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IMPROVEMENT OF THERMAL PERFORMANCE OF AN INDIRECT FLAT PLATE SOLAR COLLECTOR IN SOLAR WATER HEATER APPLICATIONS

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The object in this study is the process of heat transfer, energy conversion, and heat distribution through solar collectors in indirect systems. The problem to be solved is to develop sustainable alternatives powered by renewable energy sources, such as solar energy

This study is focused on the research of a solar water heater (SWH) system incorporating flat plate solar collectors (FPSC). The system enhances the thermal performance of the FPSC through an indirect, closed-loop configuration. Water from the hot water tank (HWT) is circulated through the FPSC copper pipes by a pump powered by a Solar Power Plant, ensuring continuous heat transfer and efficient thermal performance. The system operates at a flow rate of 0.116 kg/s. A K-type thermocouple connected to a data logger records the water temperatures at the HWT's inlet and outlet every 30 seconds. In addition to the system, the features of this study also focuses on phase change material (PCM) which uses mannitol material as thermal energy storage (TES) which will be used during cloudy or rainy weather. All equipment such as plunger pumps, heaters for PCM use solar electricity. The feature of this study also uses the Internet of Things (IoT) to find out the temperature in the solar water heater tank. The test results indicate a maximum FPSC thermal efficiency of 72% and a coefficient of performance (COP) of 10 under a pump power of 100 W and an absorbed heat input of 1000 W. The average solar irradiance ranged from 850 to 950 W/m^2. These results demonstrate the potential of this technology to efficiently meet domestic hot-water demand and its suitability for deployment in tropical regions

Keywords: solar collector, water tank, indirect system, power plant, water heater

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1. Introduction

Improving the operational aspects of renewable energy systems is accompanied by efforts to enhance the performance of the systems and their supporting components. It can be seen in the optimal results of wind-based and solar energy systems [1]. Rapid population growth, accelerating urbanization, and sustained economic development have significantly increased global demand for thermal energy, particularly for domestic and industrial water-heating applications. In the residential sector, water heating is a critical end-use energy service, predominantly supplied by electric water heaters (EWH), due to their operational simplicity, reliability, and widespread availability. However, EWH systems are inherently energy-intensive and contribute substantially to overall household electricity consumption, leading to elevated operational costs that can reach approximately 500 USD per household annually, depending on usage patterns and regional electricity tariffs. It is estimated that water heating alone accounts for nearly 40% of total residential energy demand, making it one of the largest energy-consuming activities in households. Furthermore, a significant portion of this electricity is generated from fossil fuel-based power plants, resulting in indirect carbon emissions associated with residential energy use. Heat storage is the heart of solar-based water heaters, making the development of this technology extremely important to improve the operational aspect of domestic water heaters. Key finding on the storage operation assessment shows the hybrid thermo-electric offers high charging efficiency, which ranges between 60.3 and 74.3%, while fluid-active operation has maximum value of 33.9%. The energy transfer rate becomes higher as the material is directly in contact with the heat source for hybrid thermo-electric operation, resulting in an excellent charge rating, particularly for high thermal capacity storage material. The finding shows that the technical limitation of using high melting temperature and thermal capacity material is solved by introducing a hybrid thermo-electric configuration. Also, the proposed model achieves a high system efficiency around 31–57%. Overall, hybrid thermo-electric operation might be considered as cost-effective approach to maximizing the operation of domestic water heaters [2]. The continued dependence on fossil energy sources has intensified environmental concerns, as it contributes to increasing greenhouse gas (GHG) emissions and accelerates global climate change. Furthermore, the increasing demand for electricity puts considerable strain on existing energy infrastructure and raises critical concerns about long-term energy security and sustainability. Therefore, these challenges underscore the urgent need for the development and deployment of sustainable, energy-efficient, and low-carbon water heating technologies, such as renewable energy-based systems to reduce environmental impacts and enhance overall energy system resilience.

Therefore, the study devoted to the improvement thermal performance of an indirect flat plate solar collector in solar water heater applications is of current relevance.

2. Literature review and problem statement

In the paper [3], the experimental investigation of absorber plate and outlet water temperature of a solar flat plate collector with straight riser and header arrangement is investigated. The effect of different operating parameters, viz., inlet water temperature, solar insolation, ambient temperature, and mass flow rate on the outlet water temperature and thermal efficiency were studied. Numerical simulations were carried out using a 3-dimensional computational fluid dynamics (CFD) to predict the outlet water and absorber plate temperatures using the experimental values of solar insolation, ambient temperature and inlet water temperature within one-hour interval. The CFD results were validated with the experimental results. It was found that the developed model could predict the outlet water and absorber plate temperature of the heating system with reasonable accuracy. However, it should be noted that the authors did not study the optimization of collector design in its entirety (geometry, materials, and real-time operating conditions) as well as the integration of economic aspects and long-term real conditions. The authors of [4] aims to boost the effectiveness of a flat plate solar collector through the use of a twisted strip to generate turbulence in the flow. Three twisted tapes, made of Aluminum and copper, were placed inside the collector's tubes, each with a different shape. All the twisted tape shapes – square, rectangle, and triangle – were identical in size, measuring 1000 mm in length and 1 mm in thickness. Both experimental tests and a numerical study were conducted on these three shapes of twisted tape. For each shape, three pitches were used: 2, 3 and 4 cm. The results indicated that the efficiency of the collector using the double-cutting rectangular twisted tape with a 2 cm pitch was superior to other collector shapes. Moreover, the copper tapes exhibited greater efficiency than the aluminum tapes. However, it should be noted that the authors focus on partial improvement of thermal efficiency, but have not yet answered whether the design is total energy optimal, economical, and applicative under real conditions. The study [5] is aimed to enhance the efficiency of the solar water heater (SWH) due to the increasing demand of renewable energy. It compared use three different solar collector models, namely Model A (square-shaped polycarbonate), Model B (v-corrugated zinc), and Model C (trapezoidal aluminum) to identify the most cost-effective configuration. However, it should be noted that the authors have the main unresolved problems are the generalization of results, broader design optimization, and long-term analysis from both the technical and economic sides. In [6], the modifications include integrating SWHs with storage collectors, combining SWHs with photovoltaic cells, integrating thermosyphon and twisted tapes, enriching collectors with nanofluids, phase change materials and using different types of evacuated tube SCs. Furthermore, improvement in materials, design and operating conditions have led to performance enhancement of parabolic trough and linear Fresnel SCs. However, it should be noted that the main unresolved problem by the authors is that the paper is still weak in integration, comprehensive evaluation, and practical implementation.

