

Effect of Flow Rate Variation on Solar Water Heater Performance

Baharudin Priwintoko^{1,*}, Agus Lutanto¹, Yusuf Subagyo², Saeful Rofi Romadhon³, Agus Prasetyo⁴

¹Department of Manufacturing Engineering Technology, Akademi Inovasi Indonesia, Salatiga 50711

²Department of Mechanical Engineering, Semarang State Polytechnic, Semarang 50275, Indonesia

³Department of Mechanical Engineering, Faculty of Engineering, Universitas Diponegoro, Jl. Prof. Soedarto, SH, Tembalang, Semarang 50275, Indonesia

⁴Department of Mechanical Engineering, Faculty of Engineering and Technology, Al Hikmah University of Jepara, Jepara 59465, Indonesia

* Corresponding: baharudinpriwintoko@inovasi.ac.id

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Abstract.

Solar energy potential in Indonesia is very large, yet its utilization for daily thermal needs still requires improvement through simple, economical, and efficient collector designs. This study analyzes the effect of fluid flow-rate variation on the performance of a trickle-type solar water heater with a V-shaped collector under local outdoor testing conditions. The novelty of the work lies in the combined evaluation of a V-shaped zinc-sheet absorber, trickle-type flow arrangement, north-facing 30° collector orientation, and practical flow-rate range of 2, 4, 6, and 8 L/min. The outdoor experiment was conducted from 09:00 to 12:00 Western Indonesia Time with repeated field observations for each flow-rate condition. Inlet temperature, outlet temperature, ambient temperature, collector temperature, cover temperature, wind speed, and solar radiation intensity were recorded and processed to determine useful heat gain, heat absorbed by the fluid, collector efficiency, fluid heat-absorption efficiency, and total efficiency. The results show that a lower flow rate produces a greater increase in fluid temperature, but it does not always produce the highest total efficiency. The 4 L/min flow rate provided the best performance, with a total efficiency of 55%, fluid heat-absorption efficiency of 71%, average fluid heat-transfer rate of 559.53 W, and estimated test-period fluid energy of 1678.59 Wh (6.04 MJ) during the 3 h test period. These findings indicate an optimum balance between fluid residence time and mass flow rate in improving solar water heater performance.

Keywords: solar water heater; flow rate; V-shaped collector; thermal efficiency; solar energy

INTRODUCTION

Solar energy is a strategic renewable energy source for Indonesia because it is abundantly available and can be utilized in almost all regions. The national solar energy potential has been reported to be very large; however, its utilization remains relatively limited. Therefore, simple, economical, and easily applicable solar energy conversion technologies are needed to support community needs [1], [2]. Solar energy utilization is not limited to photovoltaic conversion; it can also be carried out using thermal collectors. A thermal collector converts solar radiation into heat that can be used directly, one application being a solar water heater (SWH) system [3]-[5].

SWH performance is influenced by many factors, including solar radiation intensity, ambient temperature, wind speed, collector material characteristics, collector geometry, absorber area, cover thickness, thermal insulation, heat demand, and system operating conditions. Therefore, SWH design should consider the compatibility between collector configuration, thermal load, and local climatic conditions so that the energy received by the working fluid can be maximized [6], [7]. Various modifications to collector geometry and components have been developed to improve radiation absorption and heat transfer. A V-shaped collector has been reported to increase radiation absorption compared with a flat profile due to repeated reflection on the absorber surface [8]. In addition to absorber geometry, collector material selection [9], tilt angle [10], number of heating pipes [11], collector design [12], and glass-cover configuration [13], [14] have also been reported to affect the thermal performance of the system.

Previous studies have shown that changes in flow rate can affect the outlet temperature and thermal efficiency of SWH systems. In several designs, increasing the flow rate decreases the temperature difference between the inlet and outlet because the residence time of the fluid in the collector becomes shorter. However, a higher flow rate can also increase the total energy carried by the fluid up to a certain optimum point [15]-[18].

