Solar Thermoelectric Generator Prototype with Flat Black Color Coating on Copper Plate Heat Absorber

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Abstract – Solar Thermoelectric Generators (STEGs) present a promising avenue for renewable energy production by converting solar heat into electricity. This study investigated the impact of a black coating on a copper heat absorber plate on STEG performance. A prototype incorporating eight TEG SP 1848-27145 SA modules connected in series was constructed for this experimental study. Copper plate temperature, voltage, and current were measured and analyzed using descriptive statistics and graphical representations. Results demonstrate that the black coating significantly elevated the copper plate temperature from 47.04°C to 49.14°C. This thermal enhancement led to improved thermoelectric performance, as evidenced by increased voltage from 5.54 V to 6.27 V and current from 50.64 mA to 63.73 mA. These findings confirm that a black coating on the copper heat absorber is an effective, low-cost strategy for enhancing the efficiency of solar-to-electric energy conversion in STEG prototypes.

Keywords: solar thermoelectric generator, copper heat absorber plate, flat black color coated

I. INTRODUCTION

Humanity stands at a crossroads marked by unprecedented advancements and formidable challenges. Central to these is the accelerating phenomenon of global climate change. This multifaceted crisis is manifested in rising global temperatures, intensified extreme weather events, and a proliferation of natural disasters. Empirical evidence conclusively demonstrates an upward trend in the frequency and severity of heatwaves, wildfires, droughts, and floods [1].

The international community has acknowledged the urgency of this issue, culminating in the Paris Agreement. This landmark accord sets forth ambitious goals to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels [1]. A cornerstone strategy for achieving these targets is the accelerated transition to renewable and sustainable energy sources. By supplanting fossil fuels, renewable energy offers a viable pathway to reducing greenhouse gas emissions and attaining carbon neutrality.

Solar energy, in particular, presents a vast and untapped resource with the potential to significantly contribute to this global endeavor. Solar energy has enormous potential to be utilized, especially in Indonesia which has a relatively long and stable duration of daylight throughout the year. The potential for renewable energy derived from solar energy in Indonesia is 207,898 MW assuming 4.8 kWh/m2 per day [2]. Thermoelectric technology emerges as a promising avenue for harnessing the solar thermal energy and converting it into electricity.

Thermoelectric generators (TEGs) harness the Seebeck effect to convert thermal energy into electrical energy. This phenomenon arises from the differential electrical conductivity exhibited by distinct semiconductor materials, namely n-type and p-type. N-type semiconductors possess an excess of free electrons, enhancing their electrical conductivity relative to insulators. Conversely, p-type semiconductors exhibit a deficiency of free electrons, leading to lower electrical conductivity [3].

When a p-n junction is exposed to a heat source, a temperature gradient is established across the junction. This thermal disparity induces the migration of charge carriers within the semiconductor material. Consequently, an internal electric field is generated within each semiconductor type. In n-type materials, electrons migrate from the hotter region towards the cooler region, resulting in a negative charge accumulation at the cold junction and a positive charge at the hot junction. Simultaneously, in p-type materials, holes move from the cold to the hot side, creating a positive charge at the cold junction and a negative charge at the hot junction. The opposing internal electric fields within the n-type and p-type semiconductors combine to produce an electromotive force, manifesting as a voltage difference. Upon connecting the TEG to an external circuit, this potential difference drives an electric current from the hot to the cold side through the external load [3].

In STEG, the conversion of thermal energy into electrical energy is highly dependent on the ability of the heat-absorbing plates to capture and absorb thermal energy from the sun. Copper has a high thermal conductivity, but has a relatively low surface absorptivity and emissivity when compared to the black color. A shiny surface not only emits less radiation, but also absorbs less radiation that hits it. Thus, a good absorber is also a good emitter. Absorptivity refers to the ability of a material to absorb radiant energy [4]. The higher the absorptivity value, the more heat energy is absorbed by the material. Other than absorptivity, emissivity refers to the ability of a material to emit infrared energy, which in STEG, plays a role in the absorption and release of solar heat emission.

