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Original Research Article

Analysis of Serpentine Collector Performance Based on Flow Rate Variation for Improving Efficiency and Environmental Impact of Solar Water Heater

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ABSTRACT

Environmentally friendly technology provides sustainable solutions to reduce non-renewable energy use and carbon emissions. This study investigates efficiency, optimal flow rate, and environmental impact of solar water heater with serpentine configuration. Data were collected during summer in Solo, Indonesia. Inlet and outlet water temperatures, wind speed, and solar radiation intensity were measured from 9:00 AM to 3:00 PM (Western Indonesian Time) at flow rates of 60, 120, 180, and 240 L/h. The optimal flow rate was 180 L/h, thermal efficiency of 57.02%, heat absorption efficiency of 81.93%, and collector efficiency of 69.60%. High flow rates caused too short contact time, while low flow rates increased heat loss. Life cycle assessment showed usage phase dominated energy consumption and significantly reduced carbon dioxide emissions, whereas materials and manufacturing impacted costs and emissions. The serpentine solar water heater offers highly sustainable, efficient, and eco-friendly heating solution by optimizing energy efficiency and production process.

KEYWORDS

Solar water heater, Serpentine collector, Improving efficiency, Life-cycle assessment.

INTRODUCTION

The energy emitted by the sun to Earth is abundant, with the potential to meet human energy needs comprehensively [1]. The amount of solar energy exceeds the total annual commercial energy consumption by up to two hundred times [2]. Additionally, the average intensity of solar radiation entering Earth's atmosphere can reach approximately 1367 W/m^2 on a clear day [3]. In this context, solar water heater (SWH) is designed to harness solar radiation

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to heat water, offering a sustainable solution that reduces dependence on non-renewable energy sources and minimizes carbon emissions [4].

SWH has secured significant attention due to the contributions to resource conservation, reduced equipment investment costs, operational savings, and longer service life [5]. These systems typically consist of three main components namely solar collector, storage tanks, and water as the working fluid [6]. Furthermore, the thermal efficiency of SWH depends heavily on the type of collector used, the intensity of solar radiation, and the required water flow rate [7]. These factors determine how effectively the system can convert solar energy into useful heat, directly impacting energy savings and operational efficiency. In addition, improved efficiency reduces the need for additional energy from non-renewable sources, lowers energy costs for users, and supports global sustainability objectives by using a clean and abundant energy source.

Despite the vast potential of solar energy, SWH still face several optimization challenges. The efficiency largely depends on the design of the solar collector, which is a crucial component of the system. The flat-plate collector is a well-established type of collector. However, flat-plate faces several significant issues, such as unavailability at night and early morning, high reflectance and heat loss, suboptimal solar radiation absorption, as well as low heat transfer between the tubes and fluid. Collector should be designed to absorb solar radiation as efficiently as possible. Modifying the absorber surface can improve the absorption of solar radiation and reduce optical and thermal radiation losses, leading to improved system efficiency [8].

Materials such as copper, aluminum, and alloys are commonly used to build collector because they have high thermal conductivity, which is essential for effective heat transfer. Additionally, applying coatings and glazing insulates heat in the system and allows optimal sunlight penetration. The configuration of the pipes in collector also performs a crucial role in determining the total system efficiency. Various collector configurations are modified to facilitate more stable water flow and even heat distribution, significantly improving heat absorption capacity. Moreover, current studies need to focus on exploring optimal collector designs and developing technologies that can reduce production costs while improving thermal performance.

A study by Alhabeeb *et al.* [9] shows that using flat aluminum reflectors on solar collector with evacuated tubes increases thermal efficiency by up to 17.42%. Similarly, Al-Dujaili *et al.* [10] developed an electric/solar water heater (ESWH) that combines aluminum reflectors to reduce dependence on grid electricity. Furthermore, various explorations have also explored the use of parabolic collector, testing diverse geometric parameters and providing understanding into improving the potential of solar energy use. For instance, Bhuyan *et al.* [11] used computational fluid dynamics to analyze heat loss from parabolic trough solar collector (PTSC) absorber tubes, developing a correlation based on emissivity effects. Patil *et al.* [12], focused on optimizing Half Insulation Filled Receiver (HIFR) and Linear Cavity Receiver (LCR) designs for smaller rim angle PTCs to minimize heat loss and improve optical efficiency. Kumar and Kumar [13] evaluated the overall heat loss coefficient (OHLC) of parabolic trough collector receivers and its components. Meanwhile, Farzan *et al.* [14] developed a combined collector storage system with flat thermal diodes. The explorers found that creating a partial vacuum improves collection efficiency by up to 29.33% and retention by 16.97% at a total pressure of 0.70928 bar (0.7 atm). However, at a lower pressure of 0.50663 bar (0.5 atm), retention efficiency drops significantly to 3.26%. This innovation enables the thermal diode to function as a unidirectional heat transfer mechanism, improving thermal efficiency without being significantly affected by changes in partial vacuum.

