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Optimization of Parallel Solar Water Heater Using Six Flat-Plate Collectors with Stainless Steel Pipes

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ABSTRACT

This study aims to optimize the thermal performance of a parallel-type solar water heating system employing six flat-plate solar collectors with stainless steel pipes. Experimental testing was conducted in Pontianak City, Indonesia, under tropical equatorial conditions during three time sessions from 11:00 AM to 2:00 PM. The system was designed as a passive configuration to enhance heat absorption and uniform flow distribution. Data were recorded at 5-minute intervals, including water temperature variation, solar radiation intensity, and thermal efficiency. The results indicate that the water temperature increased significantly with a temperature difference (ΔT) ranging from 3.4˚C to 13.6˚C, while the thermal efficiency varied between 1.74% and 6.31%**,** reaching its maximum during the 1:00–2:00 PM session. Solar radiation intensity was observed in the range of 65–89 Lux, which showed a direct influence on system performance. Although efficiency decreased slightly under high thermal load conditions, the overall results demonstrate that the proposed parallel collector configuration performs effectively even in the afternoon period. These findings confirm that a parallel-type flat-plate solar water heater using stainless steel pipes has strong potential as an energy-efficient and environmentally friendly water heating system for tropical regions.
Keyword: Solar Water Heater, Flat-Plate Collector, Thermal Efficiency, Stainless Steel Pipe, Renewable Energy

Keywords: Solar water heater; Flat plate collector; Thermal efficiency; Stainless steel pipe; Renewable energy.

ABSTRAK

Penelitian ini bertujuan untuk mengoptimalkan kinerja termal sistem pemanas air tenaga surya tipe paralel yang menggunakan enam kolektor pelat datar berbasis pipa stainless steel. Pengujian eksperimental dilakukan di Kota Pontianak dengan kondisi iklim tropis khatulistiwa selama tiga sesi waktu, yaitu pukul 11.00–14.00 WIB. Sistem dirancang secara pasif untuk meningkatkan penyerapan panas dan pemerataan distribusi aliran fluida. Pengambilan data dilakukan setiap 5 menit yang meliputi perubahan suhu air, intensitas radiasi matahari, dan efisiensi termal sistem. Hasil penelitian menunjukkan bahwa suhu air mengalami peningkatan dengan selisih temperatur (ΔT) berkisar antara 3,4˚C hingga 13,6˚C, sedangkan efisiensi termal berada pada rentang 1,74% hingga 6,31%**,** dengan nilai tertinggi terjadi pada sesi pengujian pukul 13.00–14.00 WIB. Intensitas radiasi matahari terukur pada kisaran 65–89 Lux dan berpengaruh langsung terhadap performa sistem. Meskipun terjadi sedikit penurunan efisiensi pada kondisi beban panas tinggi, hasil secara keseluruhan menunjukkan bahwa sistem pemanas air tenaga surya tipe paralel ini mampu bekerja secara efektif hingga sore hari. Dengan demikian, sistem ini memiliki potensi yang baik untuk diterapkan sebagai teknologi pemanas air hemat energi dan ramah lingkungan di daerah tropis.

Kata kunci: Pemanas air tenaga surya, kolektor pelat datar, efisiensi termal, pipa stainless steel, energi terbarukan.

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1. Introduction

The increasing demand for thermal energy in domestic and industrial sectors, particularly for water heating applications, has led to a growing reliance on fossil fuel-based energy sources such as electricity, LPG, and petroleum fuels. These energy sources not only increase operational costs but also contribute significantly to greenhouse gas emissions and environmental degradation [1]. Consequently, the development of renewable and sustainable thermal energy systems has become a global priority.

Indonesia, as a tropical country located along the equator, possesses abundant solar energy potential throughout the year, with an average solar radiation intensity ranging from 4.5 to 5.5 kWh/m² per day [2]. Despite this favorable condition, the utilization of solar energy for domestic thermal applications, particularly solar water heating systems, remains relatively limited. This gap indicates the need for practical, efficient, and affordable solar-based water heating technologies.