In addition to experimental approaches, the development of SWH and solar thermal systems has also involved phase change material (PCM)-based thermal energy storage, hybrid control systems, and numerical modeling using CFD or Engineering Equation Solver (EES) to analyze heat transfer and system performance [19]-[25]. However, specific experimental evidence on flow-rate optimization for a simple trickle-type SWH using a V-shaped collector under Indonesian outdoor conditions is still limited. Therefore, this study focuses on a trickle-type SWH with a V-shaped collector tested at flow-rate variations of 2, 4, 6, and 8 L/min. The specific novelty of this work is the combined evaluation of the V-shaped absorber geometry, trickle-flow configuration, practical flow-rate range, and local field-test condition using measured thermal and radiation data. The objectives of this study are to determine the effect of flow rate on

SWH performance and to identify the most effective flow rate for the tested system configuration.

METHODS

This study used a quantitative experimental method by operating a trickle-type solar water heater prototype directly under outdoor conditions. The quantitative experimental approach was selected because the main data, namely temperature, radiation intensity, wind speed, and flow rate, were analyzed numerically to compare performance among treatments [26]. Testing was conducted on 8-19 August 2022 from 09:00 to 12:00 Western Indonesia Time. The original field-data source contains 12 outdoor test days, consisting of three daily runs for each flow-rate condition of 2, 4, 6, and 8 L/min. Each daily run contained seven observations at 30 min intervals from 09:00 to 12:00. The experimental work involved the Energy and Society Laboratory, Universitas Sebelas Maret, Surakarta, and the Mechanical Engineering Laboratory, Universitas Negeri Semarang. The same SWH prototype, collector dimensions, north-facing orientation, 30° tilt angle, instrumentation set, measurement interval, and data-processing method were used for all flow-rate variations.

Because outdoor testing cannot provide identical solar radiation and wind conditions for every day, the flow-rate variations were evaluated within the same daily time window and with measured environmental inputs for each test. Solar radiation intensity, ambient temperature, wind speed, and weather condition were recorded together with the water temperatures. The original data-reduction procedure selected the best available time-series data for each flow-rate condition to reduce the effect of cloudy periods on the main performance comparison. This procedure improves comparability under field conditions, but it does not replace a full uncertainty analysis; therefore, the repeatability summary is reported descriptively rather than inferentially.

The independent variable was the working-fluid flow rate with four treatment levels: 2, 4, 6, and 8 L/min. The dependent variable was SWH performance, expressed through fluid temperature increase, useful heat gain, heat absorbed by the fluid, collector efficiency, fluid heat-absorption efficiency, and total efficiency. The controlled variables included collector dimensions, V-shaped collector configuration, collector tilt angle, fluid type, testing period, and flow system. Water was used as the working fluid because it is widely available, safe, and has a high specific heat capacity.

The SWH prototype consisted of a water pump, flowmeter, V-shaped collector, glass cover, inlet and outlet pipes, and thermal insulation. The pump was used to circulate water from the reservoir to the collector. The flowmeter was used to adjust the flow-rate variation. The glass cover transmitted solar radiation to the absorber while reducing convective heat loss, whereas the

insulation was used to reduce heat loss from the lower side of the collector [13], [14].

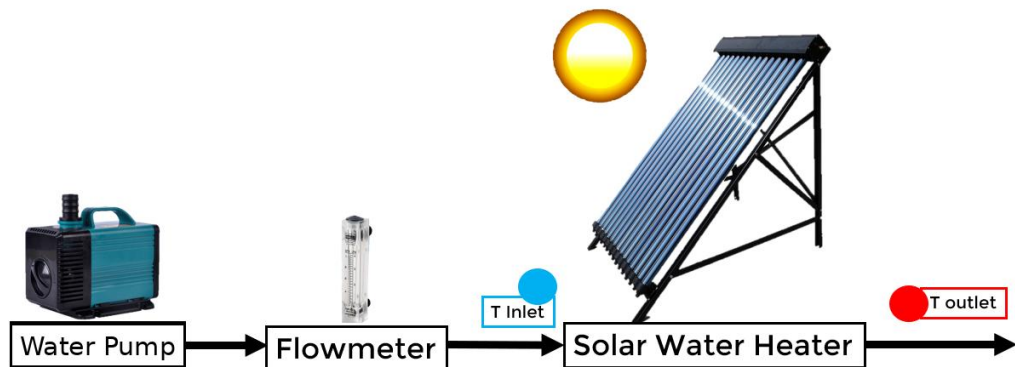


Figure 1. Schematic of the trickle-type solar water heater used in this study

The main gross dimensions of the collector were 1500 mm in length and 840 mm in width. The absorber was made from black-painted zinc sheet with a thickness of approximately 0.2 mm. The collector had 24 V-shaped profiles, each with a width of 35 mm and a depth of 30 mm. The inlet pipe diameter was 6.35 mm, the supply-pipe diameter was 76.2 mm, and the pump-pipe length was 3000 mm. The distance between the cover and the collector was 20 mm. The glass cover was 1500 mm long, 840 mm wide, and 5 mm thick. Aluminium-foil insulation and a 5 mm plywood base were used to reduce heat loss from the lower side of the collector. The V-shaped configuration was selected because this profile has the potential to increase effective absorptivity through repeated radiation reflection on the absorber surface [8].