Studies have shown significant advancements in improving the thermal efficiency of evacuated tube solar collector (ETSC). Chen *et al.* [15] investigated the effects of angle modifications and the addition of reflectors on ETSC, achieving a substantial increase in thermal efficiency. Additionally, the optimization of a compound parabolic concentrator

(CPC) using Particle Swarm Optimization (PSO) and Monte Carlo Ray Tracing (MCRT) algorithms resulted in a maximum optical efficiency of 61.68% in a different study [16]. Another study [17] examined the use of reflectors inside the vacuum tube, which led to a 10% increase in thermal efficiency.

Further advancements in heat pipe design have significantly improved the thermal efficiency of solar collector. The combination of micro-grooves on flat aluminum heat pipes has successfully increased thermal performance by up to 80%. Additionally, structural improvements such as using sintered copper heat pipes with a thickness of 7.3 mm have proven highly effective, providing excellent thermal efficiency. The use of coaxial heat pipes with two concentric tubes in solar collector has increased thermal efficiency by up to 67% at a mass flow rate of 0.009 kg/s [18].

Computational explorations using Monte Carlo methods to analyze evacuated tube collector have shown that the Zone-V configuration offers the lowest life-cycle cost for water heating and a short payback period [19]. Active cooling methods based on heat pipes have successfully reduced the temperature of solar systems by up to 53%, causing a more uniform temperature distribution [20]. Furthermore, combining fin arrays into the condenser section of heat-pipe solar collector has increased efficiency by up to 60% [21]. Applying thin membranes to heat-pipe solar collector has achieved thermal performance ranging from 40% to 70% [22].

The study signifies the importance of developing compact and efficient heat pipe designs in solar thermal collector, which are crucial for efficient heat transfer. Prioritizing the improvement of surface area, the use of advanced geometries, and the optimization of flow patterns will significantly improve heat transfer between the working fluid and the absorber surface. Furthermore, the choice of specific advanced geometries should be based on the desired output temperature of the working fluid, which is determined by energy needs. There are currently no fixed standards for determining the specifications of geometric modifications. Therefore, developing appropriate conditions for these modifications is essential to achieve uniform thermal improvements in SWH and ensure sustainability [23].

The design and use of serpentine pipe SWH aim to produce hot water for bathing needs affordably while maintaining good environmental sustainability by minimizing energy consumption. To further improve thermal efficiency, SWH system has been tested with four flow rate to find the optimal value, enabling the practical application of automatic flow control standards for SWH. Although the general principles of SWH have been extensively explored, the adaptation of serpentine design offers significant improvements in thermal efficiency and operational practicality. The research focuses on how serpentine configuration improves heat absorption and reduces heat loss, identifying effective methods for managing thermal energy. This shows the potential for implementation in tropical climates and similar installations. Additionally, the advantages of serpentine design include optimizing contact between water and collector, promising greater efficiency, potential cost savings, and general support for efforts to reduce the use of non-renewable energy and carbon emissions.

Study of serpentine solar water heater

Solar water heater (SWH) with serpentine configuration uses a unique parallel flow thermal collector design. Explorations [24] show that the application of serpentine configuration yields approximately 2.62% more usable thermal energy compared to other configurations. In addition, the thermal performance of serpentine-type SWH is significantly influenced by the rate of heat transfer between the absorber surface and the water, as well as the amount of solar radiation incident on the absorber surface [25]. Compared to other SWH designs, serpentine configuration shows superior thermal performance, with a maximum thermal efficiency reaching 82.5% [26]. Eventually, serpentine SWH is also more economical compared to electric water heaters, giving rise to a cost-effective alternative to traditional heating systems [27].

Table 1 presents a comparative analysis of previous research on serpentine collectors and the current research, showing the novelty and differences of the methods. Research by Hasan *et al.* (2018) [28] using a serpentine thermosyphon flat-plate solar heater collector design showed that the exertion efficiency reached 3.72%. However, the application is limited to the influence of geometric and operational parameters without considering more economical materials. Hossain *et al.* (2016) [29] reported double-sided serpentine collector efficiency of 70.24% in June and 70.96% in July, but did not explore water flow rate variations that might further influence performance. Wang *et al.* (2019) [30] used phase change material (PCM) with a high melting point in Serpentine flat plate collectors and different pipelines. The complexity of using phase change material (PCM) showed the potential to increase costs and reduce economic competitiveness. Das *et al.* (2024) [31] achieved an energy efficiency of 62.28% in serpentine tubes with copper sheets behind photovoltaic (PV) panels. This showed that copper improved efficiency but cheaper pipe materials were not tested. Shahsavar *et al.* (2021) [32] found that the efficiency of 6 rib rifled serpentine increased by 22.5%, although dependence on nanofluid flow and nano additives can increase the cost and complexity of the system. Abdalla *et al.* (2023) [33] recorded an energy efficiency of 88.23% in sheet-and-serpentine tube collectors. The research did not sufficiently explore the influence of material variations and simpler designs. Finally, Chopra *et al.* (2024) [34] reported an efficiency of 82.45% for a serpentine evacuated tube collector (SR-EVTC) with copper annular fin. Meanwhile, the use of expensive materials such as copper can limit the applicability of this technology.