The urgency of solar energy utilization is particularly evident in Pontianak City, West Kalimantan, which lies directly on the equatorial line and experiences high and relatively stable solar radiation throughout the year, averaging 5.0–5.4 kWh/m² per day [3]. However, the application of solar thermal technologies in this region is still minimal, especially at the household and small-scale industrial levels. This condition highlights the relevance of conducting localized experimental studies to optimize solar water heater performance under equatorial climate conditions.

Flat-plate solar collectors are among the most widely used technologies for converting solar radiation into thermal energy due to their simple construction, low cost, and ease of maintenance [4]. The performance of these systems is strongly influenced by collector configuration, flow arrangement, and material selection for absorber plates and pipes [5]. Stainless steel pipes offer advantages such as high corrosion resistance, good mechanical strength, and economic feasibility compared to copper pipes; however, their relatively lower thermal conductivity requires careful system optimization to maintain acceptable efficiency levels [6].

One approach to improving system performance is the application of a parallel flow configuration using multiple flat-plate collectors. This configuration can enhance flow uniformity and increase the effective heat absorption area, but it may also introduce challenges related to flow imbalance and thermal losses if not properly designed [7]. Previous studies have investigated various collector arrangements and materials; however, experimental data on parallel flat-plate solar water heaters employing stainless steel pipes under equatorial conditions remain limited.

Therefore, this study aims to experimentally optimize the performance of a parallel-type solar water heating system using six flat-plate collectors with stainless steel pipes under the climatic conditions of Pontianak City. The system performance is evaluated based on water temperature variation, solar radiation intensity, and thermal efficiency. The findings of this study are expected to contribute to the development of efficient, environmentally friendly, and locally applicable solar water heating systems for tropical regions.

2. Method

This study employed an experimental method to evaluate and optimize the thermal performance of a parallel-type solar water heating system consisting of six flat-plate solar collectors with stainless steel pipes. The experimental setup was designed to investigate the effect of solar radiation intensity and heating duration on water temperature variation and thermal efficiency under equatorial climatic conditions.

2.1Experimental Setup

The solar water heating system comprised six flat-plate collectors arranged in a parallel flow configuration. Each collector had an effective surface area of 0.80 m × 1.27 m and was equipped with a black matte-coated absorber plate. Heat transfer fluid (water) flowed through ½-inch diameter AISI 304 stainless steel pipes attached to the absorber plate. Thermal insulation was applied on the rear and side surfaces of the collectors to minimize heat loss, while a 5 mm transparent glass cover was installed on the top surface. All collectors were connected to a 12-liter stainless steel storage tank and operated under a passive thermosiphon mechanism without the use of a circulation pump. The collectors were installed at a fixed tilt angle optimized for the geographical latitude of Pontianak City.

2.2 Instrumentation and Measurement Accuracy

Water temperatures at the collector inlet, outlet, and storage tank were measured using type-K thermocouples with an accuracy of ±0.5˚C. Solar radiation intensity was measured using a digital lux meter and converted into solar irradiance values (W/m²) using a standard conversion factor. Ambient temperature was monitored using a digital thermometer with an accuracy of ±1˚C. All measurements were recorded at 5-

minute intervals during three testing sessions conducted between 11:00 AM and 2:00 PM under clear-sky conditions to minimize environmental variability.

2.3 Experimental Procedure and Controls

To ensure repeatability and consistency, all experiments were conducted on days with similar weather conditions, and the initial water temperature was maintained at approximately the same level before each test session. The collector orientation, tilt angle, and water volume were kept constant throughout the experiments. No external heating sources were introduced during testing.