The paper [7] evaluated the performance of a flat plate solar water heater (SWH) theoretically and experimentally. SWH was designed as a square shape with dimensions of 110 cm length, 120 cm width and 10 cm depth and tested by integrating with a modified solar distiller to increase the water temperature in the basin at a constant mass flow rate of 1.2 l/min. A simultaneous increase in the water temperature and the intensity of solar radiation has been observed. However, it should be noted that the main problem that has not been resolved by the authors is the lack of optimization of operating parameters, thorough efficiency analysis, and dynamic and economical evaluation of system performance in the integration of SWH with solar refiners.

This study [8] investigated the impact of the introduction of a horizontal barrier within the internal cavity of a flat-plate solar collector on its thermal efficiency. The authors proposed a collector with four barriers, the thermal efficiency achieved an increase of up to 12%. This method presents an easy yet effective approach to improving the performance of solar collectors. Future study should focus on refining the design and placement of barriers for different collector sizes and geometries, potentially supporting the wider adoption of solar thermal energy systems and contributing to sustainable energy solutions. However, it should be noted that the main issues that have not been resolved by the authors are design optimization, more in-depth fluid and thermal analysis, and a thorough evaluation of system performance (including energy and economics). In [9], the thermal performance of the SWH was predicted using Fortran 90 programming language. SWH was designed as a square shape with dimensions of 110 cm length, 120 cm width and 10 cm depth and tested by integrating with a modified solar distiller to increase the water temperature in the basin at a constant mass flow rate of 1.2 l/min. The authors give the results of the heightened thermal efficiency of FPSC undergoes numerical scrutiny, incorporating various factors for analysis, including aspects like the configuration of the porous block introduced, Darcy number (Da = 10−5 ~ 10−2), types of nanoparticles, volume fraction (φ), and mixing ratio (φc). The numerical findings indicate that the dominant factor in the channel is the global Nusselt number (Nug). However, it should be noted that the main problem that has not been resolved by the authors is that this paper is strong in numerical analysis and understanding of heat transfer mechanisms, but still has gaps on experimental validation, economic feasibility, nanofluid stability, system optimization as a whole. Paper [10] is about analysis considers both the improved heat transfer and the pressure drop in the collector channel. The FPSC registered a maximum PEC value of 1.8 when rectangular porous blocks were inserted under conditions of Da = 10–2 and Re = 234 and the nanofluid concentrations of $\varphi = 3\%$ and $\varphi c = 100\%$. The findings can be provided to technically support the future commercial applications of FPSC. The findings may serve as a technical foundation for FPSC in upcoming porous media and support commercial applications. However, it should be noted that the main problems that have not been resolved by the authors are optimizing the increase in heat transfer without increasing energy costs, maintaining the stability of the nanofluids, and ensuring that the system can be implemented in a real and economical manner in the long term. In [11], hybrid nanofluids are developed by combining conventional fluids with various nanoparticles in specific proportions. The authors gathers and analyses recent studies published between 2020 and 2024 on the application of hybrid nanofluids in solar collector energy systems. It examines the types of nanoparticles, nanoparticle loading, and system design. The findings demonstrate that the performance of flat plate solar collectors (FPSCs) can be significantly enhanced by employing hybrid nanofluids. However, it should be noted that the main problem that the authors have not solved is how to make a stable, economical, and optimal hybrid nanofluid under real operating conditions. The authors of [12] use different methodologies and methods to improve the efficiency and the thermal performance of the solar collector by introducing twisted strips that cause increased mixing of fluids and friction for FPSCs. As for hybrid nanofluids, the best fluids are ($CuO + Al_2O_3$/water) for the same reason above. As a result of design improvements and the use of nanofluids, temperatures up to (75°C) were obtained. However, it should be noted that the main problem that has not been resolved by the authors is that nanofluids ($CuO + Al_2O_3$/water) do increase thermal conductivity, but the risk of particle agglomeration, the potential for sedimentation in the long term, the possibility of channel blockage.

Having analyzed the literature [3–12], it can be concluded that currently the study of the improvement thermal performance of an indirect flat plate solar collector in solar water heater applications has not been given due attention. Therefore, there is a need to conduct a study in this area.

3. The aim and objectives of the study

The aim in this study is to evaluate the thermal performance of improvement solar water heaters using a flat plate solar collector (FPSC) system with an indirect system. This will make it possible to increase in the efficiency of solar water heaters through the improvement of the flat plate solar collector (FPSC) system.