Despite the drawbacks, modifications to serpentine pipe arrangement aimed at increasing the amount of solar energy converted into useful heat had slightly reduced the total system efficiency. The higher complexity of manufacturing collectors with serpentine pipes also posed production challenges and increased material costs. However, the advantages offered by serpentine design served as attractive options for SWH applications. To further improve the thermal performance and efficiency of serpentine SWH, several investigations and developments are being conducted. These include optimizing serpentine flow design, exploring the use of new materials with higher thermal conductivity, and combining reflective methods to maximize solar radiation absorption.

This research focuses on a serpentine solar water heater (SWH) using low-cost copper pipe material and varying water flow rates. The results obtained 81.93% efficiency of heat absorbed by water, with the highest value achieved at a flow rate of 3 lpm. This is an important novelty, showing that efficiency can be achieved with more affordable materials, as well as identifying the potential of higher flow rates to reduce efficiency due to increased inlet temperatures. The results contribute to the development of more efficient and economical serpentine collectors, which are relevant in the application of more affordable renewable energy technologies. The current research position and collectors' research on serpentine can be seen in **Table 1**.

METHOD

This research compares the water flow rate used by a serpentine solar water heater at a certain time to achieve thermal efficiency, with variations made during testing. Each variation of water flow rate was tested at the same time and configuration. Subsequently, the data was processed into tables and graphs of water temperature at the inlet and outlet channels, collector temperature, environmental temperature, solar radiation intensity, and wind speed. Next, an analysis was conducted to determine the highest thermal efficiency of the serpentine solar water heater.

Table 1. Study serpentine collector and study position

Reference	Collector Design	Efficiency	Main Result
[28]	Serpentine thermosyphon flat-plate solar heater	Exertion efficiency 3.72%	Exertion optimization using MATLAB shows that geometric and operational parameters greatly influence system efficiency
[29]	Two-side serpentine tube collector	70.24% (June) and 70.96% (July)	Low water inlet temperature can reduce the absorber surface temperature significantly
[30]	Serpentine flat plate collectors with different pipeline and phase change material (PCM)	Not measured	High melting point phase change material (PCMs) are used to limit sudden increases in water temperature and reduce heat loss during hours without sunlight
[31]	Serpentine tube with copper sheet behind photovoltaic (PV) panel	Energy 62.28 ± 5.53%, exertion 51.13 ± 5.53%	Good energy efficiency and exercise are achieved by the use of copper sheets behind the photovoltaic (PV) panels
[32]	Rifled serpentine tube with 3 and 6 ribs	6-start rifled serpentine reached 22.5% higher	Nanofluid flow rate and nano additive concentration improve energy efficiency by 22.5% compared to basic photovoltaic/thermal (PV/T) systems
[33]	Sheet-and-serpentine tube collector	Energy efficiency 88.23%, exertion 15.36%	Nanofluid mixture, mass flow rate, and nanoparticle volume concentration influence energy efficiency and maximum exertion
[34]	Serpentine evacuated tube collector (SR-EVTC) with copper annular fin and sensible heat storage liquid	82.45% (sunny), 87.78% (cloudy)	SR-EVTC (serpentine evacuated tube collector) system embedded with a copper annular fin and sensible heat storage liquid (SR-EVTC/SS-AF) shows the highest energy efficiency at flow rate of 0.016 m³/h during sunny days and 0.008 m³/h during cloudy days compared with the control EVTC (SR-EVTC/CS)
This study	Serpentine solar water heater (SWH) with low-cost copper pipe material and variations in water flow rate	Efficiency of heat absorbed by water 81.93%	The highest thermal efficiency is achieved at flow rate of 3 lpm, while higher flow rate decreases efficiency due to higher inlet temperature increases

Solar water heater configurations

Solar water heater (SWH) featuring serpentine pipe configuration was used in the research. The system used copper pipes with a diameter of 12.7 mm and a length of 1850 mm, bent at a 90-degree angle. The collector, measuring 1500 × 840 mm, was painted black to improve heat absorption. The pipes were installed with a 50 mm spacing to ensure even heat distribution. The collector was tilted at 30° facing north to maximize exposure. The specifications of SWH with a serpentine design are presented in **Table 2**.