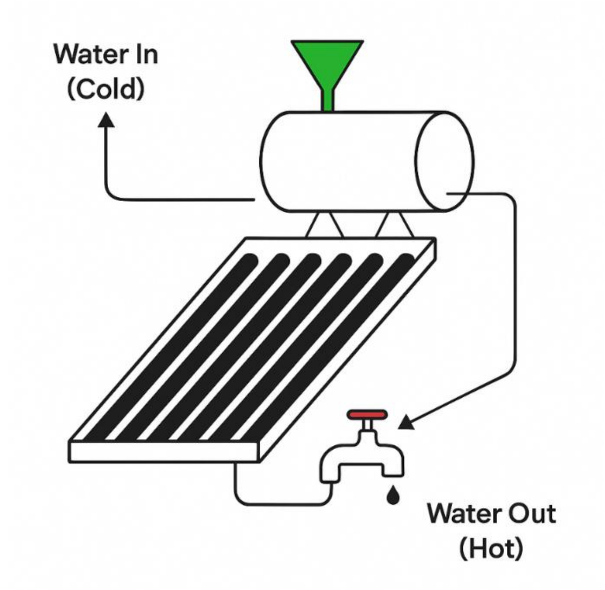

Figure 1. Initial Research Equipment Schematic

In this study, measurements of heat transfer occurring in solar water heaters were taken to determine how much heat energy was absorbed by the water from the solar collector. Calculations for inter-surface radiation used the following formula [11]:

q=σ . ε. ΔT 1

Where q is the rate of heat transfer of radiation , is the $W/_{m^2}$) , σ Stefan–Boltzmann constant (5.67×10^{-8} W/m.K) and is $\varepsilon$the surface emissivity of the absorbent plate for stainless steel (0.20), as well as ΔT is the thermoperture change between the outgoing and incoming water.

The water discharge is obtained from the equations:

$Q = \frac{V}{t}$ 2

$$Q = \frac{12}{3600} = 0.0033\ L/s$$

with as the discharge of water ($Q\ ^{m^3}/_{s}$) and V is the volume of flowing water (liters), and t is the flow time(s) Furthermore, to find out the amount of solar radiation energy absorbed by the collector's surface, the equation is used:
The formula for the heat of the sun is accepted

$Q_{rad} = G.A.t$ 3

By being the Q_{rad} total energy of the received solar radiation (J), for G is the intensity of solar radiation (W/m²) A is the total area of the total active surface of the collector (m²) and t is the heating time(s). Because the collector configuration on this side consists of 6 collectors, the total collector area is:

$A_c = 6\ .A_{Colector}$ 4

The intensity of solar radiation is measured using G_ta luxmeter, which is converted into Watts per square meter (W/m²). The measurement location was carried out at the Mechanical Engineering Laboratory of the University of Muhammadiyah Pontianak, West Kalimantan, which is geographically located on the equator, so that it gets high sunlight and is relatively stable throughout the day. This greatly supports the success of research in optimizing the performance of solar collectors.

To calculate the thermal efficiency of a solar collector, it is calculated using the efficiency equation [12]:

$$\eta = \frac{Q_{water}}{Q_{rad}} x\ 100\% \qquad (5)$$

where η is thermal efficiency, is the heat energy that water absorbs, is the energy from solar radiation received by the collector $Q_{water} Q_{rad}$

Untuk rumus energi panas yang diserap oleh air adalah [13]:

$$Q_{water} = m.c.\Delta T \qquad (6)$$

Q_{water} is the heat energy absorbed by water, and m is the mass of heated water (kg), and c is the heat of the water type (4186 J/Kg), and is the temperature change that occurs at the inlet and outlet temperatures ΔT

In addition, to determine the convection heat transfer in a stainless steel pipe that conducts water, a formula is used [14] [15]:

$$Q = h \cdot A \cdot \Delta T \qquad (7)$$

where is the heat transfer rate (Watt), is the Qhconvection heat transfer coefficient (W/m²°C) for this *case* because the water flows naturally due to the slope, then h = 300, A is the area of the inner surface of the pipe in contact with water (m²), and ΔT is the temperature difference between the plate and the water in the pipe.

