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Performance analysis of a solar cooker using aluminum and stainless steel containers

Siwan Perangin Angin*, Richard Napitupulu
Teknik Mesin, Universitas HKBP Nommensen, Medan, 20135, Indonesia
*Corresponding author: siwan.peranginangin@uhn.ac.id

Abstract
The utilization of solar energy can be adapted for household needs, such as powering electric stoves. Solar panels function as devices for converting heat into electricity, which is then used to power solar cookers as substitutes for LPG-powered stoves. This study was conducted at the Faculty of Engineering, HKBP Nommensen University, located on Jl. Sutomo No. 4A, Medan, North Sumatra, Indonesia. The objective of this study is to compare the performance of a solar cooker PV DC system using an aluminum cooking container to that of a solar cooker using a stainless steel container, with a focus on differences in the rate of temperature increase. The test results indicate that aluminum containers conduct heat more efficiently than stainless steel containers. In an experiment on heating 2 liters of water, the rate of temperature increase in an aluminum container is 1.01°C per minute, compared to 0.91°C per minute in a stainless steel container. The thermal conductivity of aluminum is approximately 205 W/m°C, with a density of 2.7 g/cm³, whereas stainless steel has a thermal conductivity of 15–25 W/m°C and a density of 7.8 g/cm³. The highest average solar radiation recorded during the test was 424.1 W/m². The solar cooker successfully cooked potatoes to a normal level in 48 minutes, from 14:26 to 15:13 on August 3, 2024, reaching a final temperature of 100.1°C, under the lowest average radiation of 216.22 W/m². In another test, 104 grams of potatoes were cooked in 35 minutes, with the temperature increasing at a rate of 1.62°C per minute in the aluminum container, reaching a final temperature of 103°C. In contrast, the stainless steel container had a rate of 1.31°C per minute and reached a final temperature of 91.3°C. The test also demonstrated that battery voltage significantly impacts cooking efficiency, as it influences the power required for cooking materials, such as water.

Keywords:
Photovoltaic, solar cooker, solar energy, solar radiation.

1 Introduction

According to government regulations and presidential decrees from 2006 to the issuance of the Indonesian Presidential Regulation No. 112 of 2022 on the Acceleration of Renewable Energy Development to reduce greenhouse gas emissions, solar energy can become an alternative energy source to reduce the use of environmentally harmful fossil fuels [1].

One of the major contributors to emissions is cooking. This is evident from the low pollution-free cooking practices in regions such as Africa, Asia, and Central and South America. As a result, the number of people suffering from the adverse effects of environmentally harmful cooking practices is significant**:** 71% in Africa, 41% in Asia, and 11% in Central and South America [2]. Observations in Africa show the impact of traditional cooking methods, causing 85% of the local population to be displaced to camps due to emissions of 14.3 million tonnes of CO_2 in 2014 [3]. One of the alternatives to mitigate the pollution from the household sector is the use of solar cookers.

The use of solar cookers has been shown to reduce emissions and greenhouse gases compared to cooking systems using fossil fuels, biomass, gas, and other energy sources that rely on combustion to generate energy, especially in developing countries like Africa, Asia, and Indonesia [4][2]. Not only do solar cookers have low emissions, but their implementation can also help areas still dependent on biomass fuels such as firewood, tree branches, and others. This can reduce deforestation caused by the demand for cooking fuel, thereby contributing to environmental preservation [5]. Generally, solar cooking systems have two types: direct systems and indirect systems [6].

Previous research has demonstrated that solar energy development and application have been ongoing for years to improve the efficiency and performance of solar cooking systems. With innovation and design development, performance has been improved by adding Phase Change Materials (PCM) as thermal energy storage in solar heating units, making solar cookers more effective and efficient [7][20]. For example, in previous studies, researchers designed a trapezoidal solar cooker shape and added a reflector that is easy to obtain and inexpensive, resulting in faster cooking times—about 2 hours faster compared to the box-type solar cooker [3]. Similarly, other studies tested a box-type solar cooker with three-sided reflectors made of aluminium and glass. The results showed higher temperatures and efficiency with reflectors, achieving 16.8% efficiency without a reflector, 23.5% with an aluminium reflector, and 39.4% with a mirror glass reflector [8]. Performance improvements in solar cookers were also made by varying the reflector type to a funnel shape with different opening sizes of 60%, 70%, 80%, 90%, and 100%. The results showed that a 100% opening could reach temperatures up to 180°C when the solar radiation was at its peak of 1100 W/m² [9].

Increased performance of solar cookers has also been achieved by adding PCM material (stearic acid) as thermal energy storage and using four reflectors, which significantly increased the solar radiation exposure to PCM by 42.3%. This led to an improvement in efficiency from 19.04% to 22.3% and reduced cooking time to 15.7 minutes per kilogram [10][11]. Further research compared two configurations of the Haines 2 solar cooker (blue and red) and studied the effect of the reflector's tilt angle. The findings showed that the angle of tilt significantly affects the solar cooker's performance [12]. Not only direct systems, but many studies have also investigated the effectiveness of solar cookers that utilize electricity generated by solar panels, which is then stored in batteries to power AC- or DC-electric cookers [13]. A study with varying voltage outputs of 24V 11.5A and 75V 5A showed that both systems were able to cook food with an average power consumption of 375 watts [14]. Similarly, in 2024, researchers tested a DC solar cooker system powered by solar panels and compared its performance with a parabolic solar cooker. The results showed that the solar PV DC cooker performed well, even with fluctuating weather and solar radiation between 200-1200 W/m², whereas the parabolic cooker was heavily influenced by weather conditions and solar intensity [4].