To achieve this aim, the following objectives were accomplished:

– to determine the design parameters that have the greatest impact on overall system performance through systematic thermal improvement;

– to efficiency indicator of test result with the improvement of the flat plate solar collector system;

– to validate the test results through an experimental assessment of the modified flat plate solar collector system.

4. Materials and methods

The object in this study is the process of heat transfer, energy conversion, and heat distribution through solar collectors in indirect systems.

The principal hypothesis assumes that modifying the flat plate solar collector system and adding phase change material using mannitol material as thermal energy storage can contribute to increasing heat and efficiency for solar water heater applications.

The basic assumption it was proposed that there is no use of electrical energy to move circulation pumps and heaters in thermal energy storage. In this case it was proposed to use solar panels as a substitute for electrical energy in renewable energy.

The simplifications adopted in this study is to use outdoor panels for solar power generation with a solar panel capacity of 200 Wp to drive pumps and heaters.

This study focuses on PCM material as thermal energy storage (TES), which uses sugar alcohol (SA) material with the type of mannitol. In addition to heating systems, TES and PCM, this study also uses the Internet of Things (IoT) to find out the temperature in the solar water heater tank when the temperature is below 25°C, the system will instruct the plunger pump and heater in TES to operate and when the temperature reaches 38°C the plunger pump and heater will stop and during the rainy season or at night. The heater on TES can automatically be used as a water heater that can be connected to a smart phone. To power the plunger pump and heater, TES uses solar power through a battery that is stored and converted from direct current (DC) to alternating current (AC).

The flat plate solar collector (FPSC) is widely employed in low- to medium-pressure solar thermal systems (Fig. 1) owing to its simplicity and cost-effectiveness. It captures solar radiation using a dark-colored absorber plate, converting the incident energy into thermal energy. This energy is then transferred to a working fluid-commonly water-via conduction through the absorber plate and convection into the fluid circulating through pipes or channels beneath the plate. The FPSC design directly influences its thermal performance: a black absorber plate maximizes solar absorption, a transparent glass cover minimizes radiative and convective heat losses, thermal insulation on the sides and back reduces heat dissipation to the environment, and properly configured riser pipes enhance fluid circulation and heat transfer [13]. From a mechanical engineering perspective, the FPSC performance is governed by the coupled mechanisms of radiation absorption, conductive heat transport, and convective heat transfer, and can be further optimized through design parameter adjustments to improve thermal efficiency [14]. The system typically produces thermal energy at low to medium temperatures (≤100°C), which makes it suitable for residential water heating, light industrial processes, and drying applications. The geometric and dimensional specifications of the FPSC used in this study are summarized in Table 1, which also highlights the design features influencing the collector's overall performance and heat transfer efficiency.

The FPSC unit used in this study is shown in Fig. 1. Water flows to the hot water tank (HWT) through a copper pipe with a 1/2-inch diameter. The FPSC is supported by 1 mm-thick iron plates on the sides and bottom and a 3 mm-thick acrylic top cover. The transparent top cover and insulation minimize heat loss through conduction, convection, and reradiation, while the absorber is coated with a selected material to optimize solar absorption. Water circulation is driven by a 100 W pump, and a valve regulates the flow rate to maintain steady operating conditions. The highest thermal energy for phase change material (PCM) is stored/discharged with unsubstantial temperature changes during the isothermal phase transition. However, the convective latent heat storage system uses temperature differences between the thermal load and working fluid. It restricts the temperature operation of the storage system since the temperature of the working fluid is limited by the melting temperature of PCM [15].

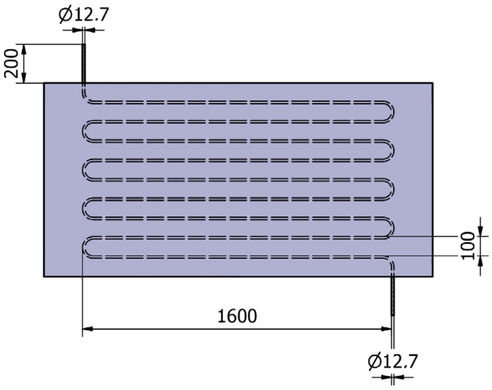

Fig. 1. Design of the flat plate solar collector (FPSC)

Table 1

Specifications of the flat plate solar collector (FPSC)

Description	Type and specification
Solar collector length	2.0 m
Solar collector width	1.0 m
Absorber plate length	1.8 m
Absorber plate width	0.9 m
Thermal conductivity of the absorber plates	386 W/mK
Material density of the plate	8960 kg/m^3
Thickness of the plate	0.001 m
Riser and header pipe diameter	0.0127 m
Riser and header pipe thickness	0.0008 m
Center distance between pipes	0.1 m
Amount of acrylic cover	1
Distance between cover glass and absorber plate	0.1 m
Thermal conductivity of the absorber plates	0.044 WmK
Thickness of acrylic material	0.003 m

Under steady-state conditions, FPSC performance is determined by the energy balance between incoming solar radiation (solar gain), heat loss to the environment (thermal losses), and optical losses from reflection or unabsorbed transmission. The useful energy is the difference between absorbed radiation and total energy losses during conversion. Quantitatively, it is expressed by formula [16]

$$Qu = Ac\,[S - UL\,(Tpm - Ta)], \tag{1}$$

where Qu – useful heat (kW), Ac – collector area (m^2), S – radiant heat absorbed per unit area (kW/m^2), UL – heat transfer coefficient (kW/m^{2}K), Tpm – average plate temperature (K), Ta – ambient temperature (K).

