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Research Article

Evaluation of the thermal efficiency of nanofluid flows in flat plate solar collector

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ABSTRACT

In this research, flat plate solar collectors (FPSC) were studied due to their simplicity, low maintenance, and cost-effectiveness. The study focused on comparing FPSC thermal performance using CuO/H_2O nanofluids. Experiments were conducted over three months during the Iraqi weather conditions (January, February, and March) with carefully selected nanoparticle concentrations. Data was collected from 9 A.M. to 3 P.M., using various mass flow rates (ranging from 0.003 to 0.076 kg/s). Results showed a direct correlation between temperature and nanoparticle concentrations, with the highest outlet temperature (50°C) observed at 3 P.M. for 1% CuO-water nanofluid. Notably, at 1 P.M. in March, the 1% CuO-water nanofluid exhibited a 32% increase in collector thermal efficiency, surpassing pure water by 11.3%. This would improve the performance of FPSC by achieving higher efficiency increments. These improvements were attributed to the unique physical properties of nanoparticles, their increased surface area, and higher thermal conductivity. The study determined that the optimum nanofluid concentration for superior collector efficiency was 1%.

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INTRODUCTION

Renewable energy is becoming electricity's top source in the world. It is more efficient to supply electricity under demand. Solar energy is one of the significant renewable energy sources. According to their renewable resource, solar energy can meet the increasing energy demand in the world. For instance, solar energy can save energy in different applications such as desalination and other common uses requiring water boiling [1-3]. Solar collectors can be classified into concentrating and non-concentrating collectors [4]. For instance, non-concentrating collectors can be subdivided into flat plate solar collectors (FPSC) and evacuated tube collectors (ETC). FPSC prefers for their lower cost and ease of installation [5]. Furthermore, FPSC requires minimal cleaning, no need for a sunlight tracking system, and maintenance. In FPSC, heat transfers directly from the reflected

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sunlight into the working fluid, i.e. water. According to the above advantages, FPSC prefers household water heating systems. Due to heat losses by radiation and convection, the thermal efficiency of FPSC is reduced. Therefore, there are many studies conducted on the improvements in the thermal performance of FPSC [6]. In fact, merging solar PV and thermal technologies boosts efficiency, providing electricity and heat without separate systems [7].

Choi and Eastman, 1995, [8], had made the first study on nanofluid. Increasing volume concentrations of nanoparticles by 1% would lead to double thermal conductivity of nanfluid [8].