The analysis was carried out by comparing parameters such as the temperature distribution in the water, the rate of temperature increase over time, and the thermal efficiency of each collector during the heating process. The optimization of the water heating system is carried out by evaluating the response of the collector to variations in heating time and fluctuations in the intensity of sunlight. This measurement is very important because the efficiency of the collector is greatly influenced by the stability of the intensity of solar radiation, the even distribution of temperature, and the thermal characteristics of the stainless steel pipe as a heat transfer medium.

3. Results and Discussion

Figure 2 shows a prototype of a parallel-type solar water heater designed to optimize solar energy absorption and water heating efficiency. This system consists of six flat plate solar collectors arranged in parallel in a tilt frame that has been adjusted to the angle of incidence of the sun in the Pontianak City area. The collector plate is coated with heat-absorbing material and covered with transparent glass to minimize heat loss due to convection and radiation. The cold water from the upper holding tank is flowed into the collector through a Stainless Steel piping system, then heated by the solar radiation absorbed by the collector's surface. After going through the heating process, warm water is collected in a lower reservoir which is also made of Stainless Steel material to maintain the temperature. The system is passive, utilizing the force of gravity and temperature density differences to naturally flow water without the use of an electric pump.

Figure 2. Solar Water Heater

The appliance is tested in an open space with direct sunlight to determine the heating efficiency, optimal heating time, and maximum temperature that can be achieved. In addition, the system is designed to support the development of renewable energy and can be applied in areas with limited access to electrical energy, as an alternative solution to environmentally friendly and energy-efficient water heaters.

Table 1 Data Collection Results 11. AM – 12.00 pm

No	Time (Minutes)	Lux W/m^2	ΔT ($°C$)	Q (W/m^2)	Q_{rad} (J)	Q_{water} (J)	Efficiency (%)
1	5	67.9637	3.4	3.85×10^{-8}	97867.73	170788.8	1.745098
2	10	68.335	4.1	4.64×10^{-8}	98402.4	205951.2	2.092949
3	15	68.73	4.7	5.32×10^{-8}	98971.2	236090.4	2.385445
4	20	68.967	5.7	6.46×10^{-8}	99312.48	286322.4	2.883046
5	25	69.52	6.7	7.59×10^{-8}	100108.8	336554.4	3.361886
6	30	70.0967	5.0	5.67×10^{-8}	100939.2	251160	2.488229
7	35	70.705	8.3	9.41×10^{-8}	101815.2	416925.6	4.094925
8	40	71.258	9.0	1.02×10^{-7}	102611.5	452088	4.405821
9	45	72.285	9.8	1.11×10^{-7}	104090.4	492273.6	4.729289
10	50	72.8775	11.0	1.24×10^{-7}	104943.6	552552	5.265228
11	55	73.312	12.5	1.41×10^{-7}	105569.3	627900	5.947753
12	60	73.6438	11.5	1.30×10^{-7}	106047.1	577668	5.447279