The materials used for the cooking vessel also determine the efficiency of the solar cooker. Typically, materials such as aluminium and stainless steel are used for cooking vessels as they are food-grade and tested for cooking purposes. The materials used in solar cooking vessels should have good thermal conductivity to transfer heat efficiently. Metals like aluminium are often preferred because of their high thermal conductivity, allowing for faster heat transfer [17]. Solar cooker vessels are exposed directly to sunlight and external weather conditions. Therefore, the material must be resistant to high temperatures, UV radiation, and moisture, which can accelerate degradation. Materials like stainless steel or tempered glass are commonly used due to their durability against these weather elements [18]. These two materials are the most suitable and commonly used for cooking vessels.

This forms the basis of this study, which aims to compare the performance of a DC PV solar cooker using aluminium material versus stainless steel material. How significant is the difference in performance between the two when tested under the same conditions is.

2 Research Methods

The research was conducted at the Mechanical Engineering Laboratory, Faculty of Engineering, HKBP Nommensen University, Jl. Sutomo No. 4A, Medan, North Sumatra. The research scheme is shown in Fig. 1.

Fig. 1 shows the research scheme and the data collection points. The test points are: (1) photovoltaic solar panel, (2) solar charge controller, (3) battery, (4) inverter, (5) solar cooker PV 1 (stainless steel), (6) solar cooker PV 2 (aluminum), (7) temperature data logger, and (8) automatic weather station to measure solar radiation (Watt/m²). For temperature data collection, the points are indicated as T1-T8 (Table 1).

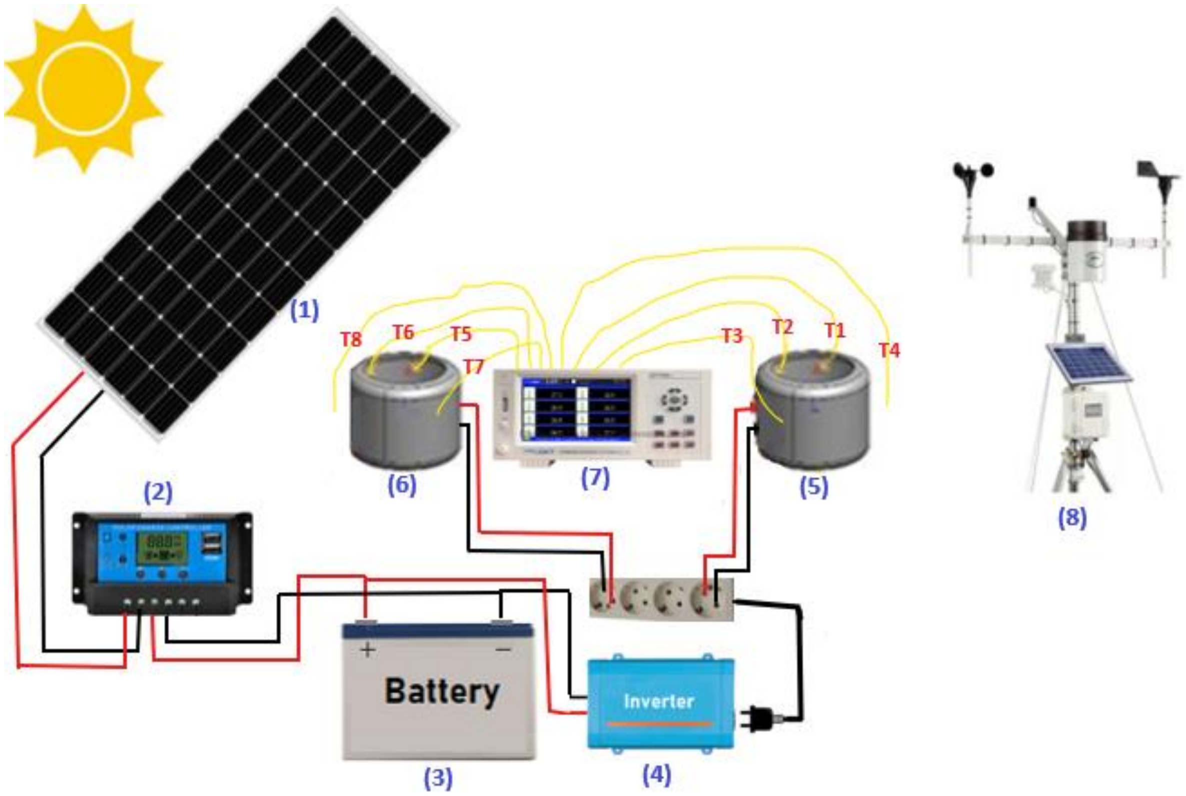

Fig. 1. Research scheme.