Previous investigations have explored STEG development. Yulong Zhao et al. [5] demonstrated that elevated car exhaust temperatures can boost STEG power output. Muhammad Irfan et al. [6] evaluated a STEG model using a charcoal combustion furnace, achieving a voltage of 0.5V and current of 0.03mA under a 9°C temperature difference.

Zhiwei Xuan et al. [7] concluded that Fresnel lens-based heat concentration offers limited effectiveness in STEG systems. Muhammad Ady Pradana et al. [8] reported superior voltage and current outputs with brass hot sectional plates and series-connected modules compared to aluminum and zinc alternatives. Nazaruddin et al. [9] identified black-colored zinc roofs as exhibiting optimal solar heat absorption. Deo Dwi Cahya et al. [10] observed increased voltage and current generation from a black-plated brass heat-absorbing plate in a STEG configuration.

The calculation of the output voltage on a prototype Solar Thermoelectric Generator (STEG) is an important step in assessing the performance of the system. The formulas used for this calculation are based on the principles of physics and the material characteristics of thermoelectric elements.

In an open circuit state where there is no current flowing through the circuit, the voltage is determined using Equation 1 below.

$$V_{OC} = \propto (T_H - T_C) = \propto \Delta T \qquad (1)[11]$$

In equation 1 is the calculation of the V_{OC} or output voltage under opencircuit conditions determined in Volts, where $\propto$ is the Seebeck coefficient in V/K, T_H is the temperature of the hot side of the thermoelectric generator in Kelvin, T_C is the temperature of the cold side of the thermoelectric generator Kelvin, ΔT is the difference temperature between the hot side and the cold side in Kelvin.

Based from description above, this research aims to enhance a Solar Thermoelectric Generator (STEG) prototype. The proposed improvement involves applying a black coating to the copper heat-absorbing plate on the hot side. Simultaneously, a heat sink immersed in ice water will serve as the cold side, amplifying the temperature differential across the thermoelectric module.

II. METHODS

This research employs an experimental and quantitative approach. A prototype Solar Thermoelectric Generator (STEG) was constructed utilizing copper heat absorption plates coated with black paint. The primary objective of this study is to conduct a comparative analysis of the average copper plate temperature, voltage, and current generated by the STEG prototype before and after the application of the black coating.

Hardware Design

The hardware and system design of the STEG prototype is based on the results of the literature study. This design includes material selection, component dimensions, module circuit configuration, and load circuit configuration.

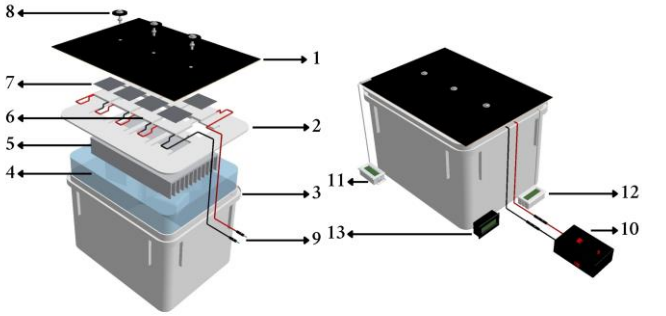

Figure 1. Hardware design of STEG with black color

As shown in Figure 1 is the hardware design of the STEG prototype with a copper plate coated with black color. the description based on the figure is described: 1. copper plate coated with black color; 2. acrylic board; 3. plastic container; 4. ice water; 5. heatsink; 6. thermoelectric generator module circuit; 7. thermal paste layer; 8. bolt and nut set; 9. jumper cable; 10. external load; digital thermometer to measure: 11. copper plate temperature; 12. ice water temperature; 13. surrounding environment. The specifications of tools and materials used are shown in Table 1.