Nanofluid can be produced by dispersing nanoparticles into the heat transfer fluid. While, Maxwell was the first who provides a theoretical foundation for forecasting suspension conductivity [9]. Maxwell's theory is used to predict thermophysical properties of nanofluid. Due to higher thermal conductivity of nanoparticles, heat transfer of nanofluid improved. Thermal efficiency of FPSC by [9] has been increased by [10]. Furthermore, in forced conventional heat transfer systems, the presence of nanoparticle in nanofluid can increase the viscosity, pressure drop, and power [11]. For instance, these solid nanoparticles own higher specific gravity; therefore, nanofluid is denser than base fluid. Effect of TiO_2-water nanofluid, range of volume percentage were 0.1%-0.3%, on flat plate solar collectors had been examined [5]. Said et al. [5] tested a range of mass flow rate were 0.5-1.5 kg/min. In order to ensure the stability of the nanofluid, ethylene glycol, poly (PEG 400) have been used. They found that highest energy efficiency (16.9%) achieved at 0.1 vol/% nanofluid with 0.5 kg/min [5]. There were no differences in the pressure drop and pumping power between the base fluid and nanofluid. Moreover, the nanofluid were stable for a period of one month. 0.3 vol. % TiO_2-nanofluid improves the heat conductivity by 6%. Overall, nanofluid increase the exergy and energy efficiency of the solar collector. It found that nanofluid showed higher performance of FPSC. Heat transfer of nanofluid improved due to the higher thermal diffusivity and surface area of nanoparticles [12, 13]. The foundation by [8] has been validated by others [14-16]. Although the concentrations of nanoparticles are low, the improvement in thermal conductivity of nanofluid are promising. Keblinski et al., [17] established the effect of dispersing carbon nanotubes or copper nanoparticles (volume fraction of less than 1%) to oil or ethylene glycol; nanoparticles increase thermal conductivity of nanofluid. Alumina (Al_2O_3) nanoparticles improves thermal conductivity of nanoafluid by 44% [18]. Additionally, 3 vol. % alumina-nanofluid shows an increment in the heat conductivity by 10% [19]. Maga et al. [20] explored the effect of single-phase model of nanofluid in a tube. Maga et al. [20] founds that nanoparticles increase the heat transfer coefficient and Reynolds number. Chandrasekar et al. [19] emphasized on the importance of stability of nanofluid using a physical and chemical dispersion treatments. There are different methods to prepare nanofluid mentioned by [21]. Yousef et al. [22] examined the effect of Al_2O_3-nanofluid on FPSC efficiency. They found 0.2 wt.% Al_2O_3-nanofluid increases the efficiency of the solar collector by 28%. Moreover, parabolic trough solar collectors (PTSCs) offer high operating temperatures (100-700°C) and are popular for both power generation and industrial process heating [23]. Hybrid nanofluids show potential for enhancing thermal performance of PTSCs [23]. The effect of tilting angle and porosity of the pipe on the heat transfer in FPSC using nanofluid (water-CuO) have been conducted by [24]. This study shows that increasing tilting angle and curvature parameter improves heat transfer, while increasing porosity reduces it [24]. It was found that adding Al_2O_3-H_2O nanofluid to FPSC improves heat transfer compared to base fluid by increasing heat parameters, Grashof number, and nanofluid volume fraction [25,26]. Furthermore, an experimental study explores silver/water nanofluid in a solar collector, revealing improved convective heat transfer and efficiency [27]. The combinations of porous media and nanofluids would enhance solar collector efficiency by 60.12% [28].

Previous studies have predominantly emphasized the dispersing of nanoparticles into conventional fluids like water, oil, and ethylene glycol to improve nanofluid heat transfer properties. This involves modifying thermal and physical characteristics and assessing their impact on the efficiency of FPSCs. Various nanoparticles, including copper oxide (CuO), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), zinc oxide (ZnO), magnesium oxide (MgO), and diamond, have been utilized alongside various base fluids. Researchers focused primarily on nanoparticle concentration and its dispersion within the base fluid, a critical aspect of enhancing heat transfer. Overcoming the challenge of maintaining a stable nanoparticle distribution, typically within the range of 0.1% to 0.3%, has been a key consideration. Typically, 20-nanometer diameter nanoparticles were employed. The primary objective of this research is to demonstrate how nanoparticles impact the performance of nanofluids in FPSCs. Consequently, this investigation will undertake a comprehensive thermal assessment of FPSCs, utilizing various fractions nanofluids (0.5 vol. % and 1 vol.%) of CuO/water nanofluids will be examined experimentally in the study. Additionally, different rates of mass flow have been studied, specifically 0.003, 0.007, 0.022, and 0.076 kg/s. The aim of this study is to show the impact of nanotechnology on the FPSC system.

METHODOLOGY

Material Preparation

In this research, CuO nanoparticles (purchased from HiMedia Laboratories Pvt. Ltd., Mumbai, India) are used without any processing. Various fractions of CuO nanoparticles (0.5 vol. % and 1 vol.%) were examined. Equation (1) is established to calculate the nanoparticle mass [29,30]. (Table 1)

Table 1. Material properties

Properties	Water	CuO	0.5% nanofluid (0.5% CuO-water)	1% nanofluid (1% CuO-water)
Density (kg/m³)	992	6507	1775	1930
Specific heat capacity (J/kg.K)	4198	540	3380	3120
Thermal conductivity (W/m.K)	0.59	19	1.045	1.213

$$m_p = \frac{\emptyset\, \rho_p \left(\frac{m_f}{\rho_f}\right)}{(1-\emptyset)} \qquad (1)$$