Table 1. Variables observed during testing on Solar Cooker I and Solar Cooker 2 units

Thermocouple	Description	Unit
T1	Temperature of fluid in SC 1	^{0}C
T2	Temperature of the inner wall SC 1	^{0}C
T3	Temperature of the outer wall SC 1	^{0}C
T4	Temperature of the surrounding air SC 1	^{0}C
T5	Temperature of fluid in SC 2	^{0}C
T6	Temperature of the inner wall SC 2	^{0}C
T7	Temperature of the outer wall SC 2	^{0}C
T8	Temperature of the surrounding air SC 2	^{0}C
AC current		A
AC voltage		Volt
AC power		Watt
DC voltage from PV		Volt
Solar radiation		W/m^2

2.1 Testing Procedures

The research procedures carried out include preparing research tools and assembling each component and measuring instrument. Testing the performance of the tool with variations in the amount of water with 1000 ml, 1500 ml, 2000 ml, and boiling potatoes. The intensity of solar radiation and the condition of the battery used during the study then record the results. The test conditions are shown in Fig. 2.

Each test was conducted until the water temperature in the container reached 100°C. The data collection interval was set at 1 minute. For each observed variable, data were recorded, including temperature (°C), solar radiation (W/m²), electric current (A), and voltage (V).


Fig. 2. Experiment setup.

Fig. 3 shows the placement of the Voltmeter and Ammeter measuring instruments. Fig. 4 shows the research flow diagram.


Fig. 3. Setup of measuring instrument experiments.

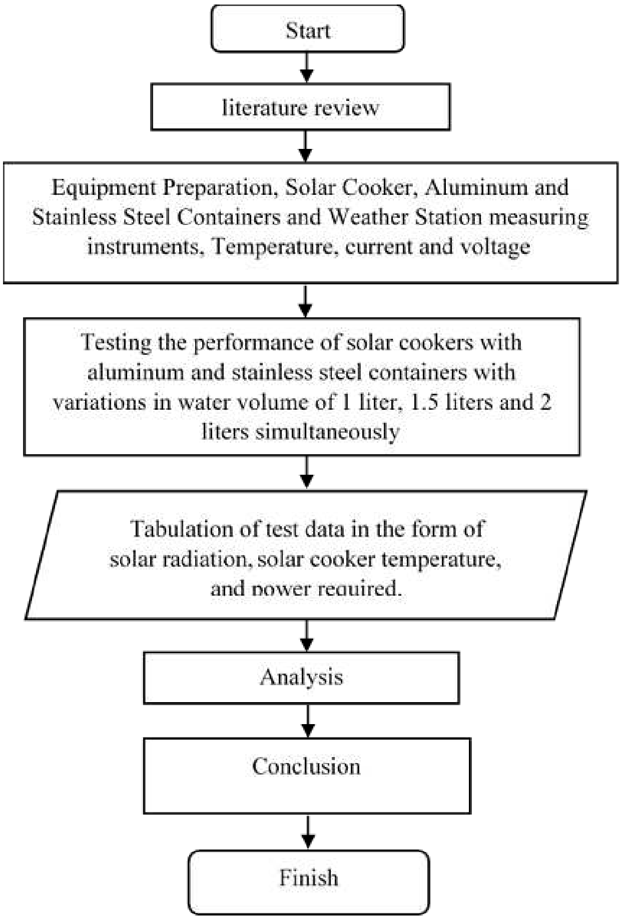

Fig. 4. Flow chart.

2.2 Thermal Performance Parameters

The electric heating power supplied to the solar cooker is calculated as the product of voltage and electric current, as shown in the Eq. 1 [4].

$$p_E = VI \quad (1)$$

Where V is the measured voltage, and I is the measured current. The power required for heating the water (P_W) to reach the boiling point of 100°C is calculated as Eq. 2 [4].

$$p_w = \frac{m_w c_w (T_{fw} - T_{iw})}{\Delta t} \quad (2)$$

Where m_w is the mass of the water being heated, c_w is the specific heat capacity of water, T_{fw} is the final temperature of the water, T_{iw} is the initial temperature of the water, and Δt is the duration of the heating. Thus, the heating efficiency can be estimated as shown in the Eq. 3 [4][15][16].

$$\eta_w = \frac{p_w}{p_E} = \frac{\frac{m_w c_w (T_{fw} - T_{iw})}{\Delta t}}{VI} \quad (3)$$

3 Results and Discussion

3.1 Results of Temperature, Power and Solar Radiation Tests for 1 Liter Water Load

During the cooking process, SC2 proved to be more effective in heating water compared to SC1. As shown in Fig. 5, at T5, the temperature of the material while cooking with SC2 increased more rapidly than at T1 for SC1. Specifically, the temperature at T5 reached 100.6°C, while at T1, it was only 91.6°C for other temperature comparisons between SC1 and SC2, SC2 consistently recorded higher temperatures than SC1. This can be observed from the final temperatures at the end of the testing: inner wall temperature of the pot: T6 (97.3°C) > T2 (86.3°C), outer wall temperature of the pot: T7 (43°C) > T3 (38.7°C), ambient temperature around the solar cooker: T8 (35.2°C) > T4 (33.8°C). These differences can be seen in Fig. 5. The significantly lower temperature on the outer wall of the pot compared to the inner wall is due to the thermal insulation provided by the rock wool material, which effectively reduces heat transfer. Consequently, T2 and T6 are much higher than T3 and T7. Additionally, the ambient temperature near the solar cooker (T8) is slightly closer to the outer wall temperature because it is located near that area.

