Performance Analysis of a Thermoelectric Generator (TEG) Integrated into a Biomass Stove Using a Continuous Cooling System

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ABSTRAK

Penelitian ini bertujuan untuk menganalisis kinerja Thermoelectric Generator (TEG) tipe SP1848-27145 SA yang diintegrasikan pada dinding kompor biomassa sebagai pembangkit listrik alternatif skala kecil. Fokus utama penelitian adalah mengevaluasi pengaruh penerapan mekanisme pendingin kontinyu terhadap perbedaan temperatur (ΔT) dan daya listrik yang dihasilkan. Metode penelitian dilakukan secara eksperimental dengan memvariasikan tiga parameter utama yaitu metode pendinginan, massa bahan bakar biomassa kayu, serta jumlah modul TEG. Hasil pengujian menunjukkan bahwa metode pendingin kontinyu menggunakan media air es memberikan performa termal paling optimal dengan kemampuan menjaga suhu sisi dingin (Tc) serendah 17℃ - 21 ℃, sehingga menghasilkan selisih temperatur (ΔT) sebesar 54.07℃. Kinerja elektrikal tertinggi dicapai pada konfigurasi 2 modul TEG yang disusun seri dengan beban bahan bakar 400 gram dan pendingin air es, yang menghasilkan tegangan 2,14 Volt dan daya listrik 0,47 Watt. Capaian ini meningkat hampir empat kali lipat dibandingkan konfigurasi 1 modul TEG. Efisiensi 2 TEG dengan sistem pendingin air es mencapai 3,63 % lebih tinggi dibandingkan dengan pengujian 2 TEG tanpa pendingin yang hanya memiliki efisiensi sebesar 2,21 %..

Kata kunci: Thermoelectric Generator (TEG) ; Kompor Biomassa; Pendingin Kontinyu; Efek Seebeck; Konversi Energi .

ABSTRACT

This study aims to analyze the performance of a SP1848-27145 SA Thermoelectric Generator (TEG) integrated into the wall of a biomass stove as a small-scale alternative power generation system. The primary objective is to evaluate the effect of implementing a continuous cooling mechanism on the temperature difference (ΔT) and the electrical power output. The research was conducted experimentally by varying three main parameters, namely the cooling method, the mass of wood biomass fuel, and the number of TEG modules. The experimental results indicate that continuous cooling using ice-water as the cooling medium provides the most optimal thermal performance, maintaining the cold-side temperature (Tc) as low as 17°C–21°C and producing a maximum temperature difference (ΔT) of 54.07°C. The highest electrical performance was achieved using a configuration of two TEG modules connected in series with a 400 g fuel load and ice-water cooling, generating an output voltage of 2.14 V and electrical power of 0.47 W. This performance is nearly four times higher than that obtained using a single TEG module. Furthermore, the efficiency of the two-module TEG system with ice-water cooling reached 3.63%, which is higher than the efficiency of the two-module configuration without cooling, which was only 2.21%.

Keywords: Thermoelectric Generator (TEG); Biomass Stove; Continuous Cooling System; Seebeck Effect; Energy Conversion.

INTRODUCTION

Biomass is a renewable energy source that continues to be developed due to its potential to replace fossil-based energy. Indonesia, as an archipelagic country, possesses abundant biomass resources in significant quantities. Among the available biomass types, oil palm waste has the highest energy potential in Indonesia, with an estimated capacity of 12,654 MWe, followed by rice biomass residues with a potential of 9,808 MWe [1], [2].

The utilization of biomass as a renewable energy source has become a major focus in sustainable energy development, supported by various conversion methods such as direct combustion, gasification, pyrolysis, and biological conversion through anaerobic fermentation. Biomass stoves have emerged as a promising alternative, particularly in rural and remote areas where LPG distribution has not been fully accessible [3], [4].