The measuring instruments consisted of thermocouples or digital thermometers for temperature, a digital solar power meter for solar radiation intensity, a digital anemometer for wind speed, and a flowmeter for flow-rate adjustment. The recorded parameters were inlet temperature (T_{in}), outlet temperature (T_{out}), ambient temperature (T_a), collector temperature (T_k), cover temperature (T_c), wind speed (V_a), solar radiation intensity (GT), and qualitative weather condition. The flowmeter was adjusted to maintain the nominal flow-rate levels of 2, 4, 6, and 8 L/min during the corresponding tests.

The values reported in the main performance tables represent average values from the selected 09:00-12:00 time-series observations used for the final comparison. The source dataset also contains three daily field runs for each flow rate; therefore, a repeatability check was calculated from the daily mean values of ΔT , GT , and wind speed. Based on the raw daily runs, the mean \pm standard deviation of daily ΔT was 3.70 ± 0.07 °C at 2 L/min, 2.07 ± 0.09 °C at 4 L/min, 1.20 ± 0.14 °C at 6 L/min, and 0.92 ± 0.04 °C at 8 L/min. This confirms that the decreasing ΔT trend with increasing flow rate remained consistent across the repeated field runs. However, the standard deviation of daily solar radiation was

relatively high for some conditions, especially 6 L/min, indicating that weather variability still affected the outdoor measurements.

Table 1. Repeatability summary from the three daily outdoor runs for each flow-rate condition

Flow rate (L/min)	Daily runs	Observations per run	Daily mean ΔT ($^{\circ}C$)	Daily mean GT (W/m^2)
2	3	7	3.70 ± 0.07	1023.09 ± 36.85
4	3	7	2.07 ± 0.09	974.46 ± 4.32
6	3	7	1.20 ± 0.14	976.43 ± 157.05
8	3	7	0.92 ± 0.04	990.84 ± 87.06

Note: Values are mean \pm standard deviation of daily means calculated from the raw field runs. The main performance comparison uses the selected representative time-series data reported in Table 2.

Performance analysis was carried out using a heat-transfer approach for solar collectors. The effective radiation absorbed by the collector was calculated based on cover transmissivity and collector absorptivity. Useful heat gain, heat absorbed by the fluid, collector efficiency, fluid heat-absorption efficiency, and total efficiency were calculated using the basic formulation of solar collector analysis and heat transfer [27]-[31].

$$S = \tau \alpha GT \quad (1)$$

$$Qu = Ac FR [S - UL (Tk - Ta)] \quad (2)$$

$$Qf = \dot{m} cp (Tout - Tin) \quad (3)$$

$$\eta k = Qu / (Ac GT) \quad (4)$$

$$\eta f = Qf / Qu \quad (5)$$

$$\eta t = \eta k \times \eta f \quad (6)$$

In these equations, S is the effective radiation on the collector, τ is the cover transmissivity, α is the collector absorptivity, GT is the total solar radiation intensity, Qu is the useful heat gain, Ac is the collector area, FR is the collector heat removal factor, UL is the total heat-loss coefficient, Tk is the collector temperature, Ta is the ambient temperature, Qf is the heat-transfer rate absorbed by the fluid, \dot{m} is the mass flow rate, cp is the fluid specific heat, Tin is the inlet temperature, Tout is the outlet temperature, ηk is the collector efficiency, ηf is the fluid heat-absorption efficiency, and ηt is the total efficiency [27], [28].