Table 1. Tools and material specifications

Name	Spesicitaion		Qty
Multimeter digital Constant 50	0.2-600 VDC		1
	0,0002-10 A		
	100-2M Ω		
Thermometer digital TPM-10	from -50 up to 110°C		3
TEG SP 1848-27145 SA	up to 3,3 V while ΔT 91°C		8
Copper plate	27 × 20 × 0.1 cm		
Acrylic 3mm	21 × 27 cm		1
Heatsink	19.6 × 12 × 3.4 cm		1
Water container	19.5 × 25.5 × 17.5 cm		1
Load container	7.5 × 5 × 2.5 cm		1
Red LED	5mm		1
Resistor	1k Ω		1
Switch	3A	250 VAC	2
Jumper cable	30 cm		q.s.
Thermal Paste GD900	4.8 W/mK		
	from -50°C up to 200°C		
Pylox paint	black flat color		1

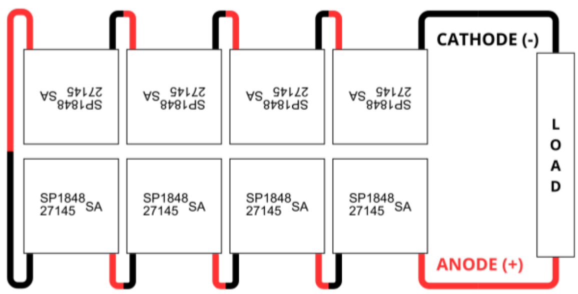

Figure 2. STEG and load circuit configuration

As shown in Figure 2, the circuit configuration of the 8 pieces thermoelectric generator module type TEG SP1848-17145SA assembled in series connected to the load circuit. The load is a 5mm red LED and a 1k ohm resistor. This load is separate from the main circuit and can be easily removed using jumper cables.

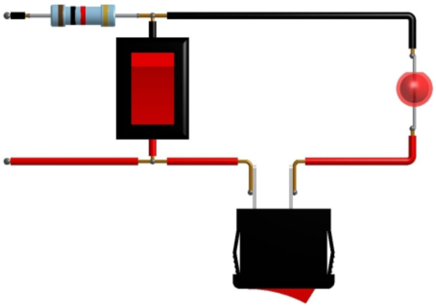

Figure 3. Load circuit configuration

As shown in Figure 3, the load system in this study is designed with two different conditions, where each condition is controlled by two switches to regulate the flow of current to the load.

Design System

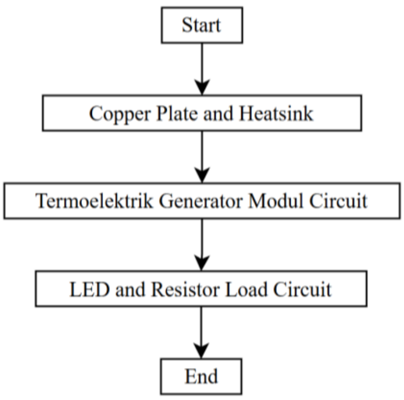

Figure 4. STEG block diagram system

Based on Figure 4, it can be explained that the process begins when the prototype operates with the hot side of the Thermoelectric Module Generator (RMTEG) circuit receiving solar heat that has been absorbed by the copper plate and the cold side of the RMTEG receiving cold through the heatsink obtained from the convection airflow of the prototype cooling media. Then, the circuit of the thermoelectric generator module performs energy conversion through the Seebeck effect so that it outputs electricity in the form of voltage. When connected to the load, there is a voltage and current flowing through the load in the form of a red 5mm LED circuit and a 1k ohm resistor.

Experiment and Measurement

The experiment was conducted for 10 days and divided into two conditions, days 1-5 using normal copper plates and days 6-10 using copper plates that have been coated with black color. Measurement of research variables was carried out periodically every hour, starting at 08.00 to 16.00 WIB. The temperature measured using a TPM-10 digital thermometer and the electrical measured using a Constant 50 digital multimeter. The variables measured during the test include the prototype hot side temperature (TH), prototype cold side temperature (TC), environmental temperature around the prototype during testing (TS), output voltage (V), and output current (I).