A Thermoelectric Generator (TEG) is an electrical power generation device capable of converting heat into electrical energy based on a temperature difference through the Seebeck effect. TEG technology offers the advantage of autonomous electricity generation, making it highly beneficial for regions that are not yet connected to the national electricity grid. However, studies and designs related to TEG applications, particularly in biomass stoves, remain limited. Although TEG systems have the potential to directly convert thermal energy from biomass stoves into electricity, limitations in terms of efficiency, cost, and cooling systems make this technology more suitable for small-scale applications such as battery charging or powering cooling fans rather than serving as the primary household electricity source [5], [6].

Therefore, a key challenge in TEG-based systems lies in designing a device capable of producing a high temperature difference between the hot and cold sides, enabling the generated current to meet practical energy demands. This study aims to develop a biomass stove integrated with a Thermoelectric Generator (TEG) to provide electrical power as an energy source for supplying combustion air. In addition, this research is expected to offer new insights into the utilization of biomass and TEG technology as part of efforts to create environmentally friendly and sustainable energy solutions, particularly in Indonesia.

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RESEARCH METHODS

2.1 Experimental Setup Scheme

In this study, the experiment was conducted by simulating the conversion mechanism of waste heat into electrical energy using a Thermoelectric Generator (TEG) integrated with a continuous cooling system. Therefore, the experimental setup was arranged to ensure smooth coolant circulation and effective heat distribution, while also allowing accurate monitoring of the system. The schematic illustration of the experimental arrangement is presented in Figure 1.

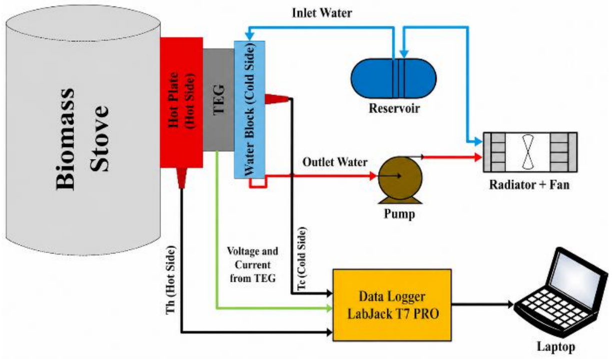

Figure 1. Experimental Setup Scheme

The testing was carried out using two different TEG module configurations. In the first test, a single TEG module was applied, while in the second test, two TEG modules were connected in series to obtain a higher output voltage.

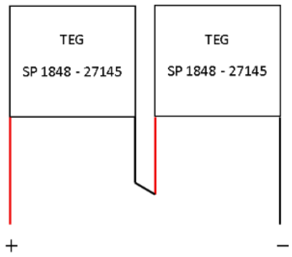

Figure 2. Series Circuit of Two TEG Modules

2.2 Testing Procedure

This study focuses on evaluating the performance of the continuous cooling system used to maintain the cold-side temperature of the Thermoelectric Generator (TEG) installed on the biomass stove at a low and stable level. The research employed an experimental method by varying the number of TEG modules installed on the biomass stove and the cooling system applied.

The experiments were conducted using two configurations: a single TEG module and two TEG modules connected in series to achieve a higher output voltage. The hot side of the TEG module was attached to the outer wall plate of the biomass stove using thermal paste to enhance heat transfer from the combustion process. Meanwhile, the cold side of the TEG was cooled using a continuous cooling system in the form of a water block, in which water was circulated by a mini pump. To maintain the water temperature at a low and stable level, a radiator was installed at the water outlet before returning to the reservoir.

This cooling mechanism was intended to maximize temperature reduction, thereby generating a large temperature difference (ΔT) between the hot and cold sides of the TEG module.

During the experimental process, temperature measurements on both sides of the TEG module were performed using K-type thermocouples connected to a LabJack T7-PRO data acquisition system. The thermocouples were placed directly on the hot side and cold side of the TEG module to obtain real-time temperature data. In addition, the electrical output parameters, including voltage (V), current (A), and power (W), were also measured using the LabJack T7-PRO. All collected data were subsequently analyzed to determine the temperature difference (ΔT), calculate the generated electrical power, and evaluate the efficiency performance of the TEG module during the experiments.