The calculation inputs explicitly used in this study were $\tau = 0.79$ for glass-cover transmissivity, $\alpha = 0.969$ for collector absorptivity, $\epsilon c = 0.90$ for cover emissivity, cover-collector gap $L = 0.02$ m, and an effective collector area Ac of approximately 1.04 m^2 as used in the original heat-gain calculation. The gross collector dimensions were $1.50 \text{ m} \times 0.84 \text{ m}$, while the effective area was

used for the thermal-performance calculation. Water properties were evaluated near the measured fluid temperature; the example calculation used $c_p = 4.0706 \times 10^3 \text{ J/kg}\cdot\text{K}$ and $\rho = 9.9548 \times 10^2 \text{ kg/m}^3$. The mass flow rate was obtained by converting the nominal volumetric flow rates from L/min to m^3/s and multiplying by water density. UL and FR were calculated for each observation from the heat-loss and heat-removal equations; in the 2 L/min, 09:00 example calculation, $UL = 0.5915 \text{ W/m}^2\text{K}$ and $FR = 0.9977$. The accumulated fluid energy was reported as energy rather than power and was estimated from $E_f = \bar{Q}_f \times \Delta t$, where \bar{Q}_f is the average fluid heat-transfer rate and $\Delta t = 3 \text{ h}$ is the test duration. Accordingly, the accumulated values are expressed in Wh and MJ. These inputs clarify that the efficiency values are comparative performance indicators for the tested configuration rather than standardized collector-certification values.

Table 2. Average testing parameters for each flow-rate variation used in the main performance comparison

Flow rate (L/min)	T _{in} (°C)	T _{out} (°C)	ΔT (°C)	ΔT/T _{in} (%)	GT (W/m ²)
2	28.25	31.95	3.70	13.10	1081.61
4	27.86	29.93	2.07	7.43	1035.90
6	28.54	29.73	1.19	4.18	1070.14
8	28.36	29.28	0.92	3.25	1053.27

RESULT AND DISCUSSION

The test results show that flow-rate changes affected the temperature rise of the working fluid. At a flow rate of 2 L/min, the average outlet temperature reached 31.95 °C with an average temperature increase of 3.70 °C. At flow rates of 4, 6, and 8 L/min, the average temperature increases were 2.07 °C, 1.19 °C, and 0.92 °C, respectively. This pattern is consistent with the concept that increasing the flow rate shortens the residence time of the fluid inside the collector, causing ΔT to decrease [15]-[18].

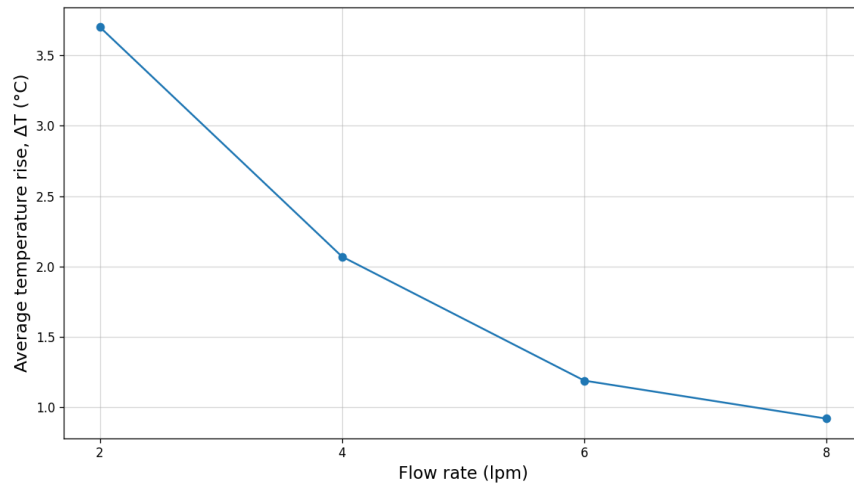


Figure 2. Effect of flow-rate variation on the average fluid temperature increase

The highest temperature increase at 2 L/min indicates that a low flow rate provides a longer residence time for the fluid to absorb heat from the collector. However, outlet temperature alone is not sufficient to determine the best performance because the thermal energy carried by the fluid is also determined by the mass flow rate. Thus, the optimum flow rate should be evaluated through the combination of ΔT and the flowing fluid mass [15], [16], [18].