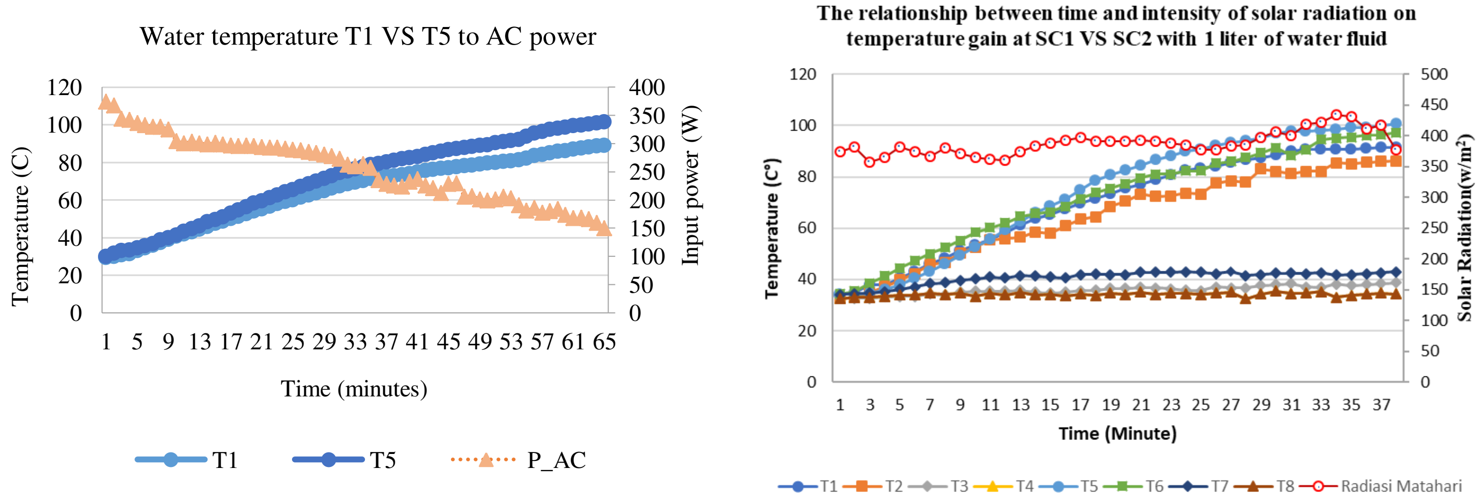

Fig. 5. The graph illustrates the relationship between time and solar radiation intensity with the temperature increase in the solar cooker system using 1 liter of water as the fluid.

For more details on the comparison of water temperature from T1 and T5, T5 is faster than T1 when cooking water. It can be seen that each has an average increase in temperature T1 is 1.51°C/minute while T5 is 1.74°C/minute. Due to the difference in material from the solar cooker pan used from SC1 and SC2, it is different from the SC1 material, which is stainless steel and aluminum for SC2. For the intensity of solar radiation, it is still relatively stable, as can be seen from the linear line of solar radiation in Fig. 6. The highest intensity of solar radiation was obtained at minute 34 with a solar radiation intensity value of 434.4 W/m^2, the average solar radiation during the test was 395 W/m².

Fig. 7 shows that the output power consistently decreases during the study. The graph exhibits a downward trend due to the declining battery power over time during the testing process. The average output power is approximately 216.3 W.

Fig. 8 shows a slowdown in temperature rise from the 19th minute to the 38th minute. This is due to the gradual reduction in battery power and output power during testing. The average rate of AC power reduction is 6.08 W/min.

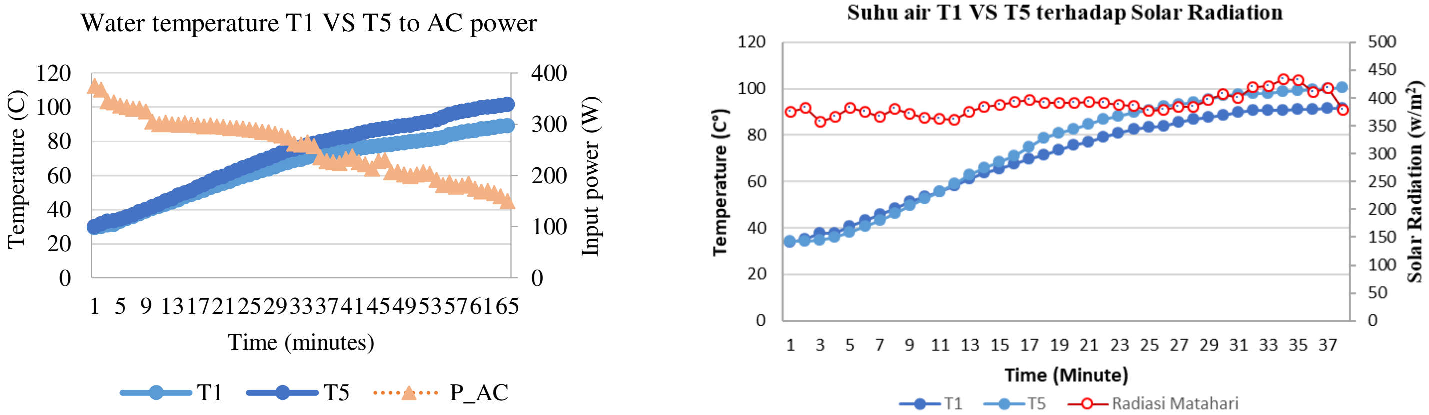

Fig. 6. Comparison graph of water temperature SC 1 (T1) vs water temperature SC 2 (T5) against solar radiation when cooking.