The thermal energy gained by the working fluid, derived from the FPSC inlet and outlet temperature difference, is expressed by formula [16]

$$Qu = m \cdot Cp \cdot (Tout–Tin), \tag{2}$$

where Qu – useful heat (kW); m – water mass flow rate (kg/s); Cp – water specific heat (kJ/kg K); Tin – temperature of water entering the collector (K); $Tout$ – water temperature leaving the collector (K).

Additionally, the efficiency of FPSC can be determined over a fixed period using by formula [16]

$$\eta = Qu\,/\,(IT \cdot Ac). \tag{3}$$

where η – efficiency (%); IT – total solar intensity during the same time period (kW/m^2); Qu – useful heat (kW); Ac – Collector Area (m^2).

A cylindrical HWT made of galvanized steel is shown in Fig. 2. To minimize heat loss through conduction and radiation, the tank is coated with aluminum foil and insulated with 75 mm thick glass wool. The technical specifications of the HWT are presented in Table 2.

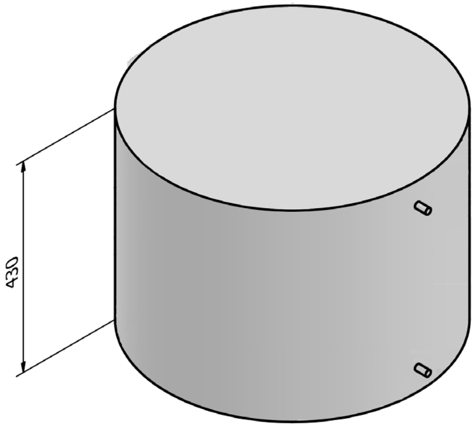

Fig. 2. Design of the hot water tank (HWT)

Table 2

Specifications of the hot water tank (HWT)

Description	Type and specification
Tank diameter	0.59 m
Tank height	0.43 m
Material density of the plate	8960 kg/m^3
Plate thickness	0.003 m
Riser and header pipe diameter	0.0127 m
Riser and header pipe thickness	0.0008 m
Material insulation	Glass wool
Thermal conductivity of plate	0.044 W/mK
Insulation material thickness	0.075 m
Insulation material density	200 kg/m^3
Tank Insulation	Aluminum foil

The experimental unit incorporating the FPSC and HWT is shown in Fig. 3. Water in Units No. 4 and No. 6 is circulated via a pump driven by a solar power plant, consisting of photovoltaic panels, batteries, a charge controller, and an inverter. DC power from the panels is stored in the batteries and transformed into AC by the inverter to power the pump. Photovoltaic (PV) is equipped with additional cooling system to reduce the cell temperature and enhance its efficiency. Numerous studies have addressed the issue using various methods such as thermoelectric, passive, and active cooling. In this work, the excess heat is taken as additional energy input considering the trend of PV direct heating system [17].

The experiment was conducted in Cikahuripan Village, Klapanunggal District, Bogor Regency, West Java (6.45°S, 106.98°E). First, the HWT was filled with 100 L of water. Next, a closed-loop configuration was established, connecting the HWT, the FPSC water heating system, and the circulation pump (Fig. 3). The 100 W circulation pump, powered by the solar power plant, was then activated to circulate water through the system. Type K thermocouples were used to measure the temperatures of the bottom plate, water, the FPSC copper pipe, the acrylic cover, and the HWT inlet and outlet. Finally, data were automatically recorded at 30-s intervals using a data logger (Fig. 4).

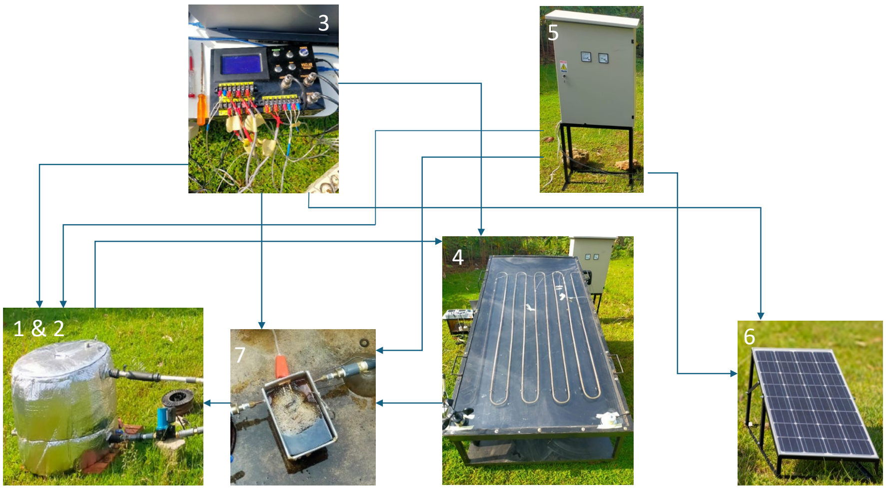

Fig. 3. Schematic of flat plate solar collector and hot water tank integration; 1 – hot water tank; 2 – circulation pump; 3 – data logger; 4 – flat plate solar collector; 5 – outdoor panel for solar power generation; 6 – solar panel 200 Wp; 7 – phase change material

Fig. 4. Flat plate solar collector temperature measurement using type K thermocouples

To evaluate the system performance coefficient, temperature data were collected from 8:00 AM to 12:45 PM at a pump flow rate of 0.116 kg/s under average solar radiation of 850–950 W/m^2. The selected time interval corresponds to peak solar radiation, and the flow rate matches the installed pump capacity.