Table 2. Serpentine solar water heater (SWH) specifications

Type	Dimension
Collector configuration	*Serpentine*
Collector dimensions	1500 × 840 mm
Collector material	Copper
Pipe diameter	12.7 mm
Long pipe	1850 mm
Distance between pipes	50 mm
Number of bends	11
Collector's color	Black
Collector tilt angle	30°
Collector thermal conductivity	390 W/m°C
Collector absorbency	0.96
Collector emissivity	0.78
Insulator thickness	3 mm
Insulator thermal conductivity	0.3 W/m°C

Experimental setup

Before the experiment was conducted, all equipment and materials were prepared. These materials included serpentine SWH, a water pump with a capacity of 3600 L/h, water hoses, a 75-liter container box, and measuring instruments such as flow meter, solar power meter, anemometer, and arduino thermocouple in **Table 3** as:

Table 3. Measuring equipment

Instrument	Justification	Accuracy
Flow Meter	Used to measure water flow rate in liters per hour (L/h)	±0.1 %
Solar Power Meter	Measures the intensity of solar radiation in the range 0 W/m² – 4000 W/m²	±1.0 W/m²
Anemometer	Measures wind speed and direction with a range of 0 – 30 m/s	±2.5 %
Thermocouple Arduino	Measures temperature in the range 0 °C – 600 °C automatically	± 0.2 °C

Figure 1 shows SWH research instrument used to obtain data, including the collector design and configuration. The collector plays a role in absorbing heat from solar radiation. In this research, the collector uses a serpentine configuration with materials namely copper pipes.

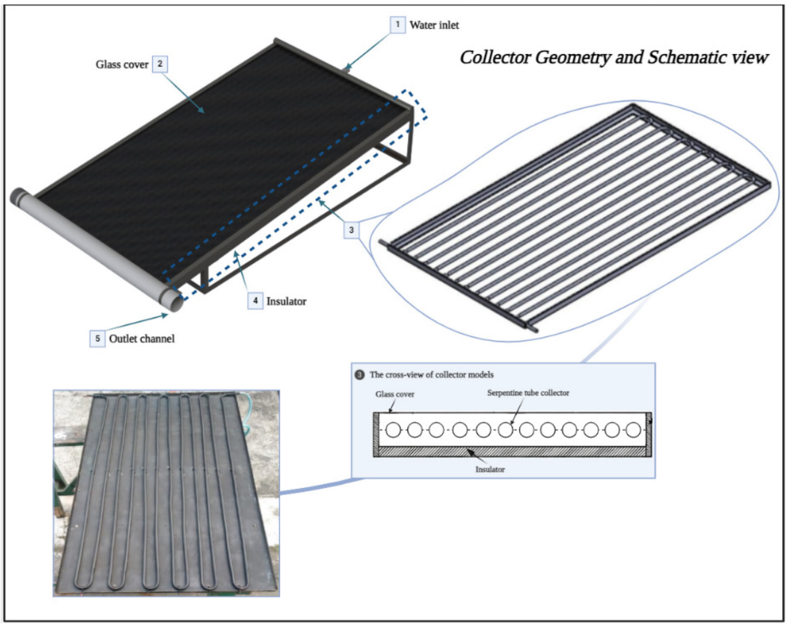

Figure 1. Collector design and configuration

Procedures

The research was conducted in Solo, Central Java, Indonesia, at an elevation of 105 meters above sea level with latitude and longitude coordinates of -7.560180 and 110.774247, respectively. Data collection was performed from 9:00 AM to 3:00 PM (Western Indonesian Time), with readings taken every 10 minutes. To ensure consistency and reliability of results, the experiment was conducted on three different days for each water flow rate (60 L/h, 120 L/h, 180 L/h, and 240 L/h) under similar conditions.

a. Collector placement: The SWH was positioned in an area receiving direct sunlight without shade. At 8:00 AM, water circulation through the system commenced using the pump. The pump functioned to determine the height difference, facilitating water flow through the system.
b. Flow rate adjustment: Water was pumped from the storage tank using a water pump. Flow meter was adjusted to a flow rate of 60 L/h, 120 L/h, 180 L/h, and 240 L/h.
c. Data collection: Data were collected every 10 minutes from 9:00 AM to 3:00 PM (Western Indonesian Time) for 12 days. The collected data included:
    - Collector temperature was measured using a thermocouple to assess the heat derived from solar energy.
    - Ambient temperature around collector was measured to calculate the heat transfer from collector to the surroundings.
    - Inlet and outlet water temperatures were measured with a thermocouple to compare temperatures before and after entering collector.
    - Wind speed was measured to calculate the convective heat transfer coefficient in surroundings.