Data Analysis Techniques

After the measurement data from the prototype Solar Thermoelectric Generator (STEG) test results were obtained, data processing was carried out to produce the temperature difference value between the hot side and the cold side of the prototype (ΔT) which was then integrated into the measurement data. Then, the data was grouped into every hour for more detailed analysis.

The data analysis technique used in this research is divided into two main stages, namely descriptive analysis and data visualization. Descriptive analysis is used to describe the characteristics of the data collected. Descriptive analysis techniques used in this research include minimum and maximum values to show the range of data values, average (mean) as a value that represents a set of measurement data and standard deviation to measure how dispersed the data is from its average value. The measurement and analysis results are then compared between before and after the addition of black color. Then, the next step is to visualize the data to facilitate interpretation and understand the patterns in the data. The data visualization technique used in this research is a graph. The graph used is a line graph to illustrate data trends over time.

In addition to descriptive analysis and visualization using graphs. To analyze the test data, the Seebeck coefficient calculation based on Equation (1) will be carried out and then substituted to estimate the output voltage of the prototype. The measurement data used in the calculation is the data that has the highest voltage value every hour. The results of this theoretical calculation will be compared with the experimental measurement data. This comparison is done to evaluate the extent to which the theoretical model used can predict the actual performance of the STEG prototype.

III. RESULT AND DISCUSSION

STEG Prototype

The assembly process involves process installing components of Solar Thermoelectric Generator prototype based on the design that has been made.

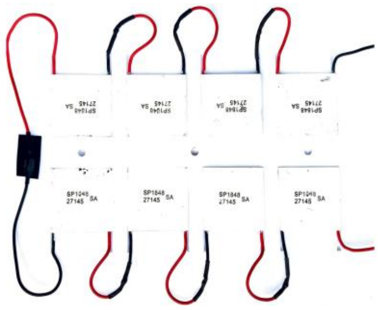

Figure 5. Modules circuit assembly result

As shown in Figure 6, TEG SP1848-27145SA modules are integrated in series using the soldering method, then applied heat shrink at the junction point to minimize being exposed to water splashes while the prototype is working.

Figure 6 is the result of the assembly of the overall components into a prototype based on the hardware design that has been determined in the prototype system design section. Figure (a) shows the STEG prototype from the outside (b) is the STEG prototype looking inside.

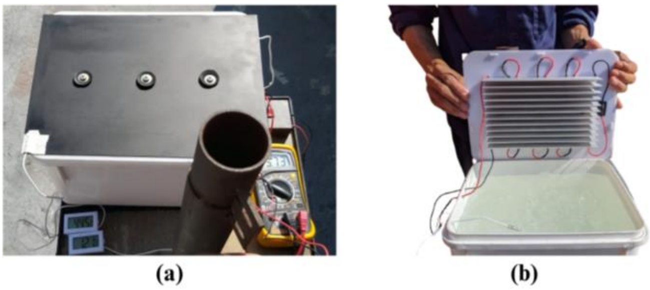

Figure 6. STEG Prototype assembly result (a) view from above STEG (b) inside view from STEG

Result

This section describes the comparison of copper plate temperature (TH), voltage (V), and current (I) based on measurement data obtained from testing the STEG prototype. The average measurement results of the copper plate temperature before and after the addition of black color are analyzed and then compared, presented in table 1.

Table 2. Average comparison of copper plate temperatures

Time (WIB)	T_H before (ºC)	T_H after (ºC)
08.00	39,28	41,54
09.00	43,74	45,2
10.00	47,46	53,36
11.00	53,8	57,12
12.00	53,28	57,02
13.00	54,16	56,86
14.00	49,18	51,48
15.00	43,94	41,78
16.00	38,52	37,98
Mean	47,04	49,1488