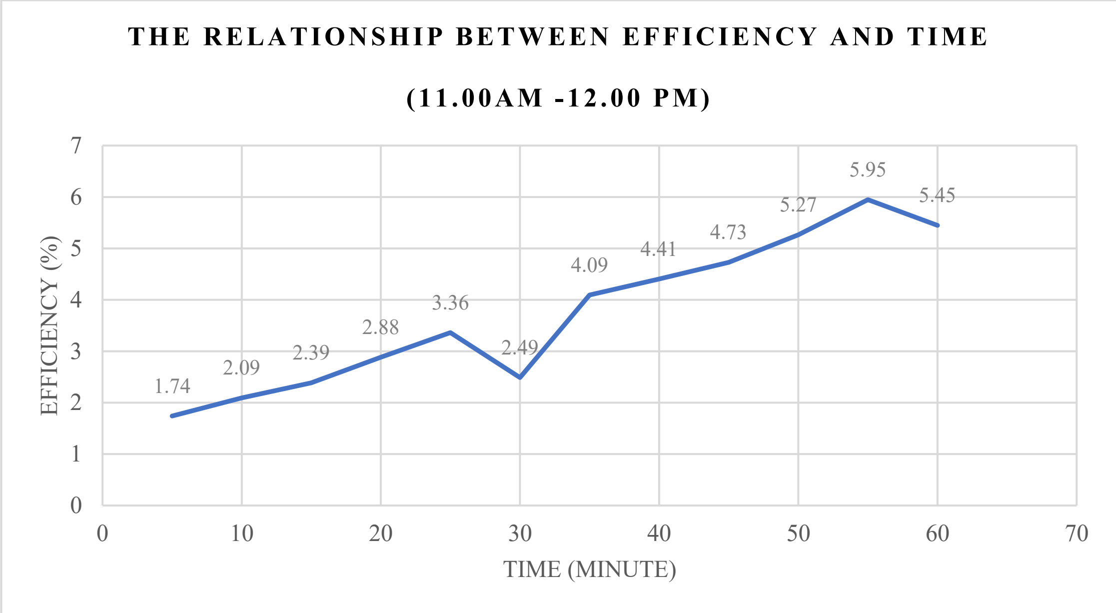

Figure 3. Graph of the Relationship between Efficiency and Time (11.00 AM - 12.00 PM)

This study aims to test the performance of a parallel-type solar water heater using six stainless steel pipe-based flat plate solar collectors. The test was carried out for 60 minutes in sunny weather conditions in Pontianak City. with data recording carried out every 5 minutes. The observed parameters included sunlight intensity (Lux). water change temperature (ΔT). incoming solar radiation energy (Q_{rad}). heat energy absorbed by water (Q_{water}). and system efficiency.

Based on the data obtained, the light intensity (lux) shows an upward trend from the 5th to the 60th minute, increasing from 67.96 lux to 73.64 lux. This increase is consistent with the rise in water temperature (ΔT), which increased from 3.4 °C at the 5th minute to a maximum of 12.5 °C at the 55th minute. After that, a slight decrease in temperature occurs at the 60th minute to 11.5 °C, which is likely influenced by fluctuations in light intensity or heat loss to the surrounding environment.

Solar radiation energy (Q_{rad}) is calculated based on radiation intensity and shows a consistent upward trend from 3.8556E-08 W/m² at 5th minute to 1.4175E-07 W/m² at 55th minute. Similarly. the heat energy absorbed by water (Q_{wtr}) has increased significantly. starting from 170.788.8 Joules in the 5th minute to reaching a peak of 627.900 Joules in the 55th minute. before decreasing slightly at the 60th minute to 577.668 Joules.

The efficiency of the heating system also increases over time. The lowest efficiency was recorded in the 5th minute at 1.75%. and the highest efficiency was achieved in the 55th minute at 5.95%. This efficiency value indicates that the system is able to absorb and utilize solar energy gradually. with optimal performance occurring in the final minutes of observation.

Overall. these results show that the use of stainless steel pipe-based parallel-type flat plate solar collectors has good potential in optimizing the absorption of solar heat for water heating. The performance of the system shows an increase in efficiency over heating time. and can be a sustainable solution for heat energy needs. especially in tropical areas such as Pontianak which have high solar radiation intensity.