The testing was conducted three times for each variation of water flow rate, totaling nine days of testing. The obtained data were analyzed to determine the thermal efficiency of the SWH with serpentine configuration. Efficiency was calculated based on the temperature difference between the inlet and outlet as well as the radiation intensity received by collector. Additionally, control testing was performed before data collection to ensure uniform experimental conditions, specifically regarding the heat contribution from the pump. Water was circulated through identical pipes for all models in terms of dimensions, material, and length to normalize the thermal input from the pump before entering collector. Furthermore, statistical analysis was conducted on the inlet temperature data, ensuring that the heat contribution from the pump was neglected and did not alter the results statistically. Consistent inlet temperatures across all models ensured that efficiency measurements reflected collector's performance independently, and any recorded temperature increase was solely due to the solar heating effect from collector.

Energy efficiency analysis

Energy efficiency analysis is a significant method for evaluating energy usage [35]. Increasing energy efficiency will enhance high levels of resource use and reduce emissions [36]. This is an effort carried out to reduce the amount of energy required to operate energy-related equipment or systems and maximize output energy. In SWH, energy efficiency can be calculated using eq. (1), eq. (2), and eq. (3) as follows:

a. Collector efficiency: Collector efficiency indicates how effective the collector is in converting the energy received into useful energy. Collector efficiency (η_{k}) can be formulated using eq. (1) as:

$$\eta_{\mathrm{k}} = \frac{Q_{\mathrm{u}}}{G_{\mathrm{T}} A_{\mathrm{c}}} \times 100\% \tag{1}$$

where are: η_k - the collector efficiency; Q_u - the useful energy (W); G_T - the total solar radiation intensity (W/m^2), and A_c - the surface area of the collector (m²).

b. The efficiency of heat absorbed by water: The efficiency of heat absorbed by water (η_f) measures how effective water is in absorbing and storing energy from a heating source, such as a solar collector or water heater, which is expressed in eq. (2) as:

$$\eta_f = \frac{Q_f}{Q_u} \times 100\% \tag{2}$$

where are: $Q_f = \dot{m} C_p \Delta T$ - the energy used to heat the fluid (W); $\dot{m}$ - the energy used to heat the fluid (kg/s); C_p - the specific heat (J/kgK), and ΔT - the temperature difference ($T_0 - T_1$).

c. Total efficiency of solar water heater: Total efficiency of a solar water heater (SWH) system indicates how effective the system is in converting solar energy into heat energy to heat water. Total efficiency of SWH is calculated by considering the collector efficiency and the heat transfer efficiency to the water using eq. (3) as:

$$\eta_t = \eta_k \times \eta_f \times 100\% \tag{3}$$

where are: η_t - the total efficiency of the SWH; η_k - the collector efficiency, and η_f - the efficiency of the absorbed by the water.

RESULTS AND DISCUSSIONS

This research focuses on the thermal efficiency of serpentine solar water heaters by testing variations in water flow rate. The data collected every ten minutes includes solar radiation intensity, wind speed, inlet and outlet temperatures, collector temperature, and environmental temperature. Varying flow rate data is used to determine the best energy efficiency. The analyses carried out include thermal efficiency, flow rate effects on the serpentine collector, and life cycle analysis (LCA).

Efficiency analysis

Solar radiation data were obtained from NASA [https://power.larc.nasa.gov/data-access-viewer] using the All-Sky Surface Shortwave Downward Irradiance or Global horizontal irradiance (GHI) variable to measure the total solar radiation received on a horizontal surface. Following the context, the radiation reflected real-world conditions experienced by the Earth's surface throughout the day under various weather conditions. Additionally, **Figure 2** shows the changes in GHI and air temperature to understand the thermal environmental conditions at a height of 2 meters above ground level at the research location during the year 2023. The data were processed into daily averages for one year for simulation purposes, allowing observations of seasonal trends and anomalies more accurately.

Figure 3 shows the variation of collector, absorber, and total efficiencies with different water flow rates. First, the consistent collector configuration during testing minimized variations in collector efficiency. However, environmental factors such as solar radiation intensity and ambient temperature affected collector's performance in absorbing heat. In this context, the heat transfer rate was directly proportional to the surface area and the temperature difference between the two media. This shows that small changes in environmental surroundings such as ambient temperature as presented in **Figure 2** influenced collector efficiency.