Where m_p the mass of nanoparticles in kg, m_f is the mass of base fluid in kg, ρ_p is the density of nanoparticles kg/m^3, ρ_f density of base fluid kg/m^3, and $\emptyset$ is the concentrations of nanoparticles

According to Equation (1), the required amount of nanoparticles is calculated. Nanoparticles are dispersed in the base fluid using two methods. Firstly, the mechanical dispersion method is employed to prepare the nanofluid using an electric mixer, which operates continuously for over 40 minutes to ensure the formation of a homogeneous mixture. Secondly, the ultrasonic dispersion method is utilized and runs for a period exceeding 40 minutes. This procedure is repeated multiple times to ensure homogeneous dispersions.

After preparing the nanofluid and ensuring it was well-mixed, it was placed in the test section and continuously stirred to evenly distribute the nanoscale particles. Continuous monitoring revealed that it took around 15 hours for the nanoscale particles to fully disperse in water and remain uniformly dispersed, confirming the stability of the nanofluid (copper oxide with water) during the experiment as shown in Figure (1).

Experimental Setup

Prior to the manufacturing process, the design, specifications, and detailed plans for the FPSCs were created to facilitate the detailed manufacturing processes for each component of the solar collector, as illustrated in Figure 2.

The system comprises a 1x1 meter square aluminum box with three layers of plastic panels on its outer sides, an inner aluminum layer, and insulating glass wool in-between. A 4 mm thick fixed glass cover allows solar radiation to pass through while minimizing heat losses. For nanofluid, a CuO/water mixture was used after thorough mixing. The solar collector features copper tubes (0.85 meters in length) with tube headers having an inner diameter of 22.5 mm and a thickness of 1 mm. The heat-absorbing tube has an inner diameter of 9.5 mm and a thickness of 1.5 mm.

The collector interior was insulated with double layers of Armaflex insulation material to minimize heat loss. Heat exchangers and tanks were connected using 1/2-inch German-made plastic pipes, valves, and connectors to regulate water and nanofluid flow rates. Two vertical pumps (0.25 HP, max height 2.5 meters) circulated fluids in the system. One pump moved nanofluid from the tank to the collector, the other transferred water. A flow meter measured their flow rates.

The setup used two iron platforms: one for fluid reservoirs and one for the solar collector, serving water and

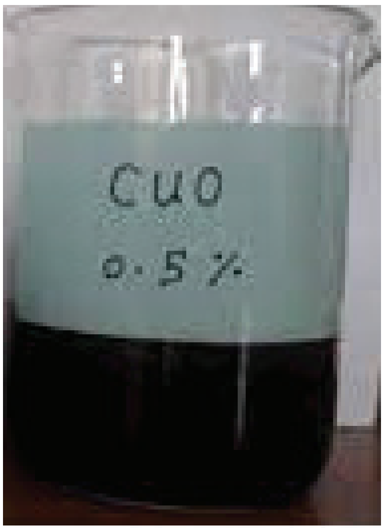

Figure 1. The nanofluid sample.

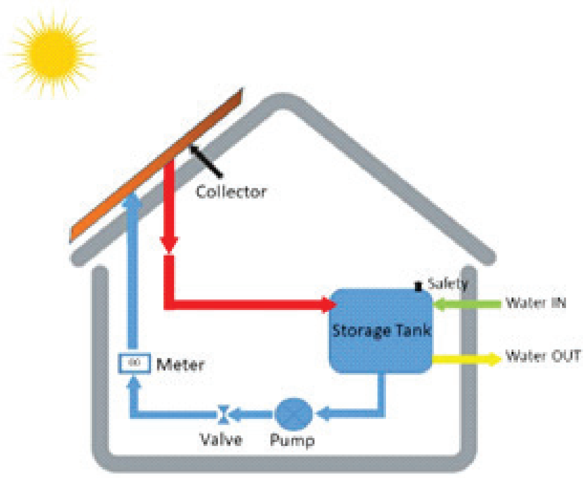

Figure 2. Schematic diagram of the FPSCs.