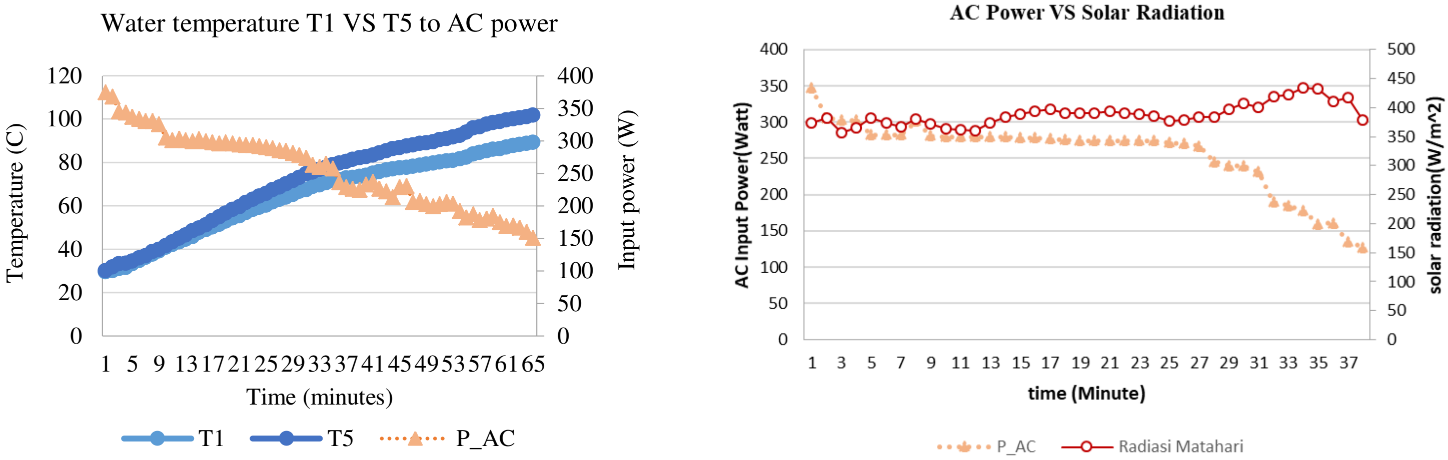

Fig. 7. Input power graph against solar radiation.

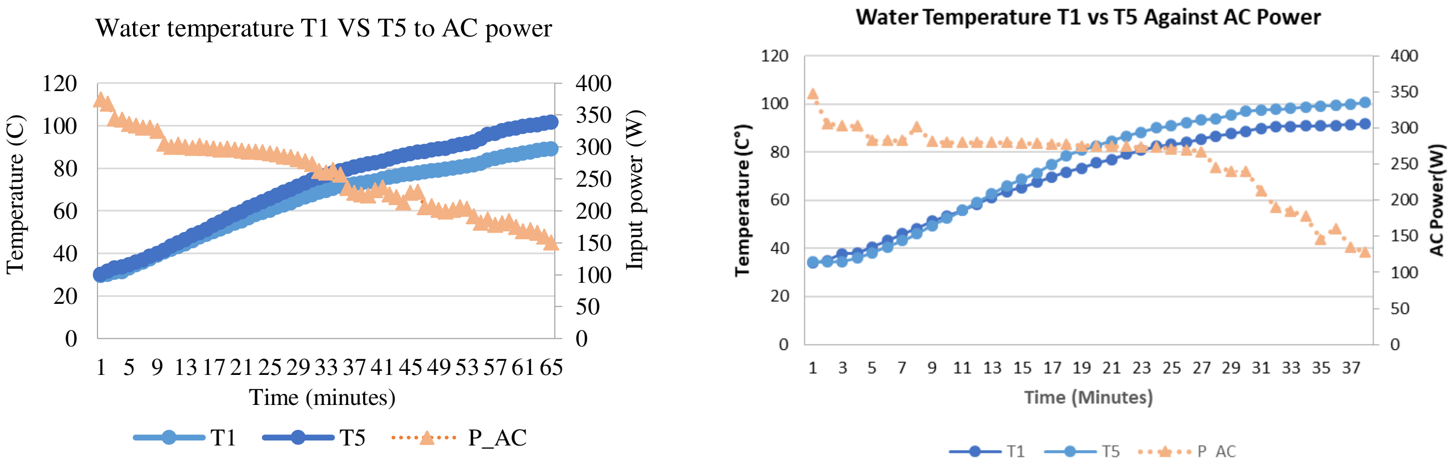

Fig. 8. Comparison chart of water temperature T1 vs T5 against AC power.

3.2 Analysis of SC1 Vs SC2 Measurement Results with 1.5 Liters of Water

The temperature measurements received by the system were taken every 1 minute using predetermined materials, specifically cooking 1.5 liters of water on solar cookers SC1 and SC2. The initial temperatures were T1 = 29.8^{0}C and T5 = 28.5^{0}C at the start of the testing. Temperature measurements for each solar cooker (SC1 and SC2) were conducted at four different points: the cooking surface in contact with the material, the inner part of the pot, the outer part of the pot, and the ambient temperature around the cooker. These measurements were carried out on July 10, 2024, from 10:58 AM to 11:55 AM.