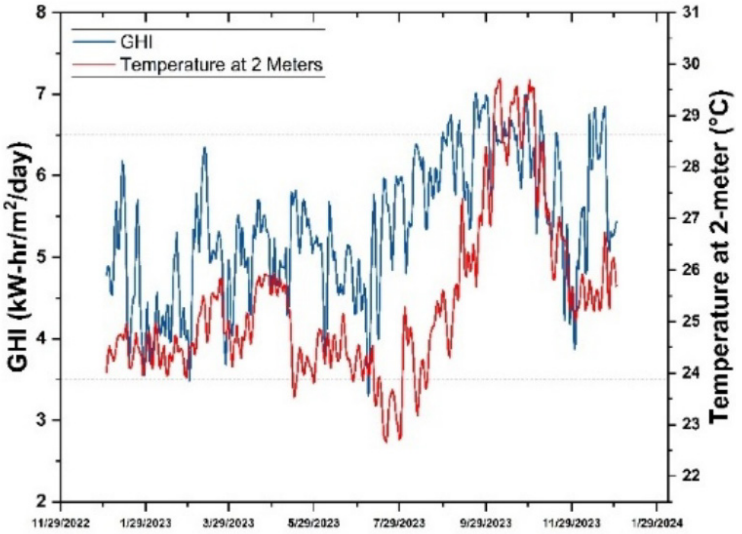

Figure 2. Global horizontal irradiance (GHI) radiation and ambient temperature

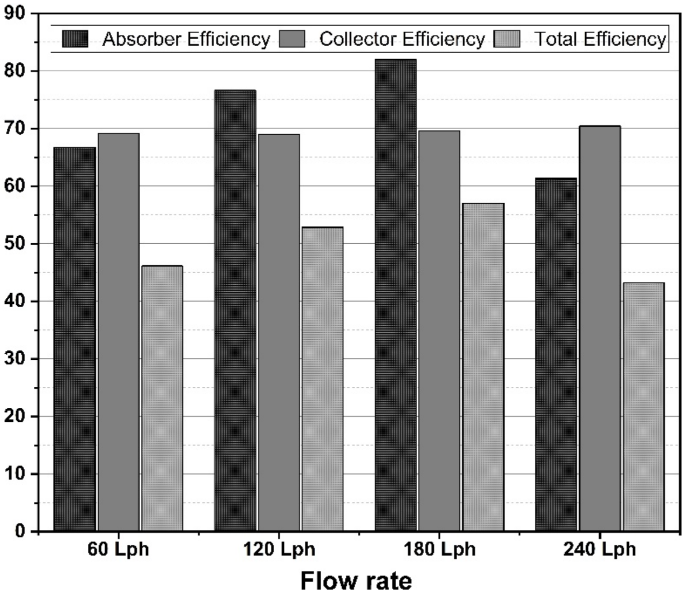

Figure 3. Efficiency comparison of collector, absorber, and total on the different flow rate

Second, the absorbed heat efficiency of water was affected by the mass flow rate and temperature difference between the inlet and outlet water. At a higher flow rate, a larger mass of water allowed for more heat absorption, with a smaller temperature change. At a flow rate of 240 L/h, efficiency decreased because the high inlet temperature led to heat loss to collector.

Third, the total thermal efficiency of the SWH system was influenced by both collector and absorber efficiencies. However, at a flow rate of 240 L/h, the total thermal efficiency decreased due to the high inlet temperature causing heat loss. Thermal efficiency was optimized by adjusting flow rate of water, ensuring that the temperature difference between inlet and outlet water was at an optimal condition for maximum heat transfer. This condition supported the fundamental principle of convective heat transfer, which increased with the rise in fluid flow rate to a certain point.

Based on the test results, flow rate of 180 L/h was identified as optimal, providing the highest thermal efficiency. The result higher than the previous research Hossain *et al.* [37] which the efficiency results are 70.24% and 70.96% which use two-side serpentine tube collector design. In addition, it shows that low water inlet temperature can reduce the absorber surface temperature significantly. This process showed the importance of adjusting the water flow rate appropriately to achieve maximum thermal performance in a solar water heating system with serpentine configuration. Additionally, the higher efficiency observed at this flow rate showed that the optimal contact time between water and collector as well as the optimal temperature difference can significantly improve heat transfer.

Effect of flow rate on serpentine collector

The influence of water flow rate on the efficiency and performance of the SWH with serpentine configuration was analyzed through variations in flow rate of 60 L/h, 120 L/h, 180 L/h, and 240 L/h respectively, as shown in **Figure 4**. At flow rate of 60 L/h, the outlet water temperature gradually increased, reaching a peak of around 42.75 °C at 12:00. Furthermore, collector efficiency at this flow rate was recorded at 69.15%, while the absorbed heat efficiency of water was 66.72%. A lower flow rate allowed for a longer contact time between water and collector surface, improving heat transfer, and increasing heat loss to environmental surrounding.