As shown in Table 2, a comparison of the mean temperature of the copper plate before (T_H b) and after (T_H a) the addition of black color to the copper plate. The total mean value of the copper plate temperature increased from 47.04°C to 49.1488°C after the addition of black color. This shows that there is an increase in the mean value of the copper plate temperature by 2.1088°C. This increase indicates the effect of black color coating on copper plate temperature. The results of the analysis of the mean temperature of the copper plate before and after being coated with black are visualized in the form of a graph in Figure 7. Graphical comparison of the average temperature of the copper plates before (T_H before) and after (T_H after) the addition of black color coating to the copper plates. Based on the graph, it can be seen that in general, the addition of black color to the copper plates increases the average hourly temperature of the copper plates. The temperature pattern of the copper plates in both conditions is in the form of an upward curve from morning to midday and then decreases in the afternoon. The average value of copper plate temperature in the condition after the addition of black color is higher than the condition before the addition of black color at almost all measurement times. There is a decrease in temperature in the afternoon (3:00 pm and 4:00 pm) in the condition after the addition of black color.

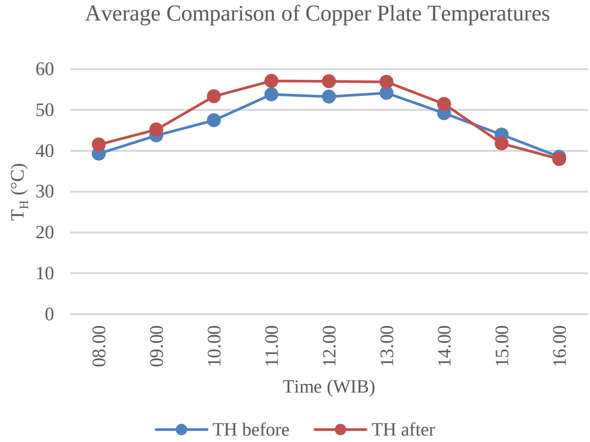

Figure 7. Graphical comparations of the average temperature of the copper plates

The average measurement results of the prototype output voltage and current before and after the addition of black were analyzed and then compared, presented in table 2.

Table 3. Average comparison of voltage and current output

Time (WIB)	V before (V)	V after (V)	I before (mA)	I after (mA)
08.00	3,97	4,664	30,96	38,62
09.00	4,44	5,638	39,02	52,32
10.00	5,974	7,386	62,72	82,76
11.00	7,672	8,07	85,68	91,84
12.00	7,336	7,688	71,62	83,56
13.00	6,416	7,65	58,16	87,32
14.00	4,694	6,55	40,64	66,78
15.00	5,74	5,076	49,02	45,88
16.00	3,698	3,736	17,98	24,54
Mean	5,5488889	6,2731111	50,644444	63,735556

As shown in Table 3, presents the average voltage (V) and current (I) output of the prototype before and after the addition of black color on the copper plate of the STEG prototype. The average output voltage of the STEG prototype increased from 5.54 V to 6.27 V after the addition of black color with a difference of 0.72 V. Then the average output current of the STEG prototype increased from 50.64 mA to 63.73 mA after the addition of black with a difference of 13.09 mA. This increase indicates the effect of black color coating on the prototype output voltage and current. The results of the mean analysis of the output voltage are visualized in graphical form in Figure 8 and for the output current are visualized in graphical form in Figure 9.

As shown in Figure 8 and Figure 9, shows a comparison graph of the average output voltage and current of the STEG prototype before and after the addition of black color coating to the copper plates. Based on these graphs, it can be seen that in general, the addition of black color to the copper plates increases the hourly average of the prototype output voltage and current. The pattern of the prototype output voltage and current under both conditions is in the form of a rising curve from morning to noon and then drops in the afternoon. The average values of the prototype output voltage and current in the condition after the addition of black color were higher than the condition before the addition of black color at almost all measurement times. There is a decrease in the prototype output voltage and current in the afternoon (3:00 pm) in the condition after the addition of black color.