When cooking SC2 is more effective in cooking water than SC1 in Fig. 9 shows that at T5 the water temperature when cooking SC2 experiences a faster temperature increase than T1, the water temperature when cooking SC1 on the solar cooker system, namely the temperature T5 = 100.3°C compared to T1 only 89.8°C. For other temperature comparisons from SC1 vs SC2, the temperature on SC2 is always higher than SC1 as seen from the final temperature when the test is finished for the temperature on the outer wall, it has a much smaller temperature than the temperature on the outer wall due to the thermal insulation of the rock wool material that inhibits heat T2, T6> T3, T7 and for the ambient temperature of the solar cooker, it has a temperature slightly almost the same as the temperature on the outer wall because it is near that point. It can be seen from Fig. 9 that the temperature on the inner wall of the pan T6 (95.4°C) > T2 (84.2°C), for the temperature on the outer wall of the pan T7 (44.1°C) > T3 (41.5°C), and for the ambient temperature around the solar cooker T8 (35.7°C) > T4 (33.7°C).

Fig. 10 shows a comparison of water temperature from T1 and T5. T5 is faster than T1 when cooking water, seen from the average increase in temperature; T1 is 1.03°C, while T5 is 1.23°C. Due to the difference in material, the solar cooker pan used from SC1 and SC2 is different from the SC1 material, which is stainless and aluminum for SC2. For the intensity of solar radiation, an increase in the intensity of solar radiation can be seen from the linear line of solar radiation, which is showing an upward trend in

Fig. 10. The highest intensity of solar radiation was obtained at minute 57 with a solar radiation intensity value of 431.9 W/m^2, the average solar radiation during the test was 281 W/m².

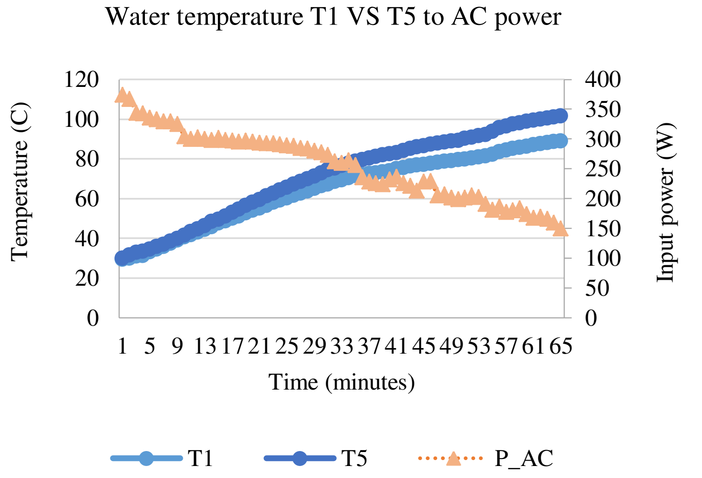

Fig. 9. The graph depicting the relationship between time, solar radiation intensity, and the temperature gain of the solar cooker's pot system using 1.5 liters of water.

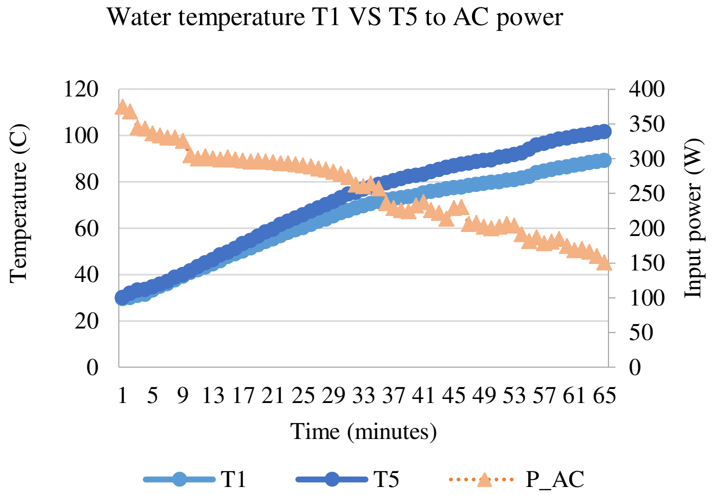

Fig. 10. Comparison chart of temperature T1 vs T5 against solar radiation.

As shown in Fig. 11, the temperature increase slows down from minute 34 to minute 58. This is due to the gradual reduction in battery power and the corresponding decrease in output power during the testing. The average rate of power reduction is 3.59 W/min.