Table 2 Data Collection Results 12.00 AM – 1.00 PM

No	Time (Minute)	Lux W/m^2	ΔT $(°C)$	Q (W/m^2)	Q_{rad} (J)	Q_{water} (J)	Effeciency (%)
1	5	70.6102	4.8	5.4×10^{-8}	101678.688	241000	2.37021154
2	10	70.942	5.4	6.1×10^{-8}	114926.04	271000	2.35803827
3	15	71.179	6.2	7.03×10^{-8}	132392.94	311000	2.34906786
4	20	71.574	7.5	8.5×10^{-8}	161041.5	376000	2.3348019
5	25	72.048	8.2	9.2×10^{-8}	177238.08	411000	2.31891476
6	30	83.266	9.5	1.07×10^{-7}	237308.1	477000	2.01004517
7	35	72.68	10.4	1.17×10^{-7}	226761.6	522000	2.30197705
8	40	73.1935	10.9	1.23×10^{-7}	239342.745	547000	2.28542545

No	Time (Minute)	Lux W/m^2	ΔT ($°C$)	Q (W/m^2)	Q_{rad} (J)	Q_{water} (J)	Effeciency (%)
9	45	82.16	12.0	1.36×10^{-7}	295776	602000	2.03532403
10	50	85.478	13.1	1.48×10^{-7}	335928.54	658000	1.95874992
11	55	86.9	13.3	1.5×10^{-7}	346731	668000	1.92656555
12	60	89.033	13.3	1.5×10^{-7}	355241.67	668000	1.88041003

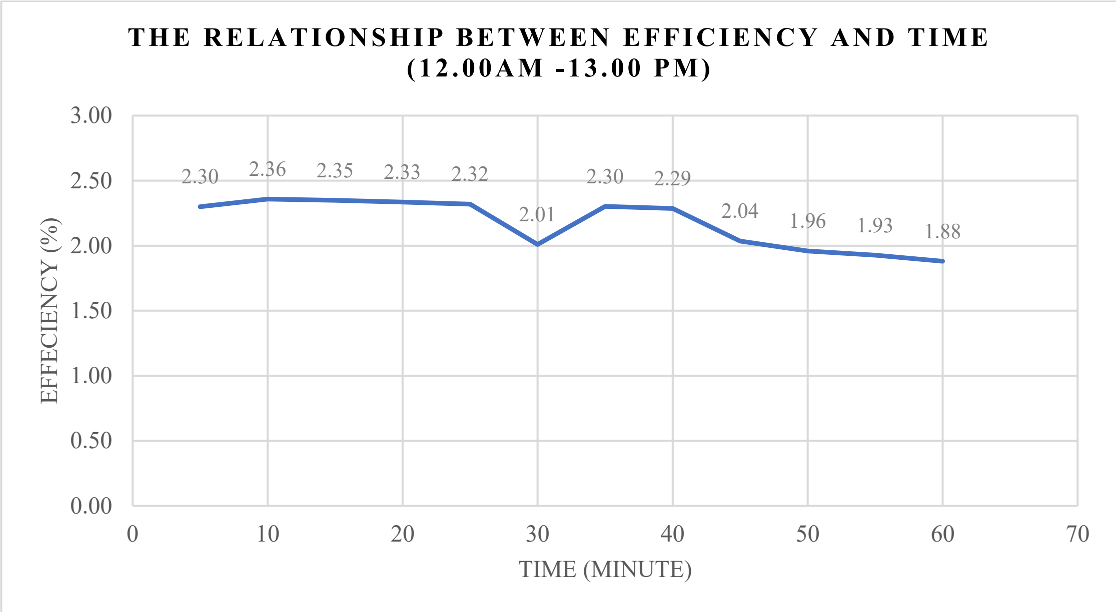

Figure 4. Graph of the Relationship of Efficiency with Time (12.00-13.00)

Observations in the time range of 12.00 AM to 1.00 PM provide a further picture of the performance of the solar water heating system when the intensity of solar radiation is at its peak. Data is recorded every 5 minutes for 1 hour with the same parameters as the previous session.