5. Results of the experimental thermal performance of the flat plate solar collector system

5. 1. Result of determining design parameters flat plate solar collector system

This study aims to design a solar/solar-based hot water system using a flat plate solar collector system with an indirect system. It also focuses on PCM material as thermal energy storage (TES), which uses sugar alcohol (SA) material with the type of mannitol. This IoT also uses to measure the temperature of the solar water heater tank at temperatures below 25°C. TES uses solar power from a battery that is stored and converted from direct current (DC) to alternating current (AC). When the temperature reaches 38°C, the plunger pump and heater in TES will start working. In the rain season or at night, the heater on TES can automatically be used as a water heater. The temperature of HWT inlet and outlet, FPSC cover pipes, acrylic cover, bottom plate, and water inside the HWT were recorded every 30 s during the experiment. Fig. 5 shows the temporal variation of FPSC inlet water temperature (*Tin*), ambient temperature (*Ta*), and solar radiation. *Tin* rose from ~31°C at 08:00 AM to 41–43°C during peak radiation (10:30–11:00 AM), then fluctuated slightly within 39–42°C until 12:45 PM. This trend follows the increase in solar radiation, which enhances energy absorption by the absorber plate. Post-peak fluctuations reflect transient cloud cover or radiation instability. Ambient temperature remained relatively stable at 29–33°C, exerting minimal influence on *Tin*, with a maximum ΔT of 10–12°C. Solar radiation increased from ~500 W/m^2 at 08:00 AM to above 1500 W/m^2 at 10:30 AM, then stabilized between 1350 and 1500 W/m^2.

The relationship between *Tin* and radiation was approximately linear at low radiation levels but approached saturation at higher radiation, indicating a steady thermal efficiency and increased convective heat loss at larger ΔT values.

Fig. 5 shows a graph of the relationship between time (hours), inlet water temperature (*Tin*), ambient temperature (*Ta*), and solar radiation (*I*) with a linear regression approach. With the linear regression equation $y = 0.3845x + 33.527$, the inlet temperature (*Tin*) increases by about 0.38°C every unit of time. This is indicated by a gradient of 0.3845. This trend is positive and quite significant, which means that the temperature of the incoming fluid increases more and more during the day. This is in line with global warming caused by increased solar radiation. The ambient temperature (*Ta*) was constant throughout the test time, with a linear regression equation $y = 0.0043x + 30.72$, with a very small, almost zero gradient of 0.0043. In Ta, small fluctuations are more caused by environmental factors such as wind and clouds than time trends. With the linear regression equation, the intensity of solar radiation (I) is $y = 31.13x + 905.91$, and the gradient of 31.13 indicates a significant increase in radiation over time. One major factor that affects the rise in temperature of the system is the intensity of the sun which increases significantly from morning to noon.

The FPSC collector outlet water temperature fluctuates over time, as shown in Fig. 6. The temperature gradually increased from 08:00 AM, peaking between 11:00 and 11:15 AM, reflecting efficient heat absorption and transfer in accordance with the collector's thermal characteristics. A notable decline between 11:15 AM and 12:00 PM likely resulted from reduced solar radiation or transient weather effects.

The outlet temperature subsequently recovered as solar radiation increased, indicating that the system maintains a relatively stable thermal response despite variations in solar input.

Fig. 6 shows a graph of the relationship between time (hours) and water outlet temperature (°C) with a linear regression approach. There is a trend line equation: $y = 0.4697x + 36.66$. Interpretation of the regression coefficient $(\text{slope} = 0.4697)$ that the slope value is positive indicates that the water outlet temperature increases over time. Quantitatively, for every 1 unit of time (hour) increase, the temperature increases by about 0.47°C. This indicates a relatively stable heating process (e.g. due to solar radiation in the solar thermal system). The intercept (36.66°C) shows that this value is the theoretical temperature when $\text{time} = 0$ represents the initial state of the system or baseline fluid temperature before significant warming occurs and this is quite realistic for an early morning water heating system.

Fig. 7 shows the temporal variation of the FPSC absorber plate temperature. As solar radiation intensity increased over time, the plate temperature rose from 47–50°C at 08:00 AM to a peak of 66–68°C at 11:00 AM.

This behavior reflects the thermal response of the FPSC collector, in which incident solar radiation strongly influences the absorber plate temperature. After 11:30 AM, the temperature slightly decreased to 63–65°C, indicating a partial reduction in radiation intensity. Minor oscillations and a gradual decline between 12:00 and 12:45 PM are likely due to reduced solar radiation around midday.

Fig. 7 shows a graph of the relationship between time (hours) and absorber plate temperature (°C) with a linear regression approach. There is a trend line equation: $y = -0.0633x + 58.799$. Intercept (58.799°C) indicates the average temperature of the system when the time is considered zero (baseline). This can be interpreted as the initial temperature or the average value of the system in general. The slope (−0.0633°C per unit of time) indicates that the negative value indicates that globally temperatures tend to decline over time, although the decrease is relatively small.