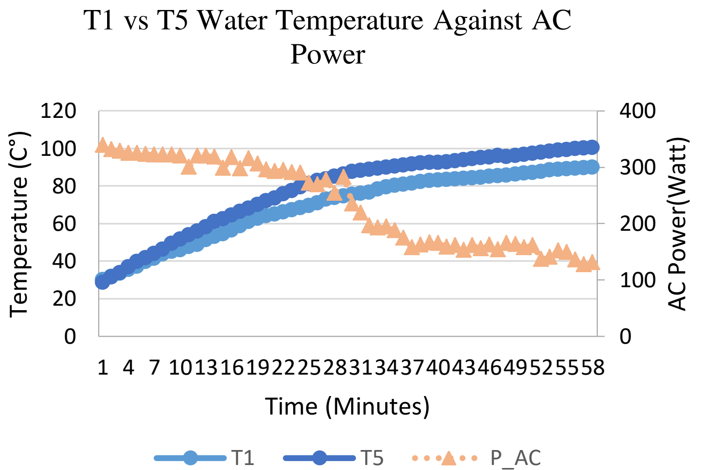

Fig 11. Comparison chart of T1 vs T5 temperature against AC power

If seen from Fig. 12, the graph of the AC input-output power always experiences a decrease in power during the study; the line appears to have a line direction that tends to decrease due to the reduced battery power that accompanies the time when testing. The average AC output power is around 234.9 W.

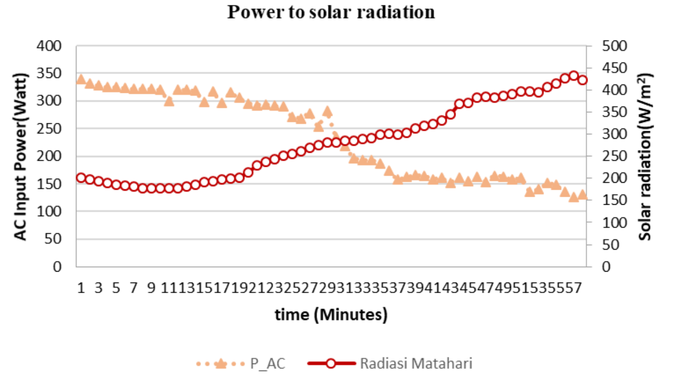

Fig. 12. AC Input output power and solar radiation graph.

3.3 Data Analysis of SC1 Vs SC2 Measurement Results with 2 Liters of Water

The temperature measurement received by the pan system is carried out every 1 minute using the specified material, namely cooking with 2 liters of water on SC1 and SC2 starting from Temperature T1 = 29.4°C and T5 = 29.9°C during testing. Temperature measurements on each solar cooker pan, namely SC1 and SC2, are carried out at 4 different points, namely in the pan area of the material when cooking, the inside, the inside, and the room temperature around the pan. This measurement was carried out at 11.36 - 2:40 PM Using 3 panels with an initial battery of 13.85 after testing 12.54.

When cooking, SC2 is more effective in cooking water compared to SC1. Fig. 13 shows that at T5 the temperature of the material when cooking SC2 experiences a faster increase in temperature compared to T1, the temperature of the material when cooking SC1 in the solar cooker system, namely the temperature T5 = 101.5°C compared to T1 which is only 89°C. For other temperature comparisons of SC1 vs. SC2, the temperature at SC2 is always higher than SC1 as seen from the final temperature when the test is finished. For the temperature on the outer wall, it has a much smaller temperature than the temperature on the outer wall due to the thermal insulation of the rockwool material that inhibits heat. T2, T6> T3, T7 and for the ambient temperature of the solar cooker, it has a temperature that is slightly almost the same as the temperature on the outer wall because it is near that point. It can be seen from Fig. 11 that the temperature on the inner wall of the pan T6(100.6°C)> T2(88.3°C), for the temperature of the outer wall of the pan T7(43.5°C)> T3(42.3°C), and for the ambient temperature around the solar cooker T8(37.5°C)> T4(36.8°C).

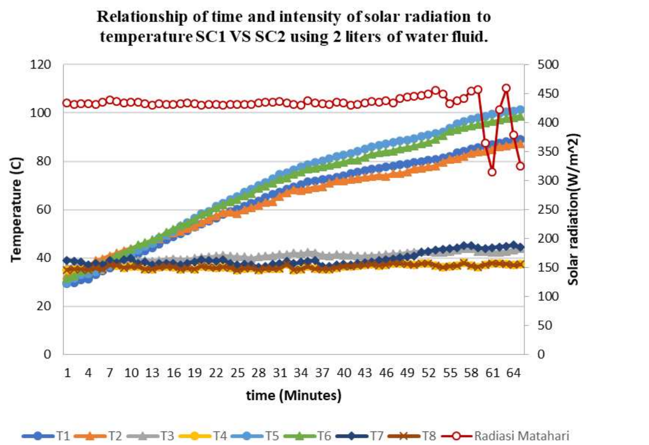

Fig. 13. Graph of the relationship between time and intensity of solar radiation on the temperature obtained by the solar cooker pan system using 2 liters of water fluid.

Fig. 14 shows a comparison of water temperature from T1 and T5, T5 is faster than T1 when cooking water. It can be seen from the temperature of each having an average increase in temperature. T1 is 0.91°C while T5 is 1.01°C. The effect of the difference in the speed of temperature increase due to the difference in material from the solar cooker pan used from SC1 and SC2 is different from the SC1 material, which is stainless steel and aluminium for SC2. For the intensity of solar radiation, stable radiation is shown and from the line of solar radiation, which is showing a flat trend, the lowest radiation is 314.4 W/m^2. The highest intensity of solar radiation was obtained in minute 63 with a solar radiation intensity value of 459.4 W/m^2 and the average solar radiation during the test was 424.1 W/m².