The intensity of sunlight (Lux) is in a fairly high range. ranging from 70.61 to 89.03 Lux. Along with the increase in light intensity. the water temperature experienced a significant increase from 4.8˚C in the 5th minute to 13.3˚C in the 55th minute and remained stable at the 60th minute. The energy of incoming solar radiation (Q_rad) also increases over time. with an initial value of 5.4×10^{-8} W/m² reaching a maximum value of 1.5×10^{-7} W/m² at the 55th and 60th minutes. This shows that solar collectors manage to capture heat energy optimally during intense hours of the sun.

Water-absorbed heat energy (Q_{water}) shows a very positive trend. starting at 241.000 Joules and increasing consistently until it reaches 668.000 Joules at the 55th and 60th minutes. However. despite the increase in energy absorbed. the efficiency value of the system actually decreased slightly from 2.37% to 1.88% at the last minute.

Decreased efficiency even though the energy absorbed is increased is likely due to an increase in the heat load of the system. the potential for greater heat loss. or the limitation of the collector's absorption power at maximum radiation conditions. This is an indication that there is an optimal limit in the system to convert radiant energy into heat energy in water efficiently.

In general. the observation session at 12.00–13.00 shows the good performance of the system in absorbing energy. but also shows the importance of considering the thermal design and insulation system so that efficiency does not decrease when high temperatures are reached

Table 3 Data Collection Results at 1.00 PM – 2.00 PM

No	Time (Minute)	Lux W/m^2	ΔT ($°C$)	Q (W/m^2)	Q_{rad} (J)	Q_{water} (J)	Effeciency (%)
1	5	65.0328	4.5	5.10×10^{-8}	93647.23	226044	2.413782
2	10	65.57	5.4	6.12×10^{-8}	94420.8	271252.8	2.872808

No	Time (Minute)	Lux W/m^2	ΔT ($°C$)	Q (W/m^2)	Q_{rad} (J)	Q_{water} (J)	Efficiency (%)
3	15	65.965	6.5	7.37×10^{-8}	94989.6	326508	3.437303
4	20	66.755	7.6	8.61×10^{-8}	96127.2	381763.2	3.971438
5	25	67.545	8.9	1.0×10^{-8}	97264.8	447064.8	4.596368
6	30	71.1	5.5	6.23×10^{-8}	102384	276276	2.698429
7	35	72.048	9.6	1.08×10^{-7}	103749.1	482227.2	4.648012
8	40	73.075	10.7	1.21×10^{-7}	105228	537482.4	5.107789
9	45	74.26	12.3	1.39×10^{-7}	106934.4	617853.6	5.777875
10	50	74.892	13.2	1.49×10^{-7}	107844.5	663062.4	6.14832
11	55	75.208	13.6	1.54×10^{-7}	108299.5	683155.2	6.308017
12	60	75.5793	12.3	1.39×10^{-7}	108834.2	617853.6	5.677017