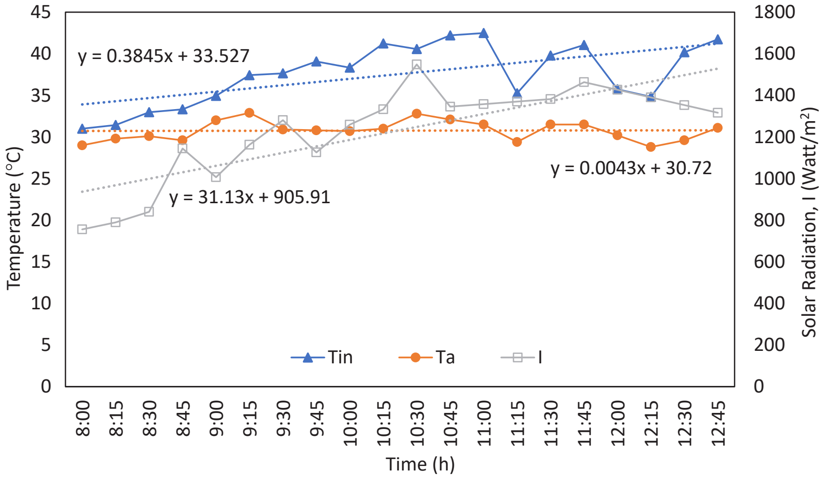

Fig. 5. Variation of flat plate solar collector inlet water temperature, ambient temperature, and solar radiation over time

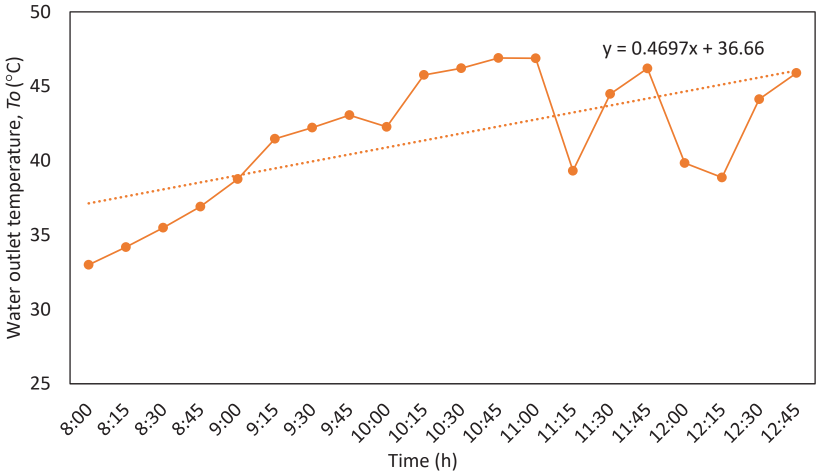

Fig. 6. Variation of flat plate solar collector outlet water temperature with time

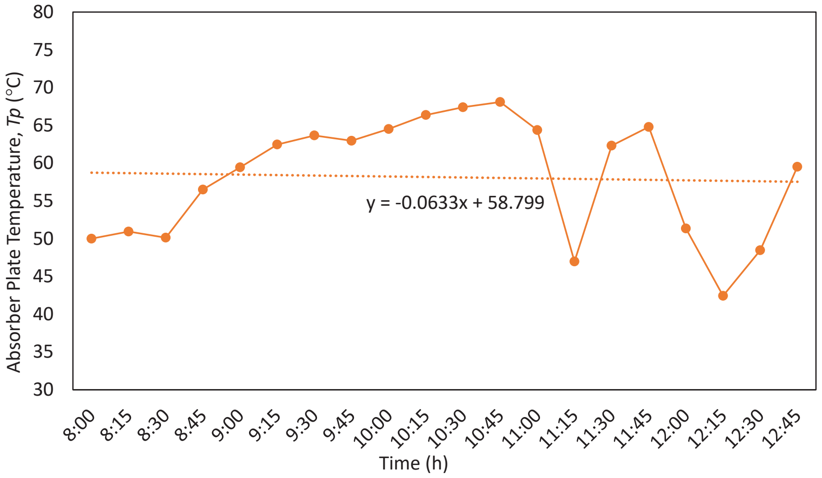

Fig. 7. Variation of flat plate solar collector absorber plate temperature with time

5. 2. Results of the efficiency indicator of the flat plate solar collector system

Fig. 8 presents the temporal variation of ambient temperature (*Ta*), FPSC collector inlet (*Tin*) and outlet (*Tout*) water temperatures, thermal efficiency (η), and solar radiation intensity (*I*). Solar radiation increased from ~900 W/m^2 at 08:00 AM to a peak of 1400–1450 W/m^2 between 10:45 and 11:45 AM, then declined after 12:00 PM. The ambient temperature remained relatively stable, rising from ~29°C to 33°C around midday. Tin increased gradually from 30–42°C due to the recirculation/thermosiphon effect and heat accumulation in the HWT, while T_{out} ranged from 33–47°C, peaking at 46–47°C during maximum solar radiation.

Thermal efficiency varied between 67–88%, reaching its highest under strong radiation and an optimal temperature gradient ($\Delta T = Tout - Tin$). Overall, the system demonstrated excellent performance, with outlet temperatures suitable for domestic use and efficiency exceeding the typical 40–75% range for FPSC absorber plate collectors, indicating high solar absorption and low heat losses.

Fig. 8 shows a graph of the relationship between time (hours), temperature (°C) and efficiency (%) with a linear regression approach. There is a trend line equation: $y = -0.0581x + 76.005$. Intercept (76,005) shows that the theoretical efficiency of the system is about 76% at the value of $x = 0$. This is the starting point or baseline of efficiency.

There is a downward trend in efficiency against regressed variables, such as possible time or temperature, because the negative coefficient (–0.0581) indicates a decrease in efficiency as the *x*-value increases. Each increase of one *x* unit will result in a decrease in efficiency of 0.0581%.