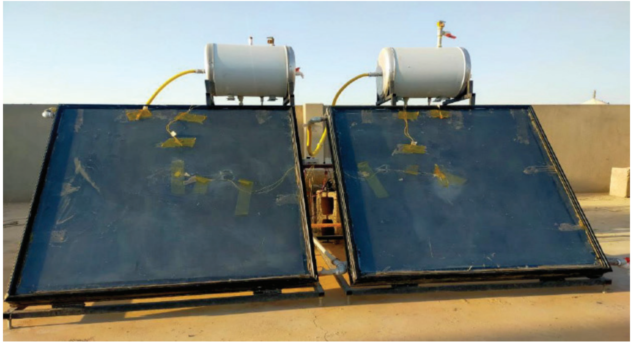

Figure 3. The experimental setup.

nanofluid systems. It included flow rate instruments and digital temperature sensors for heat measurement, Figure 3. The setup includes various sensors for measuring water and nanofluid temperatures, flow control valves, Arduino switches, water pump controls, UPS activation, insulated copper pipes, 45-liter tanks for both substances, radiation intensity measurement devices, safety valves, an electric mixer, and mass flow meters for both systems.

The data logger, designed for flat-plate solar collectors, utilized thermocouple sensors (Type K) and Arduino ‚UNO' microcontrollers. Data was stored on an external memory card, recording seven data points hourly for each system. The logger measured temperatures, including inlet/outlet temperatures of pure water and nanofluid, absorber plate, glass cover, and ambient temperatures. Flow rates for pure water and nanofluid in the solar collector were measured using a YF,S201 water flow sensor device with a range of 1 to 30 liters per minute, suitable for water pressure below 1.75 MPa.

Experimental Procedure

After setting up the experimental apparatus and calibrating the thermocouples (TCs), the experiments were initiated following this procedure. The experimental configuration included two identical flat-plate solar collectors mounted on a residential building in Kirkuk. One collector contained pure water, while the other held nanofluid (CuO + water). The setup incorporated nine temperature sensors, a 16 kbt memory card reader, mass flow rate, and solar radiation intensity measurements. The experiments ran for three months January, February, and March. The installation process involved fitting absorber plates, extensive cleaning, tank filling, and electrical checks. The sensors were accurately calibrated and positioned. Data, including solar radiation, ambient temperature, and wind speed, were collected hourly from 9:00 A.M. to 3:00 P.M., with the procedure repeated each hour while varying mass flow rates.

Data Reduction

The usable energy production of a flat plate solar water collector in steady state (Qu) is [18,19]:

$$Q_u = \dot{m} \times Cp_{nf} \times (T_{ws.co} - T_{ws.cin}) \quad (2)$$

Where: $\dot{m}$ is fluid mass flow rate (kg/sec), $Cp_{n.f}$ is nanofluid specific heat (kJ/kg.K), $T_{ws,cin}$ and $T_{ws,co}$ (K) fluid inlet temperature into solar collector and fluid outlet temperature from the solar collector. The hourly efficiency, η_{sc}, for the flat plate solar collector is [20]:

$$\eta_{sc} = \frac{\int_{t1}^{t2} Q_u \, dt}{A_{sc} \int_{t1}^{t2} I(t) \, dt} \times 100\% \quad (3)$$

Where: I(t) solar radiation intensity instantious (W/m^2), and A_{sc} is the flat-plate solar water collector area (m^2).

RESULTS AND DISCUSSION

Figure 4 illustrates solar radiation for different months (January, February, and March) at different times (9 a.m. – 5 p.m.). The variation in solar radiation reaches a peak of 805 W/m^2, 800.8 W/m^2, and 792.5 W/m^2 at 12 p.m. for March, February, and January, respectively. Following this peak, a rapid decline occurs, reaching its lowest points of 692 W/m^2, 688.5 W/m^2, and 682.4 W/m^2 for March, February, and January, respectively. Additionally, the month of March demonstrates a higher intensity of solar radiation over time when compared to both January and February, as illustrated in Figure 4.

SEM has been used to incdicate the presense of nanoparticles in the nanofluid. Figure 5 demonstrates the presence of nanoparticles in the nanofluid material and clarifies the nanosize of the CuO nanoparticles. Furthermore, the validation of our results has been conducted.

