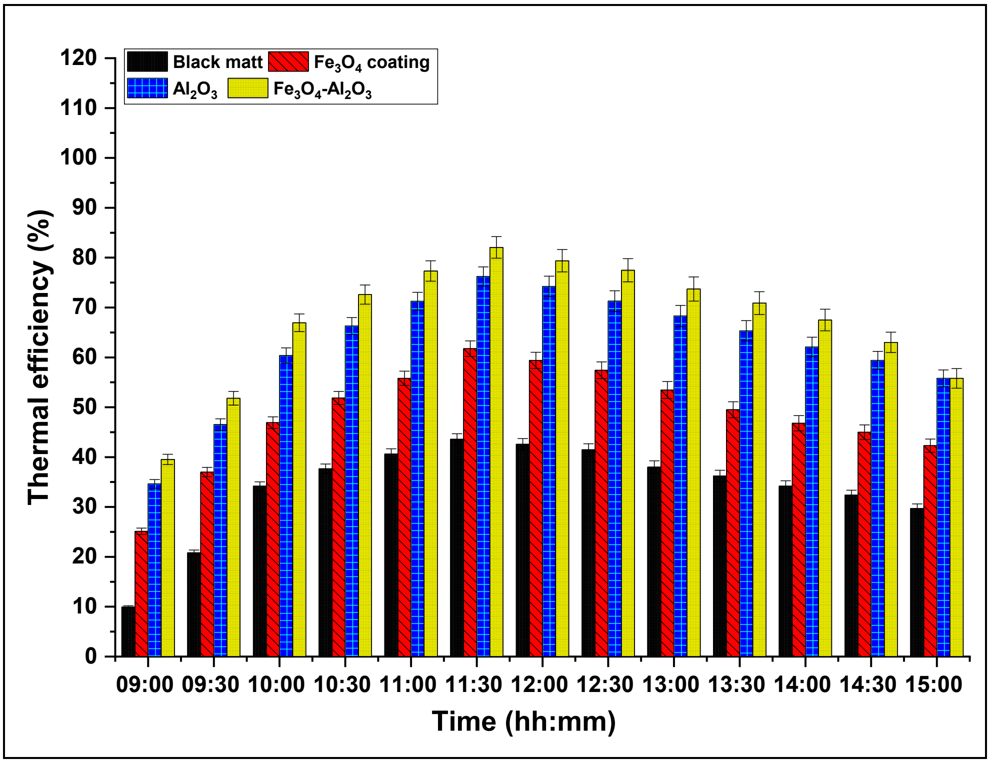

Fig 8: Effect of nano-enhanced coating on thermal efficiency

1.7 Analysis of Thermal Efficiency

Based on the absorption of heat energy and the amount of energy input, the thermal efficiency was determined for various coatings. Fig 8 shows the efficiency of the heat against time variation. The black matte coating has the lowest efficiency of approximately 42.57% as it has a high emissivity, resulting in the radiative heat losses despite a good absorption of the solar energy. The use of nano-enhanced coating also causes an increase in the solar energy absorptivity, which makes the rate of heat transfer between the absorber tube and the working fluid increase. Fe_3O_4 enhanced nanoparticle coating Fe_3O_4 enhanced nanoparticle coating increases efficacy to 59.4% by increasing optical absorption, thermal conductivity, minimizing losses, and increasing heat transfer. The efficiency is further increased to 74.25 after Al_2O_3 nano-enhanced coating, and this is attributed to the fact that the Al_2O_3 is highly thermal conductive and therefore, transfer of heat to the working fluid is accomplished with minimal energy loss.

The best thermal efficiency 79.38% occurs with the hybrid Fe_3O_4-Al_2O_3 nano-enhanced coating, and this is an effective combination of the high optical qualities of Fe_3O_4 and the high heat transfer of Al_2O_3. This synergy combination enhances the absorption, retention and distribution of solar radiation and heat, reducing convective and radiative losses. The hybrid coating can also enhance the stability of the surface and make it more wettable, and enhance thermal performance. The nanomaterials have the capacity to enhance solar thermal collector systems by increasing the use of solar energy, as observed through the increasing efficiency.

1.8 Analyses of Exergy Efficiency

The efficiency of the exergy in the various coatings as a function of time was plotted in Fig 9. Maximum coating exergy efficiency: 27.3% with black matte, 32.2% with Fe3O4, 40.48% with Al_2O_3 and 42.885% with hybrid Fe_3O_4-Al_2O_3, indicating the influence of nano-enhanced coating on the thermodynamic performance of a solar thermal collector. The matte black coating has the lowest exergy efficiency of 27.3 as it has the highest emissivity, which is the source of radiative loss and poor conversion of heat.