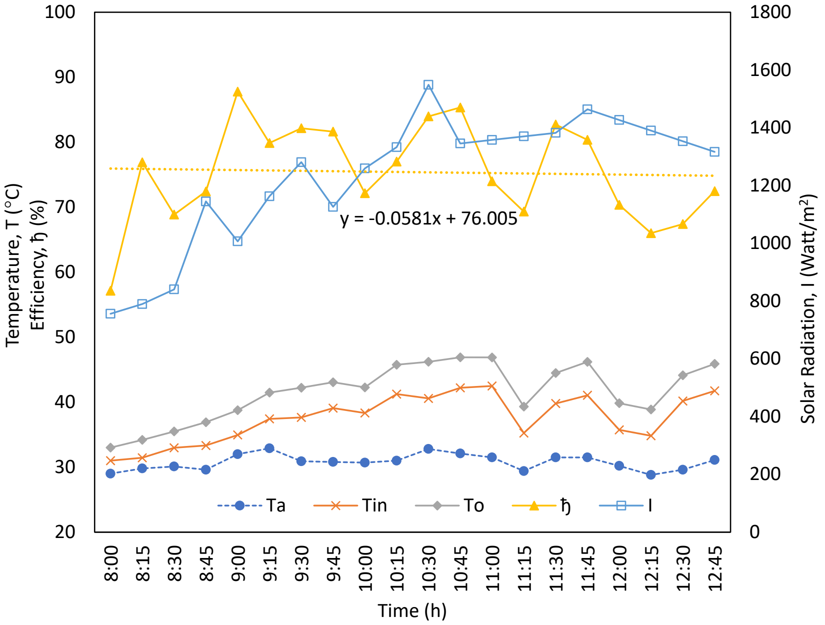

Fig. 8. Ambient temperature, flat plate solar collector inlet/outlet water temperatures, efficiency, and solar radiation as a function of time

5. 3. Result of validation of the test results through an experimental assessment of the modified flat plate solar collector system

The temporal variation of the temperature difference (ΔT) at a mass flow rate of 0.166 kg/s is shown in Fig. 9. The ΔT reflects the system's thermal response to increasing solar radiation, rising from approximately 2°C at 08:00 AM to a peak of about 5.6°C at 10:30 AM. This behavior results from the combined influence of increased solar irradiance, higher collector operating temperatures that enhance heat absorption, and a stable flow rate that supports consistent convective heat transfer.

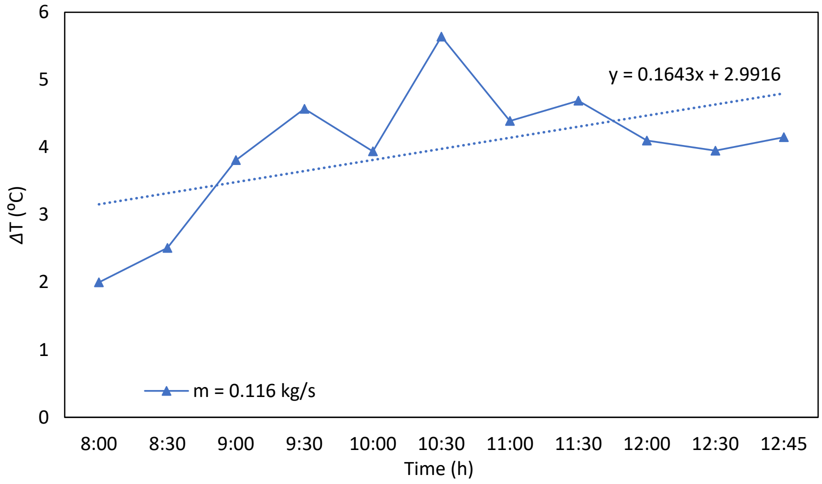

Fig. 9. Water temperature deviation at a flow rate of 0.116 kg/s as a function of time

The observed ΔT suggests that the selected flow rate is close to optimal, as it avoids both excessive overheating at lower flow rates and a significant reduction in ΔT at higher flow rates. Under these operating conditions, the estimated thermal efficiency falls within a moderate range of 40–60%, which aligns with the prevailing solar radiation levels.

Fig. 9 shows a graph of the relationship between time (hours) and temperature rise (ΔT, °C) with a linear regression approach. There is a trend line equation: $y = 0.1643x + 2.9916$. The slope (0.1643*x*) shows that the temperature rises by 0.1643°C for every unit of measurement period. This indicates that there is a consistent heating tendency in the system. The initial temperature (ΔT) when the time is near zero (or the start of the observation) is represented by the intercept (2.9916). From a physical perspective, this can be thought of as the system's original state prior to notable warming.

6. Discussion of results based on the improvement of flat plate solar collector system thermal performance compared with previous studies

The design of the study is that the flat plate solar collector (FPSC) has a length of 2 m and a width of 1 m with a pipe diameter of 0.0127 m and a pipe thickness of 0.0008 m (Table 1).