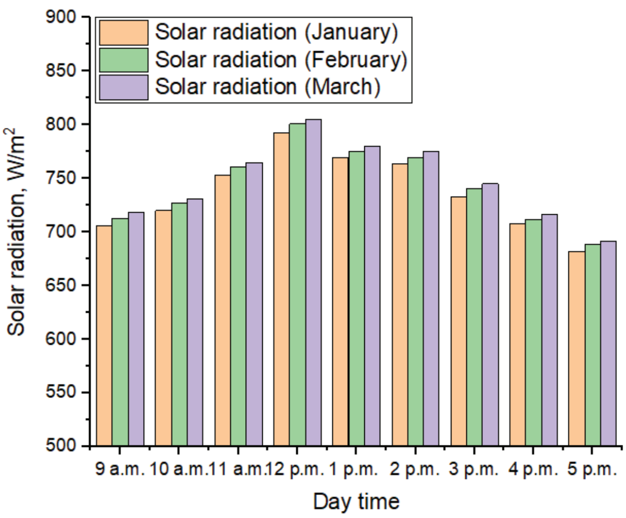

Figure 4. The solar radiations at different months (January, February, and March) vs. Day time (9 a.m. – 5 p.m.).

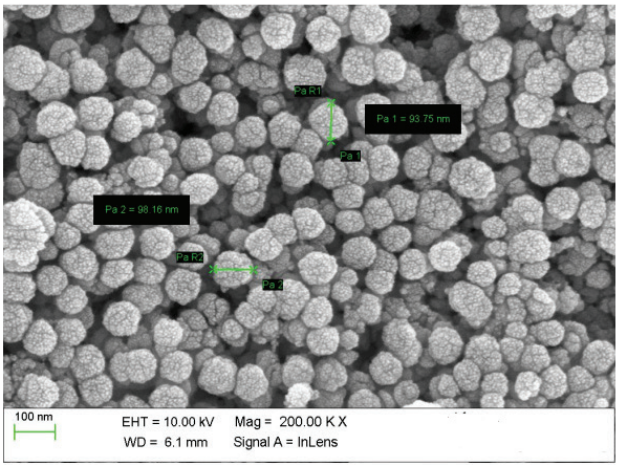

Figure 5. The presence of nanoparticles in the nanofluids using SEM (Scanning Electron Microscopy).

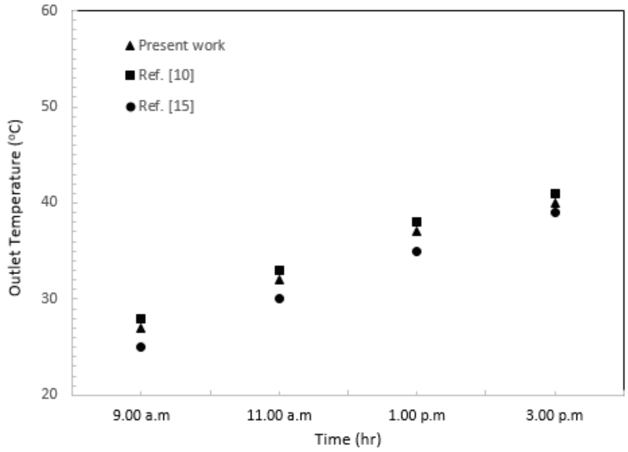

Figure 6. Validation of current results with literature.

The results obtained in this study have been rigorously validated through comparison with established literature sources [10,15]. The detailed comparison, as depicted in Figure 6, showcases a remarkable alignment between our research findings and those reported in previous studies [10,15]. This congruence not only strengthens the credibility of our results but also establishes a robust foundation for the consistency and reliability of our experimental outcomes within the broader scientific context. Such validation serves to enhance the robustness of our study and reinforces the relevance and applicability of our findings in the existing body of knowledge.