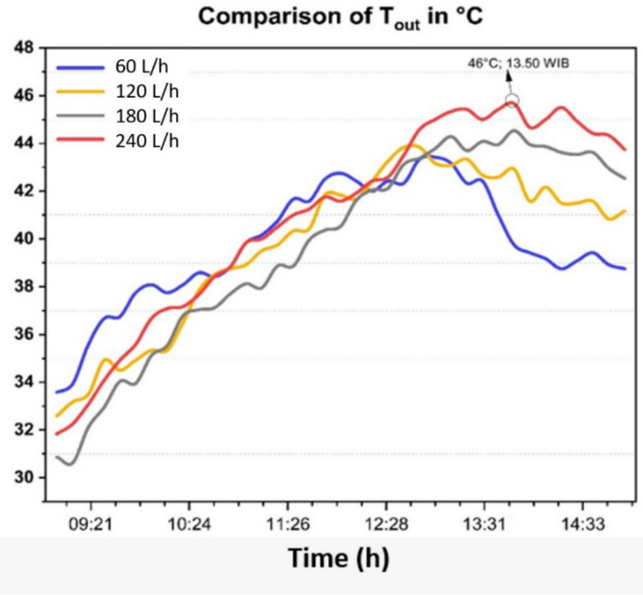

Figure 4. Comparison of average output temperatures of various flow rate

At flow rate of 120 L/h, the outlet water temperature increased more significantly, reaching a peak of around 43.83 °C at 12:50. Collector efficiency slightly decreased to 68.94%, but the absorbed heat efficiency of water increased to 76.62%. However, this process showed that a higher flow rate helped to reduce heat loss to environmental surroundings due to a shorter contact time, allowing more heat to be absorbed by the water. Fundamental thermodynamic principles supported the observation, showing that there was an optimal point where heat transfer from collector to the working fluid was most effective.

The outlet water temperature reached the highest peak of around 44.53 °C at 13:50 at flow rate of 180 L/h. Collector efficiency was 69.60%, and the absorbed heat efficiency of water was 81.93%. Furthermore, this flow rate proved optimal, providing maximum heat transfer with minimal heat loss. According to heat transfer theory, there was an optimal flow rate for fluid in heat transfer systems. A study by Hossain *et al.* [38] also found similar results, where there was an optimal flow rate that maximized heat transfer efficiency.

At flow rate of 240 L/h, the outlet water temperature peaked at around 45.67 °C at 13:50. Despite this high outlet temperature, collector's efficiency was 70.39%, but the efficiency of the absorbed heat by the water dropped to 61.34%. Furthermore, the very high flow rate led to too short of a contact time between water and collector surface, reducing heat transfer efficiency. The high inlet temperature caused greater heat loss to collector, as the temperature difference between the water and environmental surrounding decreased, reducing the drive for convective heat transfer. Moreover, a study [39] also found that an excessively high flow rate led to increased heat loss, reducing the general system efficiency.

Life-cycle assessment analysis

Life cycle assessment analysis (LCA) was crucial for understanding environmental impact of the SWH with serpentine configuration throughout its life cycle. Furthermore, LCA helped evaluate environmental contribution of each stage from production to disposal, providing an understanding of how this technology could be optimized for better sustainability. This analysis enabled the identification of areas with the greatest environmental impact and finding ways to mitigate, thereby supporting the aims of reducing carbon emissions and improving energy efficiency.

LCA analysis was conducted using ANSYS software [40] to assess environmental impact of the materials and production processes used in the manufacturing of serpentine SWH in this study. Figure 5 shows the results of the LCA analysis of the SWH with serpentine configuration. Furthermore, in Figure 5a, the use phase dominated energy consumption with significantly higher values compared to other phases. This dominion showed that although serpentine SWH relied on solar energy, there was a significant energy requirement during its operation, such as for water circulation and system control. The energy contribution from materials and manufacturing was relatively low, showing efficiency in production processes and material selection. Additionally, Figure 5b showed that the largest cost came from the material phase, followed by the manufacturing phase. The high material costs were due to the use of high-quality materials such as copper and soda-lime glass essential for the optimal performance of the system. Moreover, transportation and usage costs were relatively low, showing cost efficiency in distribution and operations.