Table 3. Summary of solar water heater performance for each flow-rate variation

Flow rate (L/min)	Average Qf (W)	Ef over 3 h (Wh)	η_k (%)	η_f (%)	η_t (%)
2	499.47	1498.41	76	62	47
4	559.53	1678.59	77	71	55
6	484.28	1452.84	77	62	48
8	499.07	1497.21	77	63	48

Table 3 shows that the 4 L/min flow rate produced the highest heat-transfer rate absorbed by the fluid. The average Qf at 4 L/min was 559.53 W, while the estimated fluid energy during the 3 h test period reached 1678.59 Wh (6.04 MJ). This value was higher than those obtained at 2, 6, and 8 L/min. The corrected unit emphasizes that Qf is an instantaneous or averaged heat-transfer rate in watts, whereas the accumulated test-period value is an energy quantity obtained by multiplying the average heat-transfer rate by the 3 h test duration. These findings indicate that SWH performance does not depend only on outlet temperature, but also on the balance between mass flow rate and fluid temperature difference [27], [28].

Physically, this phenomenon can be explained using the equation $Q_f = \dot{m} c_p \Delta T$. At 2 L/min, ΔT was relatively high, but the mass flow rate was low, so the total energy carried by the fluid was not maximized. Increasing the flow

rate can increase the Reynolds number and may improve the convective heat-transfer coefficient between the absorber or pipe wall and the working fluid. However, a higher flow rate also reduces residence time in the collector. At 6 and 8 L/min, the increase in mass flow rate could not compensate for the sharp decrease in ΔT , so the energy absorbed by the fluid was not maximized. The 4 L/min flow rate became the compromise point that produced the best combination of \dot{m} , convective heat transfer, and residence time for this system configuration [22], [27], [28].

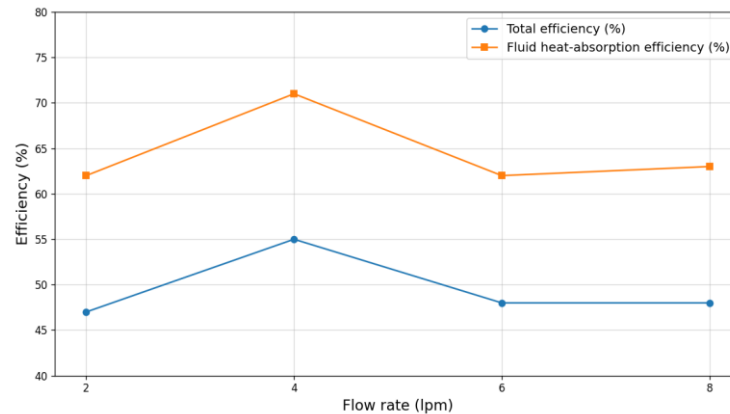


Figure 3. Comparison of fluid heat-absorption efficiency and total efficiency at each flow rate

The collector efficiency for all variations was relatively uniform, at 76-77%. This result can be explained by the fact that η_k was normalized by the incident solar input A_{cGT} and was mainly governed by the same collector geometry, absorber area, cover configuration, and heat-loss model used in every test. Therefore, flow-rate variation had only a limited effect on the calculated collector-side efficiency. In contrast, the flow rate directly changed \dot{m} and ΔT in $Q_f = \dot{m} c_p \Delta T$, so the fluid heat-absorption efficiency and total efficiency were more sensitive to flow-rate variation. The V-shaped collector continued to provide relatively stable absorption characteristics, while the working-fluid side determined the optimum operating point [8], [27]. The highest total efficiency was obtained at a flow rate of 4 L/min, reaching 55%. The 6 L/min and 8 L/min flow rates produced total efficiencies of approximately 48%, while the 2 L/min flow rate produced a total efficiency of 47%. Therefore, increasing the flow rate does not always increase total efficiency. An optimum condition exists when the increase in flow rate can still maintain an adequate temperature difference and produce the highest Q_f [15]-[18].

Solar radiation intensity also played an important role in SWH performance. The average GT during testing ranged from 1035.90 to 1081.61 W/m². These values indicate sufficiently high radiation conditions for solar water heater testing. Temporal fluctuations in GT still affected the collector temperature, cover temperature, and useful energy calculated for each flow-rate

variation [3], [27]. Wind speed around the collector affected heat loss from the cover to the environment. The higher the wind speed, the greater the external convection coefficient, so the cover temperature tended to decrease more easily. In solar collector analysis, wind-induced heat-loss correlations are used to estimate the external heat-transfer coefficient of the cover [27], [31].