Figure 7 clearly demonstrates the significant impact of nanoparticles on the outlet temperature. FPSC utilizing 1% CuO-nanofluid consistently exhibited higher outlet temperatures at various times, as illustrated in Figure 7. This is similar to the results of output power, Figure 8. However, the consumption of the output power varying with the changes of mass flow rate, Figure 9. Increasing the mass flowrate would increase the output power and this increment depend on the concentrations of nanoparticles. According to Figure 9, the maximum power consumption at 11 A.M. increased by 25.185% for a 1% nanofluid over water. Specifically, at 1 P. M. In January, the efficiency of FPSC of nanofluid containing 0.5% CuO exhibits a 24% while 1% CuO showed efficiency of 25 %. However, the efficiency of FPSC containg water as the base fluid was 23%. These increments are comapered to pure water with 4.3% and 8.7%, for 0.5% CuO nanofluid and 1% CuO nanofluid respectively, highlighting the impact of nanoparticles on performance of FPSC, Figure (10).

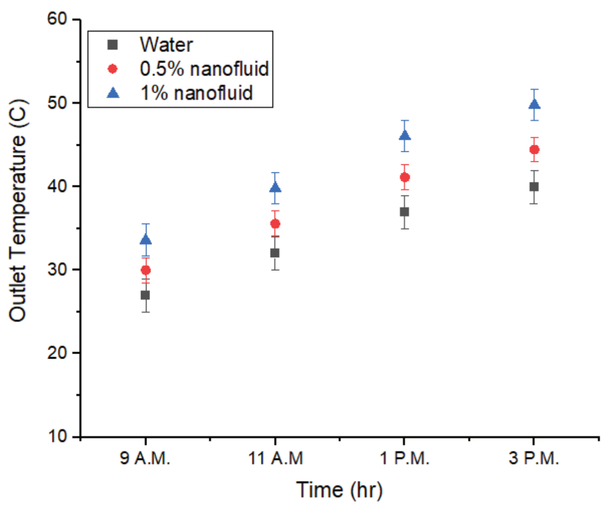

Figure 7. Outlet temperature of base fluid and nanofluids vs. time.

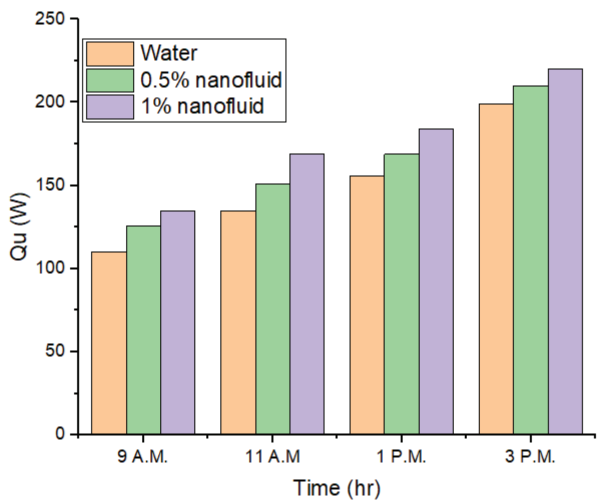

Figure 8. Output power of base fluid and nanofluids vs. time.

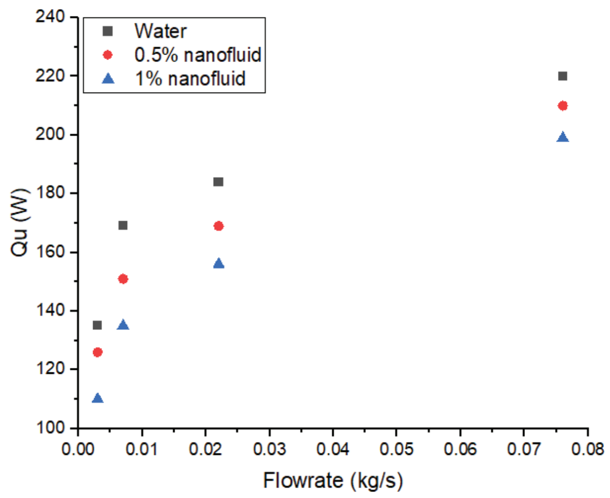

Figure 9. Output power of base fluid and nanofluids vs. flowrate.