Nevertheless, the Fe_3O_4 nano-enhanced coating increases the efficiency of exergy up to 32.2% by increasing optical absorption and thermal conductivity to maximize the utilization of the solar energy. The Al_2O_3 nano-enhanced coating increases exergy efficiency to 40.48% with a higher thermal conductivity, better transmission of heat as well as lowering enthalpy. The hybrid Fe_3O_4-Al_2O_3 nano-enhanced coating has the highest exergy efficiency of 42.88% because it enjoys the merits of the two nanoparticles. Fe_3O_4 leads to the absorption of solar energy, which facilitates optical absorption, whereas Al_2O_3 facilitates heat transfer and minimizes thermal resistance.

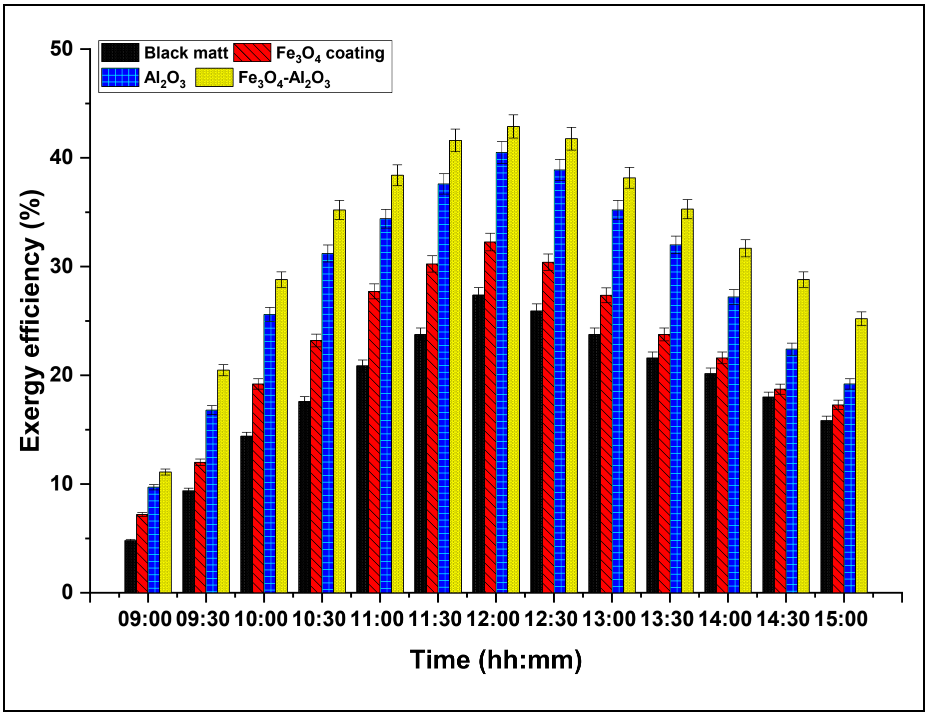

Fig 9: Exergy efficiency with different coatings over the daytime

This synergy reduces system irreversibility to enhance exergy efficiency. The hybrid coating enhances thermodynamic performance and energy consumption because it reduces heat losses and ensures that the heat is evenly distributed throughout the system. It is more efficient at exergy when the nanomaterials enhance the second-law efficiency of solar thermal collectors to enhance system sustainability and energy conversion.

Fig 10 represents the average thermal and exergy with the help of various coating absorbers. The characteristics of exergy and thermal efficiency of various coatings are 39.8% and 18.7% in the case of black matte, 51.6% and 22.3% in the case of Fe_3O_4, 57.8% and 28.5% in the case of Al_2O_3, and 64.9% and 32.6% in the case of hybrid Fe_3O_4-Al_2O_3. These values are a clear indication of the effects of nano-enhanced coatings on solar thermal collectors. The black matte coating has the lowest thermal and exergy efficiencies of 39.8% and 18.7%, as the coating has the highest emissivity, resulting in high radiative losses that decrease the effective heat transfer to the working fluid. Its reduced thermal conductivity further reduces the ability to store heat, reducing the quantity of useful energy present. With greater optical absorption and thermal conductivity to the extent of 51.6% and 22.3% thermal efficiency and exergy efficiency, the Fe_3O_4 nano-enhanced coating provides enhanced thermal efficiency and heat transfer, as well as reduced energy dissipation. The Al_2O_3 nano-enhanced coating enhances a thermal efficiency of 57.8% and exergy efficiency of 28.5% because of its superior thermal conductivity and uniform dispersion that decreases the amount of heat losses and the creation of entropy.

The hybrid Fe_3O_4-Al_2O_3 nano-enhanced coating has the highest thermal efficiency of 64.9% and exergy efficiency of 32.6%, showing a synergistic effect between the two nanoparticles. Fe_3O_4 is used to enhance the solar absorbance because the product has a powerful optical property, whereas Al_2O_3 is used to enhance the transfer of heat to ensure efficient use of energy. The combination eliminates radiative and convective losses, maximizes heat distribution and minimize system irreversibility, causing increased second law efficiency. Also, the hybrid coating improves the wettability and thermal stability of the surface, which adds to the increased performance as well. These findings underscore the usefulness of nanomaterials to the maximum use of solar energy, which has a great potential to improve both thermal and exergy efficiency of solar thermal collectors.