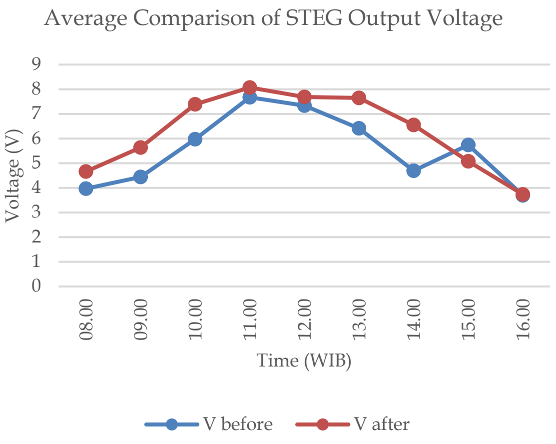

Figure 8. Graphical comparations of the average STEG output voltage

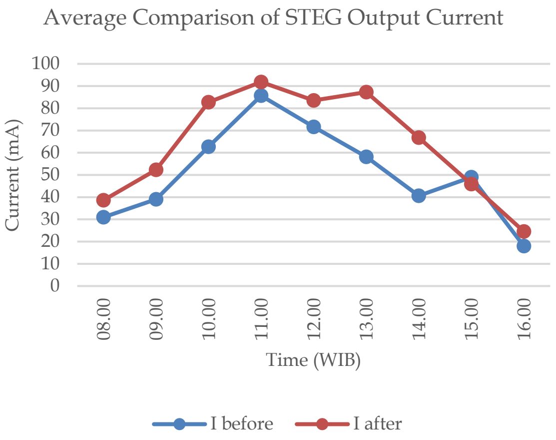

Figure 9. Graphical comparations of the average STEG output current

Based on Table 2, the average output voltage of the prototype as a whole in both conditions is calculated. The average voltage value obtained is 5.911 V. Then based on the calculation of the overall average temperature difference in this study, a value of 38.33 ° C was obtained. The Seebeck coefficient value obtained in this study is 0.01542 V/K. The voltage value used in this calculation is the highest voltage value every hour obtained from measurements for 10 days, presented in Table 4.

Table 4. Data of the highest voltage value every hour obtained from measurements

Time (WIB)	T_H (ºC)	T_C (ºC)	ΔT (ºC)	V (V)	I (mA)
08.00	38,2	2,7	35,5	5,42	49,6
09.00	49,1	9,5	39,6	6,93	81,8
10.00	55,8	4,9	50,9	9,5	110,9
11.00	63,6	4,7	59,1	11,03	136,3
12.00	62,2	7,3	54,9	9,78	106,9
13.00	60,7	8,2	52,5	9,63	108,6
14.00	57,3	13,6	43,7	7,8	79,8
15.00	41,2	3,3	37,9	6,58	60,8
16.00	38,1	4	34,1	4,43	32,3

These values in Table 4 are then substituted into equation 1 to get the voltage calculation results. The comparison between the calculated and measured output voltage is presented in Table 5.

Table 5. Data of the highest voltage value every hour obtained from measurements

Waktu (WIB)	ΔT (ºC)	V Calculated (V)	V Measured (V)
08.00	35,5	5,4745	5,42
09.00	39,6	6,1068	6,93
10.00	50,9	7,8496	9,5
11.00	59,1	9,1140	11,03
12.00	54,9	8,4663	9,78
13.00	52,5	8,0962	9,63
14.00	43,7	6,7391	7,8
15.00	37,9	5,8446	6,58
16.00	34,1	5,2586	4,43

Based on Table 4, there are differences between the calculated and measured voltage values, with some data points showing good agreement while others show significant differences.

Discussion

Based on the results of descriptive analysis and visualized in the form of graphs, it shows the effect of adding a black layer on the copper plate on the temperature profile. The measurement results show an overall increase in temperature, both at the minimum, maximum, and average values. This phenomenon can be explained based on the higher absorptivity and emissivity properties of the black colored surface compared to the normal copper surface. The increase in temperature of the copper plate after being coated with black indicates that the black coating is able to absorb solar radiation more effectively than the copper surface. This is in line with the higher absorptivity of black color. The absorbed solar radiation is then converted into heat energy, thus increasing the temperature of the copper plate.