The results of this study are consistent with the concept of convective heat transfer. Increasing the flow rate changes the flow characteristics inside the pipe and affects the Reynolds and Nusselt numbers. These changes influence the convective heat-transfer coefficient between the pipe wall and the fluid; therefore, ΔT , Q_f , and thermal efficiency also change [28], [30]. In the tested system, the heat-transfer improvement associated with higher flow velocity was beneficial only up to 4 L/min. Beyond this point, the shorter residence time became more dominant and caused a lower temperature rise, so the additional mass flow did not increase the absorbed energy. Compared with previous studies, the decrease in ΔT due to increasing flow rate has also been observed in other SWH systems. Faisal and Rangkuti [15], Budea and Badescu [16], Raditya [17], and Kristian et al. [18] showed that flow rate is an important operating parameter affecting water outlet temperature, thermal energy absorbed by the fluid, and system efficiency. The results of this study strengthen those findings for a trickle-type SWH configuration with a V-shaped collector.

Regarding quality-standard aspects, the tested system can only be discussed in relation to selected provisions of SNI 04-3021-1992 for solar water heaters [32]. The source calculation compared the collector heat-loss criterion with the SNI collector limit of 7 W/m²K. The highest calculated total heat-loss coefficient was 3.37 W/m²K at 09:00 for the 2 L/min condition, and the average total heat-loss coefficient over all flow-rate calculations was 1.41 W/m²K. Therefore, the heat-loss calculation remained below the SNI collector heat-loss limit. The prototype also used a glass cover, black-coated collector, and aluminium-foil/plywood insulation, which are consistent with basic design considerations for corrosion resistance and heat-loss reduction. However, this study did not conduct a complete SNI compliance test. Pressure-resistance, high-temperature stagnation, thermal-shock, daily hot-water capacity, and stagnation-temperature tests were not performed; the rain-seepage observation also indicated minor leakage at the inlet pipe. Therefore, the SNI-related statement should be interpreted as a limited comparison of selected design and heat-loss criteria, not as formal certification of compliance.

The limitations of this study are mainly related to outdoor testing conditions, incomplete instrument uncertainty propagation, and the use of a once-through flow system. Although the source dataset contained three daily runs for each flow rate, the outdoor runs were affected by changing solar radiation, wind speed, and cloud condition. In a once-through system, water is not recirculated back to a storage tank; therefore, stagnation temperature, daily

solar fraction, and storage-tank performance could not be comprehensively evaluated. In addition, several standard tests, such as pressure resistance, high-temperature stagnation resistance, and thermal shock resistance, were not carried out, so further testing according to national standards is required [26], [32]. Overall, the 4 L/min flow rate can be considered the most effective operating condition for the tested SWH configuration. This flow rate did not produce the highest outlet temperature, but it provided the highest absorbed fluid energy and total efficiency. These findings highlight the importance of flow-rate optimization in SWH design, especially for trickle systems with V-shaped collectors intended to achieve the best thermal performance [8], [15]-[18].

CONCLUSION

Flow-rate variation affects the performance of a trickle-type solar water heater with a V-shaped collector. Increasing the flow rate from 2 L/min to 8 L/min decreased the average temperature rise of the fluid, but it did not always decrease the energy absorbed by the fluid. The 4 L/min flow rate produced the best performance, with an average Q_f of 559.53 W, estimated 3 h fluid energy of 1678.59 Wh (6.04 MJ), fluid heat-absorption efficiency of 71%, and total efficiency of 55%. Repeatability checking from three daily field runs per flow-rate condition confirmed the same decreasing ΔT trend, with daily mean ΔT values of 3.70 ± 0.07 °C, 2.07 ± 0.09 °C, 1.20 ± 0.14 °C, and 0.92 ± 0.04 °C for 2, 4, 6, and 8 L/min, respectively. These results indicate that the optimum flow rate is determined by the balance between fluid residence time, convective heat transfer, and the mass of fluid flowing through the collector. The collector efficiency remained relatively stable at 76-77% because the collector geometry, absorber area, and incident-radiation normalization were unchanged, whereas the fluid-side indicators were more sensitive to flow-rate variation. Future research should conduct repeated outdoor testing with propagated instrument uncertainty, report complete optical and heat-loss parameters, perform full testing according to SNI 04-3021-1992, add a recirculation system or storage tank, and evaluate additional flow-rate variations to strengthen the generalization of the results [32].

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