Meanwhile, the hot water tank (HWT) has a tank diameter of 0.59 m and a height of 0.43 m with an insulation thickness of 0.075 m. HWT is coated with glass wool material and insulated with aluminum foil (Table 2). The HWT was filled with 100 L of water. Next, a closed-loop configuration was established, connecting the HWT, the FPSC water heating system, and the circulation pump (Fig. 3). The 100 W circulation pump, powered by the solar power plant, was then activated to circulate water through the system. Type K thermocouples were used to measure the temperatures of the bottom plate, water, the FPSC copper pipe, the acrylic cover, and the HWT inlet and outlet. Finally, data were automatically recorded at 30-s intervals using a data logger (Fig. 4). This study was conducted at 08.00 AM–01.00 PM. Increased solar radiation rising from about 900 W/m^2 to a peak of 1400–1500 W/m^2 directly influenced the thermal behavior of the FPSC collector. The weakness of the study is that the study was not conducted for 8 hours due to the conditions in Indonesia at the time of conducting the study in the rainy season and not conducting simulations using Ansys Fluent as a comparison of results of the study. The temperature of HWT inlet and outlet, FPSC cover pipes, acrylic cover, bottom plate, and water inside the HWT were recorded every 30 s during the experiment. Shows the temporal variation of FPSC inlet water temperature (Tin), ambient temperature (Ta), and solar radiation (Fig. 5). The FPSC collector outlet water temperature fluctuates over time (Fig. 6), the outlet temperature subsequently recovered as solar radiation increased, indicating that the system maintains a relatively stable thermal response despite variations in solar input.

By mathematical modeling that the FPSC system achieved a thermal efficiency of approximately 72% and a coefficient of performance (COP) of 10 (Fig. 8) for the indirect solar water heating system when operating with a 100 W circulation pump and an absorber heat input of 1000 W. These values indicate effective heat absorption and transfer within the collector-storage system under the prevailing experimental conditions. In comparison [3], based on experiments conducted between 08:00 AM and 1:00 PM, reported a thermal efficiency of 60% and a COP of 8 for a similar indirect solar water heating configuration operating with the same pump power but a lower absorbed heat input of 800 W. Relative to the results reported by [3] the present system exhibits an improvement of approximately 20% in thermal efficiency and about 25% in COP under comparable operating conditions. The temporal variation of the temperature difference (ΔT) at a mass flow rate of 0.166 kg/s (Fig. 9). The ΔT reflects the system's thermal response to increasing solar radiation, rising from approximately 2°C at 08:00 AM to a peak of about 5.6°C at 10:30 AM. Under these operating conditions, the estimated thermal efficiency falls within a moderate range of 40–60%, which aligns with the prevailing solar radiation levels.

The enhanced performance observed in the present study can be attributed to several factors. First, the improved collector design promotes more effective absorption and retention of incident solar energy by the absorber plate, thereby increasing the useful heat gain within the system. Second, the thermal interaction between the absorber plate and the circulating working fluid is likely improved due to better thermal contact and heat transfer characteristics, which facilitate more efficient energy transfer from the collector to the water. Third, the optimized flow conditions provided by the circulation pump contribute to maintaining a favorable temperature gradient between the collector inlet and outlet, while simultaneously reducing excessive thermal losses to the surrounding environment.

In addition, the higher absorbed heat input of 1000 W enhances the available thermal energy within the system, allowing the collector to operate closer to its optimal thermal performance range. These combined factors contribute to improved heat transfer efficiency and more effective utilization of incident solar radiation. Consequently, the proposed FPSC configuration demonstrates superior thermal performance and energy utilization compared with previously reported systems operating under similar experimental conditions. These findings highlight the potential of the proposed design to enhance the efficiency and reliability of indirect solar water heating systems for practical domestic and small-scale thermal applications.

The alternative solution that it was proposed in this study is the use of phase change material (PCM) by using mannitol material as thermal energy storage (TES) which will be used during cloudy or rainy weather. In addition to TES, a feature of this study is using solar electricity (renewable energy) to drive circulation pumps and heaters for PCM. Also, the feature of this study is using the Internet of Thinks (IoT) to find out the temperature in hot water tanks.

The limitation in this study is that the time of data collection is from 08.00–13.00 because it is the rainy season in Indonesia, so the data collection is not optimal. The shortcomings of the study is data collection that is not optimal.

Future directions for this study could be static testing using multiple materials for thermal energy storage (TES) for solar water heater applications.

7. Conclusion

1. Using a flat plate solar collector system with an indirect system and the addition of mannitol material for phase change material as thermal energy storage, then there is an increase in the performance of the flat plate solar collector system when the weather is rainy or at night. The use of solar energy replaces electrical energy there are more savings in electricity costs.

2. The relationship between Tin and radiation was approximately linear at low radiation levels but it was approached saturation at higher radiation, indicating a steady thermal efficiency and increased convective heat loss at larger ΔT values. The outlet temperature subsequently recovered as solar radiation increased, indicating that the system maintains a relatively stable thermal response despite variations in solar input. The system demonstrated excellent performance, with outlet temperatures suitable for domestic use and efficiency exceeding the typical 40–75% range for FPSC absorber plate collectors, indicating high solar absorption and low heat losses.

3. The combined influence of increased solar irradiance, higher collector operating temperatures enhances heat absorption, and a stable flow rate that supports consistent convective heat transfer. The observed ΔT suggests that the selected flow rate is close to optimal, as it avoids both excessive overheating at lower flow rates and a significant reduction in ΔT at higher flow rates. Under these operating conditions, the estimated thermal efficiency falls within a moderate range of 40–60%, which aligns with the prevailing solar radiation levels.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Data availability

All data are presented in the main text of the manuscript, either in numerical or graphical form.

Use of artificial intelligence

The authors declare that artificial intelligence technologies were not used in the creation of this work.

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Authors' contributions

Moch Sugiri: Formal Analysis, Investigation, Writing-Original Draft; **Budhi Muliawan Suyitno**: Conceptualization, Supervision, Validation; **Erlanda Augupta Pane**: Formal Analysis, Investigation, Writing-Review & Editing; **Gunadi Haryanto**: Formal Analysis, Investigation, Supervision; **Ismail**: Conceptualization, Supervision, Validation, Writing-Review & Editing.

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