RESULTS AND DISCUSSION

3.1 Experimental Apparatus Design

Figure 3 presents the experimental apparatus used to investigate the conversion of thermal energy into electrical power using a Thermoelectric Generator (TEG) integrated into a biomass stove. The biomass furnace wall served as the heat source for the hot side of the TEG module. To enhance heat transfer, the TEG hot side was mounted directly on the outer wall of the stove.

To maximize the temperature gradient (ΔT), which is the main driving factor for thermoelectric power generation, the cold side of the module was equipped with a continuous cooling system. The cooling medium was circulated through a water block using a mini pump and flexible tubing. This configuration was designed to maintain a low and stable cold-side temperature, thereby improving the thermoelectric conversion performance.

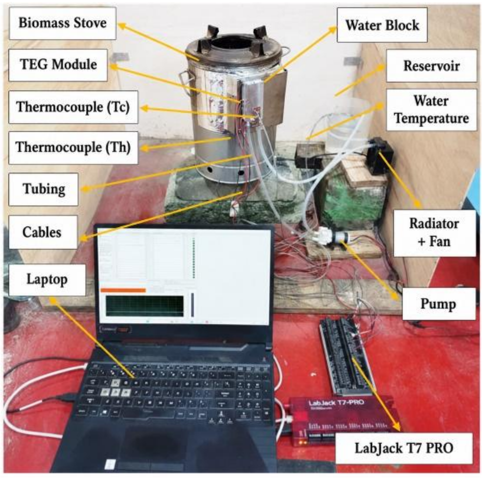

Figure 3 Experimental apparatus of the TEG-based biomass stove system.

3.2 Thermal Performance Characteristics

3.2.1 Effect of Cooling Method on Cold-Side Temperature (Tc)

The thermal performance of the system was evaluated under three operating conditions: (i) without cooling, (ii) continuous water cooling, and (iii) continuous ice-water cooling, as illustrated in Figure 4.

(a) (b) (c)

Figure 4 (a) TEG without cooling, (b) TEG with water cooling, (c) TEG with ice-water cooling.

The measured cold-side temperature (Tc) profiles as a function of time for each cooling condition are shown in Figure 3.3.

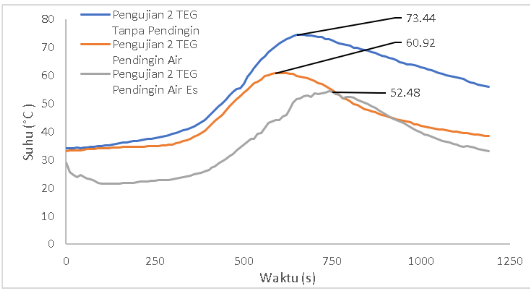

Figure 5 Time-dependent cold-side temperature (Tc) under different cooling conditions.

The results indicate substantial differences in thermal performance among the tested cooling methods. In the absence of cooling, Tc increased rapidly and reached a maximum value of 73.44°C at 600 s, resulting in a reduced temperature gradient and limiting thermoelectric output. The continuous water cooling method exhibited improved thermal control by delaying heat accumulation and maintaining Tc within the range of 33°C–35°C up to approximately 400 s, before gradually rising to 60.92°C.

The most effective cooling performance was achieved using continuous ice-water cooling, which maintained Tc at significantly lower levels, reaching a minimum range of 17°C–18°C. These findings confirm that ice-water cooling provides superior heat dissipation capability and is the most effective approach for maintaining a low cold-side temperature to enhance TEG output performance.

3.2.2 Temperature Difference (ΔT) Analysis

The variation of the temperature difference (ΔT) over time for the two-TEG configuration under different cooling conditions is presented in Figure 6.