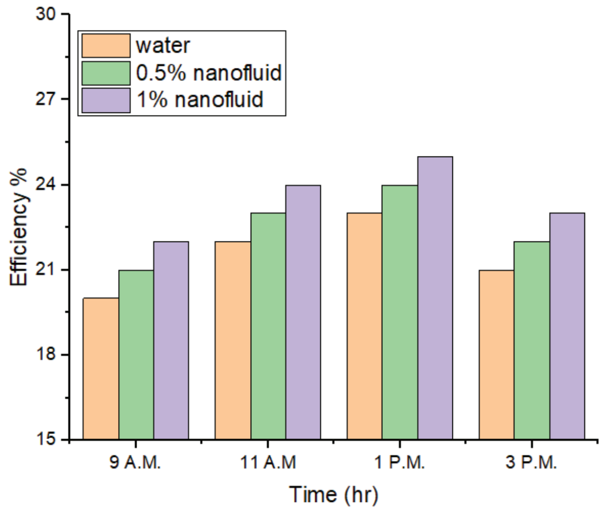

Figure 10. Collector efficiency of base fluid and nanofluids with time in January.

In February, at 1 P. M., the efficiency of 1% CuO nanofluid increased to 28% which is higher than 0.5% CuO nanofluid which owns efficiency equal to 27%, Figure (11). This clarify the impact of increasing nanoparticles concentrations. Variations in solar radiation impact the instantaneous efficiency of water/nanofluid collectors significantly. At 1 P. M. in March, the efficiency of the water collector up to 28.75%, while the 0.5 %CuO nanofluid collector and 1% CuO-nanofluid collector achieves 30% and 32% respectively, Figure (12). These efficiencies are directly related to solar radiation, solar irradiation higher in summer season than springer season. Therefore, the efficiency are higher in March comparing to February emphasizing the solar collector's dependency on solar energy density.

It is clearly noticed that increasing solar intensity would increase the efficiency of FPSC for three cases: water, 0.5% CuO-water, and 1% CuO-water. In Figures (10-12) and Table (2), it can be seen that higher efficiency was at 1 P. M. The peak of the solar irradiation occurs around noon, close to 1 P.M, a similar output obtained by [31].

The presence of copper oxide particles in nanofluids has been found to substantially enhance the efficiency, outlet temperatures, and power of the solar collectors. These enhancements observed in nanofluid systems compared to pure water can be attributed to the higher thermal

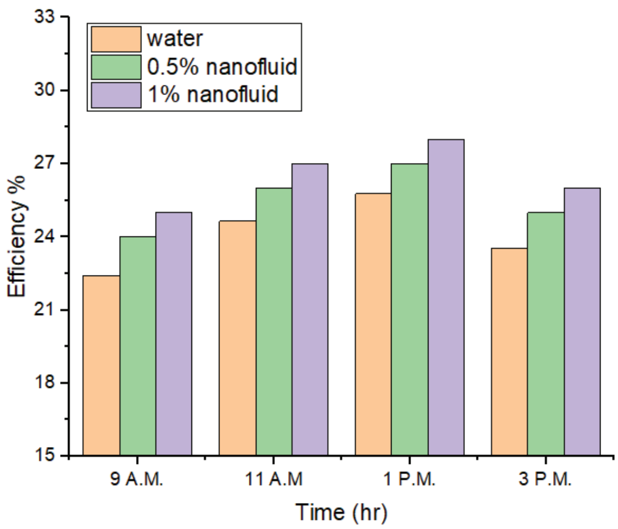

Figure 11. Collector efficiency of base fluid and nanofluids with time in February.