2. Conclusions

This study was aimed at carrying out an experimental investigation of the PTC systems under different conditions of absorber coating. Black matt material has been used as a base coating material first of all. The base coating material was subjected to the addition of nanoparticles of Fe_3O_4 and Al_2O_3, and this led to further improvement of the material. To make matters worse, the Fe_3O_4- Al_2O_3 hybrid nano-enhanced coating was developed at a volume ratio of 50:50. Based on the outcomes of the experiment, the following conclusions were made.

- ✓ The black matte registered a temperature of 59.4 °C, Fe_3O_4 was at 70.7 °C, Al_2O_3 was at 76.23 °C and the hybrid Fe_3O_4-Al_2O_3 coating registered the highest temperature of 81.5 °C proving to be better thermally and possessing greater solar absorption properties.
- ✓ On the same note, coatings had a diverse absorption of heat. Black matte absorbed 2138.4 W, Fe_3O_4 recorded 2538.9 W, Al_2O_3 recorded 2740.2 W and hybrid Fe_3O_4-Al_2O_3 recorded 3186.4 W.
- ✓ What is more, the Black matte thermal efficiency was 42.57%, Fe_3O_4 was 59.4%, Al_2O_3 was 74.25%, and Fe_3O_4-Al_2O_3 was 79.38%.
- ✓ Lastly, there was an increase of the exergy efficiency with the nano-coatings. Black matte had 27.3%, Fe_3O_4 increased to 32.2%, Al_2O_3 attained 40.48% and hybrid Fe_3O_4- Al_2O_3 was 42.88%

The article substantiates the claim that nano-enhanced coatings have a great deal of potential to enhance the thermal performance of PTC systems. The hybrid of Fe_3O_4 and Al_2O_3 coating is the most efficient because it has a high level of heat transfer and solar absorption. The radiative and convective losses are minimized successfully with nano-coatings to maximize the use of energy. Better thermal and exergy efficiencies are provided by better coatings. The results indicate the possibilities of nanomaterials to develop the solar thermal collector technology towards sustainable energy use.

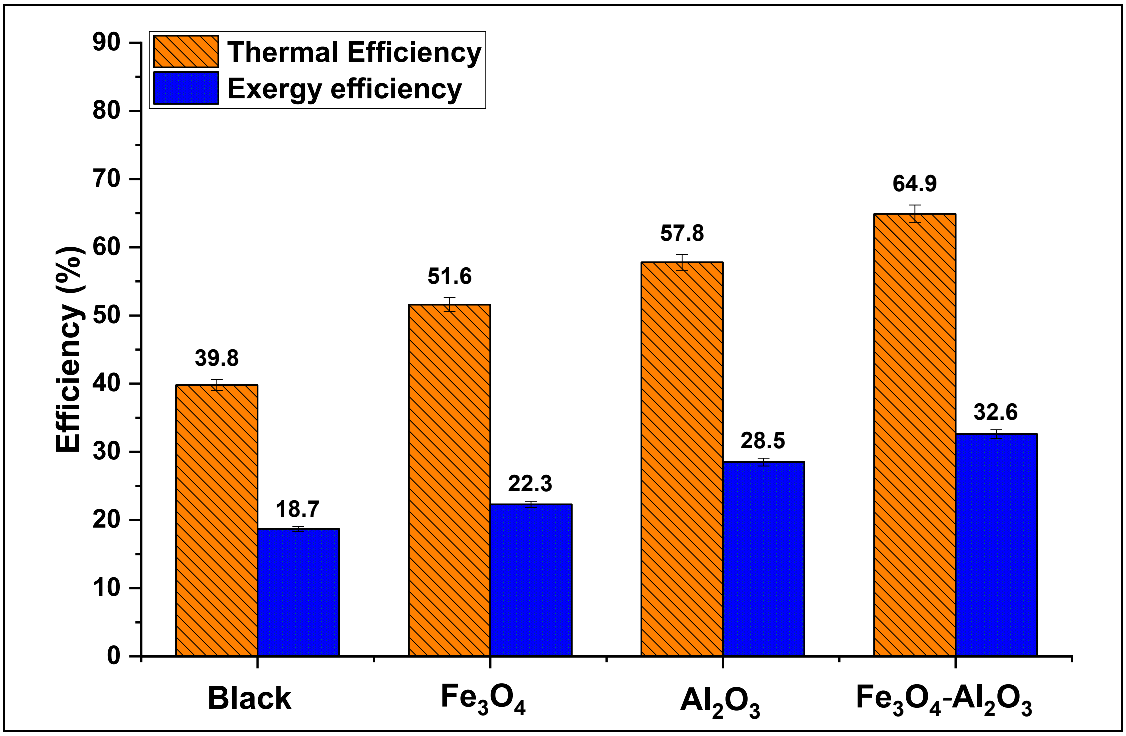

Fig 10: The comparative mean energy and exergy efficiencies with different coatings

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