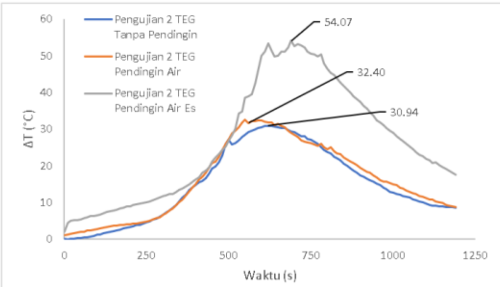

Figure 6 Time-dependent temperature difference (ΔT) for the two-TEG configuration.

The ice-water cooling system produced the highest thermal gradient, achieving a maximum ΔT of 54.07°C, which was significantly higher than the no-cooling condition (30.94°C). This substantial improvement is attributed to the ability of ice-water to maintain the cold side at a consistently low temperature while the hot side temperature increased rapidly due to biomass combustion.

Therefore, continuous ice-water cooling is demonstrated to be the most optimal method for maximizing the thermal gradient and improving the energy conversion potential of the TEG system.

Table 1 Summary of thermal measurement results.

Cooling Methods	Varian	T_h (°C)	T_c (°C)	ΔT (°C)	ΔT avr (°C)
No Cooling	1 TEG	92.50	67.17	25.33	10.80
	2 TEG	104.39	73.44	30.94	14.89
Water Cooling	1 TEG	86.23	56.38	29.86	13.69
	2 TEG	93.32	60.92	32.40	15.99
Ice Cooling	1 TEG	74.41	44.35	30.06	16.1
	2 TEG	106.55	52.48	54.07	26.31

Based on Table 1, the performance of the thermoelectric system is strongly dependent on the effectiveness of the cooling strategy in sustaining a high temperature gradient. Without cooling, Tc increased sharply to approximately 74°C, indicating insufficient heat rejection and a limited ΔT across the module. In contrast, the application of active cooling significantly enhanced the thermal performance. The highest ΔT value of 54.07°C was obtained using two TEG modules combined with ice-water cooling.

3.3 Electrical Performance of the Thermoelectric Generator

3.3.1 Voltage and Current Output Characteristics

Following the thermal evaluation, the electrical output performance of the TEG system was assessed. Figure 7 shows the time-dependent voltage and current profiles obtained from the two-TEG configuration.

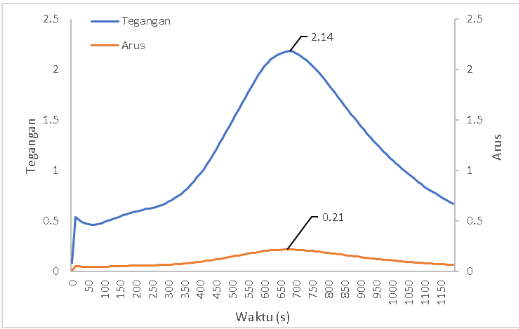

Figure 7 Voltage and current profiles over time for the two-TEG configuration.

The voltage output increased steadily and reached a maximum value of approximately 2.14 V at 650 s, while the current output peaked at approximately 0.21 A. The coincidence of peak voltage, current, and ΔT trends confirms the fundamental thermoelectric principle, where the generated voltage is directly governed by the temperature gradient across the module. This indicates that the cooling system plays a critical role in sustaining the temperature difference during peak combustion conditions.

3.3.2 Effect of Cooling Method on Output Power

To quantify the influence of thermal management on electrical performance, the output power generated under different cooling conditions was compared. The results are shown in Figure 8.

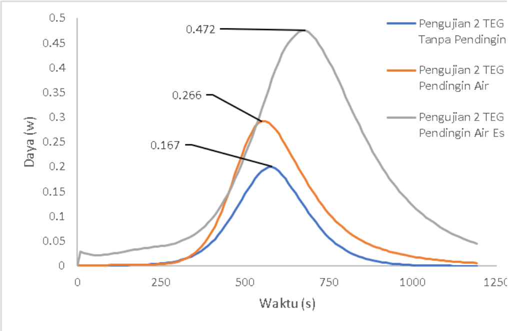

Figure 8 Power output comparison under different cooling methods.