Although the average temperature increases, the standard deviation value shows that the temperature fluctuations on the black-coated plates tend to be lower. This indicates that the black coating not only increases the average temperature, but also helps stabilize the plate temperature. This is likely due to the high emissivity of the black color. High emissivity allows the plate to release the absorbed heat more efficiently, thus reducing temperature fluctuations. Then the pattern of temperature increased during the day and decrease in the afternoon is a common phenomenon for objects exposed to solar radiation. The black color layer reinforces this pattern due to its high absorptivity and emissivity properties.

Based on the results of the analysis, it can be concluded that the addition of a black color layer on the copper plate significantly increases the surface temperature. This is due to the higher absorptivity and emissivity properties of the black color compared to the copper surface. This increase in temperature has important implications in various fields, especially in the utilization of solar energy.

Based on the results of descriptive analysis and visualized in graphical form, there is a significant increase in the output voltage and current of the STEG prototype. This increase can be attributed to the increase in the temperature of the copper plate due to the increased absorptivity of the black layer to solar radiation.

The increase in the output voltage and current of the prototype after black coating indicates an increase in the efficiency of thermoelectricity in converting heat energy into electrical energy. This can be explained by the working principle of thermoelectric, where the temperature difference between the hot and cold sides produces an electric voltage. As the temperature of the hot side (copper plate) increases, the temperature gradient between the hot and cold side (ice water) also increases, resulting in greater voltage and current. The maximum and minimum values of voltage and current increase, with the standard deviation value tending to decrease after the addition of the black layer. This indicates that the black coating not only increases the output voltage and current, but also helps stabilize the performance of the prototype. This stability can be attributed to the increased and more even heat absorption on the plate surface due to the black coating. Both voltage and current show a similar pattern, increasing during the day and decreasing in the afternoon. This pattern corresponds to the varying intensity of solar radiation throughout the day. The black layer amplifies this pattern due to its ability to absorb solar radiation more effectively.

The results of this study show an increase in the temperature, output voltage and current of the black coating copper plate STEG prototype. This supports the research findings of Deo Dwi Cahya et al. [10] regarding the effect of black color addition on brass plate temperature. Both studies showed consistency in the positive effect of black color plating on increasing the temperature of copper plates in STEG devices. This convergence finding strengthens the validity and generalizability of the research results on the effect of black plating on STEG copper plate temperature. The increase in the output voltage and current of the copper plate STEG prototype with black coating, support the findings of several previous studies. Research by Yulong Zhao et al.[5] showed that increasing the temperature on the hot side of the STEG module will increase the module output voltage. This is in line with the results of this study which show that black plating on the STEG copper plate increases the prototype hot side temperature and prototype output voltage. This finding is reinforced by the research of Deo Dwi Cahya et al. [10] which showed that the addition of black color to the STEG prototype increased the output voltage. This shows that the positive effect of black color coating on STEG output voltage is consistent with different plate materials, in this case copper and brass plates.

The results of this study have some interesting implications. The increase in copper plate temperature due to black coating has the potential to improve the efficiency of systems that utilize solar energy, such as solar thermal power plants. Furthermore, understanding the effect of color on surface temperature can be utilized in various applications, such as building design, cooling systems, and insulation. Further research can be conducted to develop materials with absorptivity and emissivity properties that can be adjusted according to specific application needs.

IV. CONCLUSION

The results showed that the addition of a black color layer on the copper plate increased the temperature of the copper plate. This is observed through data analysis and graphs of the average temperature of copper plates before and after the addition of black color. The average temperature of the copper plate before the addition of black color was 47.04°C and after the addition was 49.14°C. The increase in copper plate temperature is caused by the ability of black color to absorb solar heat with high emissivity and thermal conductivity values. Then the voltage and current output of the STEG prototype after the addition of black color showed an overall increase. The average output voltage of the prototype before the addition of black color is 5.54 V and after the addition is 6.27 V. Then, the average output current before the addition of black color was 50.64 mA and after the addition was 63.73 mA. The higher temperature difference on the hot side of the prototype improves the performance of the thermoelectric module in performing energy conversion, resulting in higher voltage and current.

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