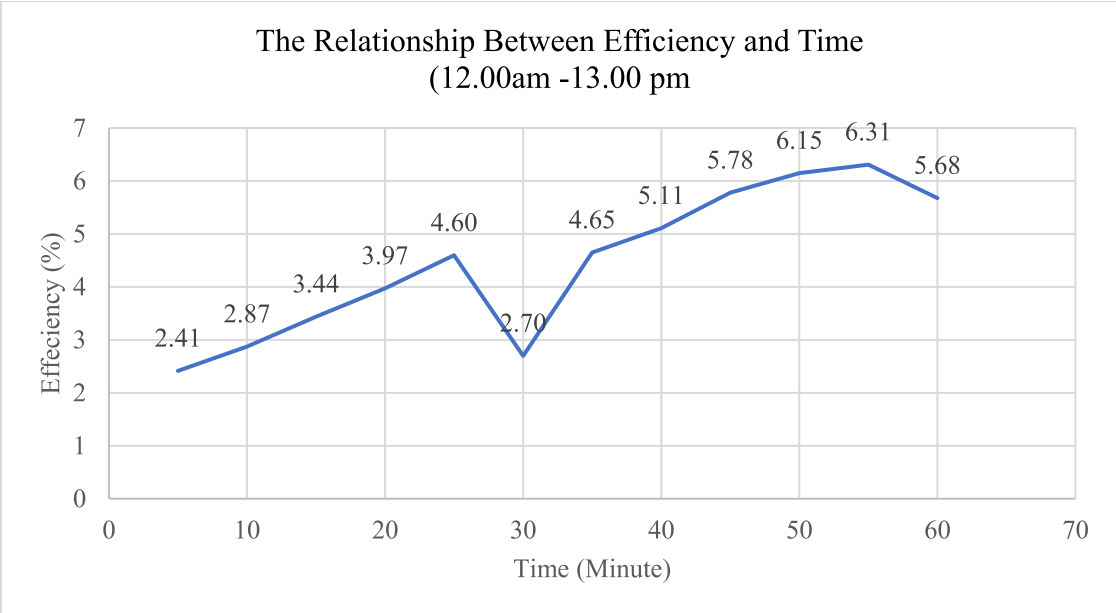

Figure 4. Graph of the Relationship between Efficiency and Time (13.00-14.00)

In the third observation session which took place from 1.00 PM to 2.00 PM the intensity of sunlight (Lux) was recorded in the range of 65.03 to 75.58 Lux. These observations show that even though it is already daylight towards the afternoon. the sun's radiation is still quite high and stable. allowing the water heating system to continue to operate effectively.

Rising water temperature (ΔT) indicates a good response to radiation. The water temperature increased from 4.5˚C in the 5th minute to a maximum of 13.6˚C in the 55th minute. This increase is an indicator that collectors can still absorb heat energy effectively in the hours approaching the afternoon.

Solar radiation energy (Q_{rad}) showed an upward trend from 5.103 $\times 10^{-8}$ W/m² to 1.54224 $\times 10^{-7}$ W/m². with small fluctuations at several points. especially in the 30th minute which had shown a lower value. This is likely due to a momentary change in weather conditions (e.g. covered with thin clouds). which reduces the intensity of radiation directly to the collector.

Heat energy absorbed by water (Q_{water}) also experienced a significant increase from 226.044 Joules to a maximum of 683.155.2 Joules at the 55th minute. After that. the (Q_{water}). value decreased again to 617.853.6 Joules at the 60th minute. indicating a possible heat loss or a decrease in absorption efficiency due to the temperature starting to stabilize.

The efficiency of the system has increased consistently from 2.41% at the beginning of observation to reach a high value of 6.31% at the 55th minute. This was the highest efficiency achievement of all observation sessions conducted. indicating that the system performed optimally when radiation exposure and collector temperature were at a stable point.

The decrease in efficiency to 5.68% at the 60th minute even though the radiation value is still high can be explained through two possibilities: first. the temperature of the water has approached its heat saturation point.

so the heat transfer becomes less effective; and second. there is an increase in heat loss to the environment due to the higher temperature difference between the collector and the surrounding air.

Overall. this observation session corroborates the previous finding that a parallel-type solar water heating system with 6 collectors based on stainless steel pipes is able to absorb and utilize solar energy optimally even until 2 pm. The stable and high efficiency shows the great potential of this system to be applied on a household and light industrial scale as an alternative to clean and sustainable energy.

4. Conclusion

Based on the results of the tests and analyses carried out. the parallel-type solar water heating system with six flat plate collectors based on stainless steel pipes shows quite good performance. The significant increase in water temperature and the continuously increasing thermal efficiency value prove that the system is able to make optimal use of solar energy. The highest efficiency of 6.31% was achieved in the 55th minute of the session at 1.00 PM – 2.00 PM

The parallel configuration allows for an even distribution of water flow and an increase in radiation absorption area. although attention should be paid to the potential for heat loss at maximum loads. This system is very suitable for application in tropical areas with high radiation such as Pontianak. and has prospects for further development on a household or small industrial scale as a clean and sustainable energy-based water heating solution.

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