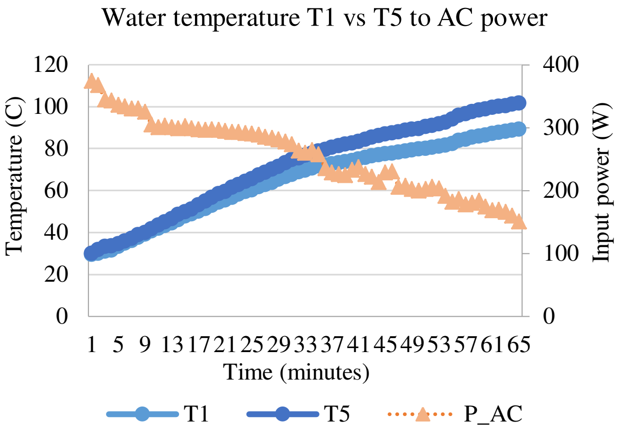

Fig. 14. Comparison chart of water temperature T1 vs T5 against solar radiation.

If seen from Fig. 15, the graph shows that the AC input-output power always experiences a decrease in power during the research; the line appears to have a line direction that tends to decrease due to the reduced battery power that accompanies the time when testing. The average AC power is around 255.02 watts.

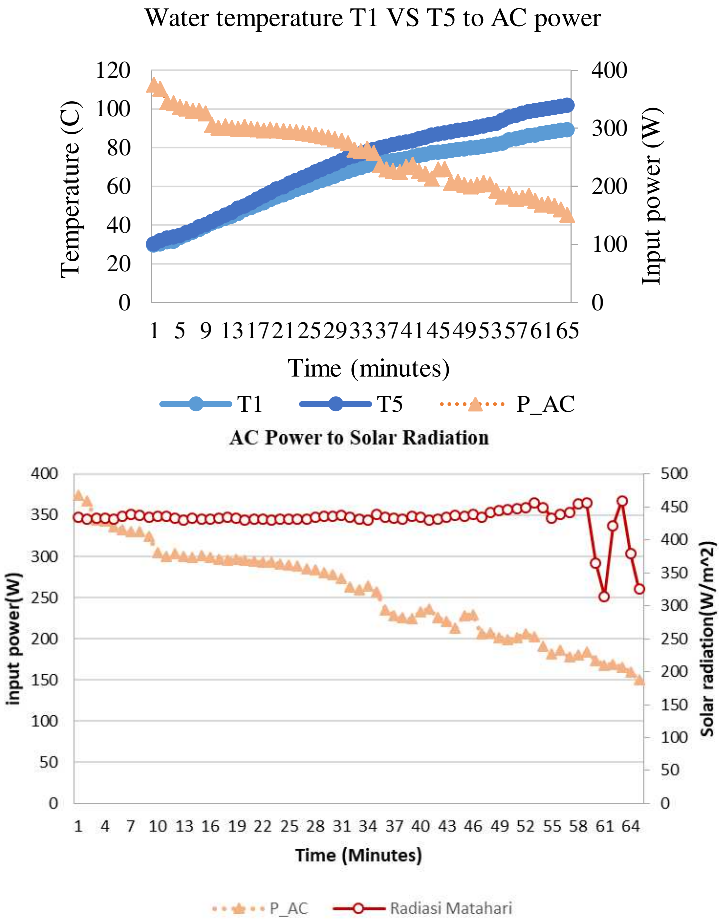

Fig. 15. Radiation power comparison graph.

As seen in Fig. 15, there is a slowdown in the temperature increase from minute 34 to minute 65. This is because every minute there is a reduction in battery power and a reduction in output power during testing. The speed of the AC power reduction for 65 minutes is 3.44 W/minute.

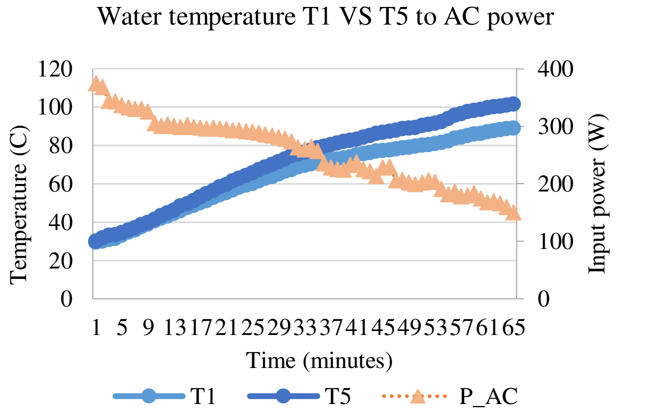

Fig. 16. Comparison chart of T1 vs T2 temperature against AC power.

4 Conclusion

From the research results, it was found that the solar cooker using aluminum containers is better at conducting heat than stainless steel, as can be seen from the tests carried out, such as when cooking 2 liters of water in aluminum, the temperature increase rate is 1.01°C/minute from stainless steel, which only has a speed of 0.91°C/ min. This is because aluminum has a much higher thermal conductivity than stainless steel. The thermal conductivity of aluminum is around 205 W/m°C and its density (around 2.7 g/cm³), while stainless steel is only around 15-25 W/m°C [19]. Likewise, with its density (around 7.8 g/cm³) lower density means aluminum is lighter for the same volume, which can be an advantage in the cooking process.

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