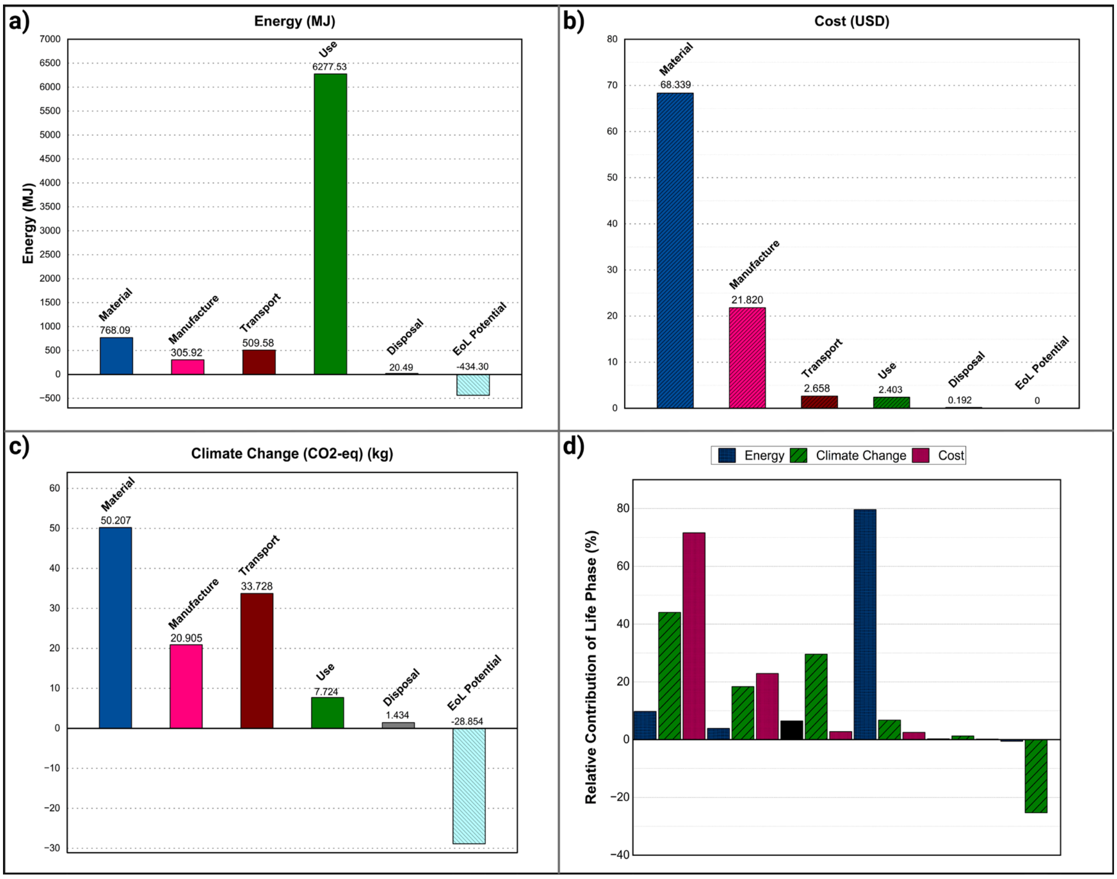

Figure 5. Life cycle assessment analysis for SWH with serpentine configuration in: Energy (a); Cost (b); Climate change (c); and Life phase (d)

Carbon dioxide equivalent (CO_{2eq}) emissions showed that the material phase contributed the most to climate change, followed by manufacturing and transportation in **Figure 5c**. The use phase showed a significant reduction in CO_2 emissions, reflecting that during operation, serpentine SWH was capable of reducing CO_2 emissions compared to conventional fossil fuel-based water heating systems. Additionally, the End of Life (EoL) potential showed a decrease in CO_2 emissions, indicating that materials could be recycled and reused, thereby reducing general environmental impact. **Figure 5d** presented the relative contributions of each life cycle phase to energy, climate change, and cost. The graph showed that the material and use phases had the highest impact on energy consumption and cost. Meanwhile, the use phase also showed a significant contribution to climate change, although with a positive impact in the form of CO_2 emission reduction due to the use of renewable energy. To improve sustainability, the focus was placed on improving energy efficiency during the use phase and optimizing production processes to reduce material costs and emissions. Generally, this serpentine SWH showed great potential as a low-cost, environmentally friendly, and efficient water heating solution.

CONCLUSIONS

In conclusion, the research successfully identified a flow rate of 180 L/h as the optimal operational condition for the serpentine SWH system under the specific experimental conditions. The condition achieved a thermal efficiency of 57.02%, the highest absorbed heat efficiency of 81.93%, and optimal collector efficiency of 69.60%. These results signified that the right balance between water contact time with collector surface and adequate temperature difference was important to optimizing heat transfer while minimizing heat loss. Furthermore, LCA analysis showed that the usage phase had dominant energy consumption but made significant contributions to CO_2 emission reduction. This analysis showed that despite significant energy needs during operation, the system's operational efficiency remained high. The system showed potential as a sustainable and environmentally friendly heating solution, with an importance on emission reduction and energy efficiency. Further improvements in production processes and material usage could help optimize environmental and economic impact of serpentine SWH. The study proposed that the adoption of serpentine SWH technology could be a step forward in global efforts to reduce reliance on non-renewable energy and promote the use of cleaner and more sustainable energy sources.

CREDIT AUTHOR STATEMENT

Nugroho Agung Pambudi: Supervision, Funding acquisition, Methodology, Project administration, Conceptualization. **Yustisia Ahnaf:** Investigation, Methodology, Formal analysis. **Iksan Riva Nanda:** Formal analysis, Software, Visualization, Writing - Original draft. **Muhammad Aziz:** Formal analysis, Writing - Review & Editing. **Desita Kamila Ulfa:** Investigation, Writing – review & editing. **Hening Asti Rahayu:** Writing – review & editing.

DECLARATION OF COMPETING INTERESTS

The authors declare no conflict of interest.

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