The results demonstrate that cooling strategy significantly affects the electrical power generation capability of the TEG system under a 400 g biomass fuel load. The ice-water cooling method produced the highest power output of 0.472 W, which was considerably higher than the power output under water cooling (0.266 W) and without cooling (0.167 W). This confirms that maintaining a low cold-side temperature is a dominant factor in maximizing electrical output, as it enables a larger and more stable ΔT.

3.3.3 Effect of the Number of TEG Modules on Power Output

The influence of module quantity was evaluated by comparing a single-TEG configuration with a two-TEG configuration connected in series. This approach ensured that the observed differences were primarily attributed to the additional module.

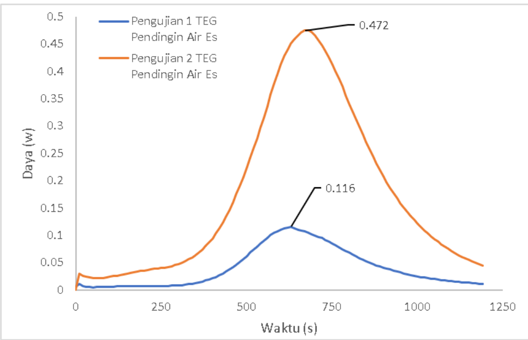

Figure 9 Power output comparison between one-TEG and two-TEG configurations.

The results show that increasing the number of TEG modules significantly improves the power output. The single-TEG configuration produced a maximum power of approximately 0.12 W, whereas the two-TEG series configuration achieved a peak power of 0.47 W. This increase is consistent with the electrical characteristics of a series connection, in which the total output voltage increases as the number of modules increases. Consequently, the output power rises substantially, provided that sufficient thermal energy is available to drive both modules.

Table.2 Summary of electrical performance results.

Cooling Methods	TEG Configuration	Voltage (V)	Current (A)	Power (W)
No Cooling	1 TEG	0.76	0.08	0.058
	2 TEG	1.29	0.13	0.167
Water Cooling	1 TEG	0.85	0.09	0.072
	2 TEG	1.63	0.16	0.266
Ice Cooling	1 TEG	1.08	0.11	0.116
	2 TEG	2.14	0.21	0.472

As summarized in Table 3.2, the highest electrical output was obtained using two TEG modules with ice-water cooling, producing a voltage of 2.14 V and a maximum power output of 0.47 W. This value was significantly higher than that achieved by the no-cooling condition under the same fuel load. Additionally, increasing the number of modules from one to two resulted in a notable improvement in power generation, confirming the effectiveness of the multi-module configuration.

3.4 Discussion

3.4.1 Relationship Between Temperature Difference (ΔT) and Output Power

The relationship between the temperature gradient (ΔT) and the electrical power output was analyzed to determine the direct impact of thermal performance on energy conversion.

For the one-TEG configuration (Figure 3.8), the no-cooling condition produced a ΔT of

25.33°C with a maximum power output of 0.058 W. When water cooling was applied, ΔT increased to 29.86°C and the power output increased to 0.082 W. The highest performance was obtained using ice-water cooling, yielding ΔT of 30.12°C and a maximum power output of 0.116 W.

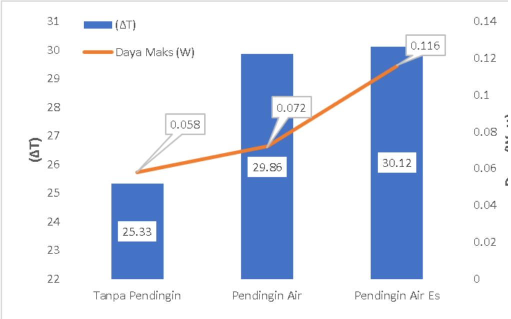

Figure 3.8 Relationship between ΔT and power output for the one-TEG configuration.