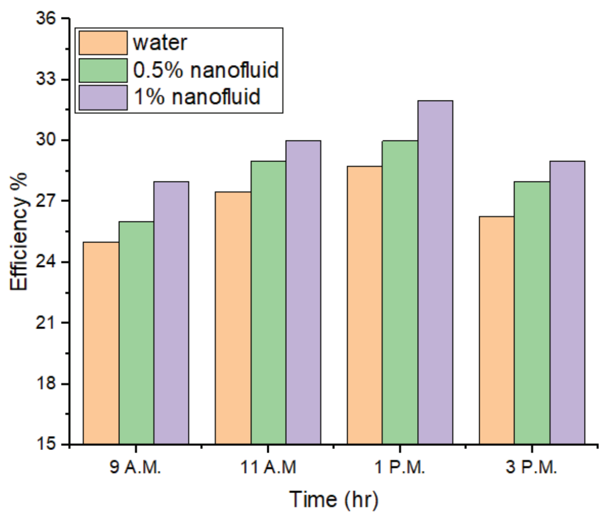

Figure 12. Collector efficiency of base fluid and nanofluids with time in March.

Table 2. Data collected of different types of materials (water, 0.5% nanofluid, and 1% nanofluid) at 1 P.M

Type of fluid	Outlet temperature (^{0}C)	Collector's Efficiency
Water	37	28.75%
0.5% nanofluid	41.144	30%
1% nanofluid	46.08128	32%

conductivity values of these nanoparticles, along with their larger surface area, both of which contribute to the improved thermal performance of the nanofluid. It is worth noting that the magnitude of these enhancements is intricately tied to the concentration levels of the nanoparticles within the fluid system. This dependency highlights the critical role that nanoparticle concentration plays in optimizing the thermal efficiency of solar collectors utilizing nanofluids, underscoring the importance of meticulous concentration control in the development and application of these advanced heat transfer mediums.

CONCLUSION

The summary of this study are:

1. This study conducted experimentally the thermal efficiency of flat plate solar collectors (FPSC) employing CuO/water nanofluids. Over three-month investigation spanning January to March, a direct correlation between temperature measurements and nanoparticle concentrations within nanofluids was established. The experiments, conducted between 9 A.M. and 3 P.M., underscored the significant potential of nanofluids in enhancing FPSC efficiency.
2. Nanofluid had been prepared in two different methods to ensure stable nanoparticle dispersion in the base fluid (water) through mechanical and ultrasonic dispersion methods.
3. By precisely selecting optimal nanoparticle concentrations, notably a 1% CuO-water nanofluid, the collector's thermal efficiency experienced a remarkable 32% increase. This enhancement, surpassing pure water performance by 11.3%, was attributed to the unique properties of nanoparticles, particularly their higher thermal conductivity and higher surface area of these nanoparticles. These properties augmented heat transfer within the nanofluid, further increasing the collector's efficiency.
4. Additionally, it was observed that increasing the mass flow rate would enhance the output power; however, these increments are constrained by the concentrations of nanoparticles, with a higher increment observed at a 1% nanofluid concentration.
5. Validation of the results through comparison with existing literature sources bolstered the study's credibility. This comprehensive exploration of CuO/water nanofluids in FPSCs significantly contributes to the understanding of nanofluid technology and holds promise for enhancing solar energy utilization across diverse applications.

In summary, this study's findings underscore the transformative potential of CuO/water nanofluids in revolutionizing flat plate solar collector efficiency. This breakthrough paves the way for more efficient and sustainable solar energy solutions, marking a significant step towards a greener future.

NOMENCLATURE

$\dot{m}$	Fluid mass flow rate. kg/sec
Cp_{nf}	Specific heat capacity of nanofluid. kJ/kg.K
$T_{ws,cin}$	Fluid inlet temperature into the solar collector. K
$T_{ws,co}$	Fluid outlet temperature of the solar collector. K
t	Time, sec
T	Temperature, ^{o}C
I(t)	Solar radiation intensity instantious. W/m^2
A_{sc}	Flat-plate solar water collector area. m^2

Greek symbols

m_f	Mass of a fluid. kg
m_p	Mass of nanoparticles. kg
ρ_f	Density of a fluid. kg/m^3
ρ_p	Density of nanoparticles. kg/m^3
Ø	Concentration of nanoparticles.
η_{sc}	The hourly efficiency for the flat plate solar collector

Subscripts

f	Refers to fluid
p	Refers to nanoparticle
sc	Refers to solar collector

DECLARATIONS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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