For the two-TEG configuration (Figure 3.9), the no-cooling condition produced ΔT of 30.94°C with a power output of 0.17 W. With water cooling, ΔT increased to 32.40°C and power output increased to 0.266 W. The best performance was achieved using ice-water cooling, producing ΔT of 53.22°C and a peak power output of 0.47 W.

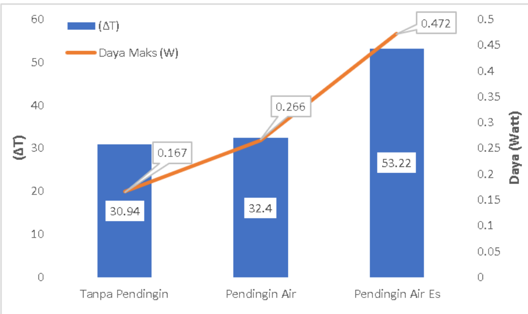

Figure 3.9 Relationship between ΔT and power output for the two-TEG configuration.

These results confirm that higher ΔT leads directly to higher electrical power output. Ice-water cooling effectively maintains a low cold-side temperature, enabling a larger thermal gradient and significantly improving the energy conversion capability of the TEG system.

3.4.2 Effectiveness of Continuous Cooling System on TEG Efficiency

The overall system performance was further evaluated using efficiency as a key indicator. Efficiency represents the ratio of electrical energy generated to the thermal energy supplied by biomass combustion.

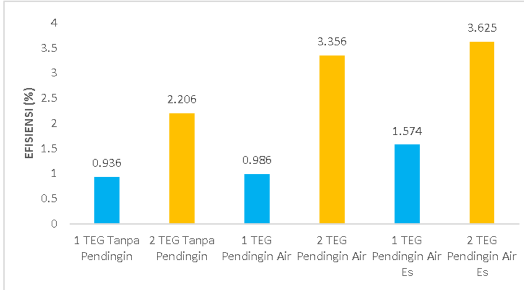

Figure 3.10 Efficiency comparison of the TEG system under different cooling methods.

The results show that system efficiency increases with both the application of cooling and the addition of TEG modules. The two-TEG configuration without cooling achieved an efficiency of 2.21%, while the two-TEG configuration with water cooling improved the efficiency to 3.36%. The highest efficiency was achieved using ice-water cooling, reaching 3.63%.

These findings demonstrate that continuous cooling significantly improves thermoelectric conversion efficiency by maintaining a larger and more stable thermal gradient across the module. Among all tested methods, ice-water cooling provides the most effective thermal management, resulting in the highest electrical output and efficiency.

CONCLUSION

Based on the experimental results and data analysis presented in this study, the following conclusions can be drawn:

1. The continuous cooling method using ice-water proved to be the most effective in maintaining a low and stable cold-side temperature (Tc), within the range of 17°C–21.44°C. This performance was significantly better than the no-cooling condition, in which Tc increased up to 68°C, leading to a substantial reduction in TEG performance.
2. The continuous ice-water cooling system generated a superior temperature difference (ΔT). Under the ice-water cooling configuration, the maximum ΔT reached 54.07°C, representing an increase of 61.83% compared to the no-cooling test, which produced only 30.94°C.
3. The two-TEG series configuration combined with ice-water cooling produced a maximum electrical power output of 0.47 W. This configuration increased the power output by 306.90% compared to the single-TEG

configuration with ice-water cooling, which generated only 0.12 W. Furthermore, the efficiency of the TEG system increased with both the number of modules and the application of cooling. The two-TEG configuration without cooling achieved an efficiency of 2.21%, whereas the implementation of ice-water cooling increased the efficiency to 3.63%.

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