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Experimental investigations on the performance of thermoelectric generator as energy conversion system

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Experimental investigations on the performance of thermoelectric generator as energy conversion system

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Abstract. Energy conversion system based on thermoelectric generator that utilized the residual heat of condenser as heat energy resource and water circulation as a cooling system has been designed. Thermoelectric generator functions as a heat-to-electricity energy conversion by using temperature difference between the two sides of the thermoelectric 4 x 4 x 0.3 cm TEG SP1848 module has been used as a thermoelectric generator that can hold back the temperature up to 125°C. The conductance value of TEG SP1848 is 0.0025 W/K. The important part of energy conversion systems are thermoelectric generator configuration, conductor and cooling system. Conductor is the component which functions as heat transfer media from condenser pipe to thermoelectric generator. The diameter of the condenser pipe in this study was 4.2 cm. The function of cooling system is cooling up the thermoelectric generator cold side in order to enhance the temperature difference between cold side and hot side. The cooling system that used in this research is water cooling that consisting of a water pump, water block, radiator, fan and water. The collecting data has been done by using series configuration of thermoelectric generator and varying the temperature of 40°C -110°C and the resistance of 10Ω-200Ω. The best resistance that can produce the greatest power is 39 Ω. The hot side temperature that can produce the greatest power in this study is 110 °C. The average of power and efficiency of energy conversion system was 0.129 W and 2%.

1. Introduction

Along with technological developments, the use of technology as an effort to maintain the availability of energy has begun to be widely proclaimed. These maintenance efforts are by minimizing the energy wasted during the process or reusing the wasted energy. One example of using this technology is thermoelectric. To utilize residual heat energy, the application of thermoelectric on concentrating solar power generation of wireless sensor network system has been designed by Sui et al, improving thermoelectric conversion efficiency by using Fresnel lens to concentrate thermal energy and using a PCM container to stored thermal energy [1]. Another research developed by Kyono et al who utilize the thermoelectric power generation in vapor condenser of steam-based power plant [2]. Development of thermoelectric module in their research is based on heat transfer theory in cylindrical heat exchanger. In their research thermoelectric conversion can generated power in 150kW.

Thermoelectric are influenced by three effects, namely, the Seebeck, Thompson and Peltier effects. The voltage will be generated by temperature differences as a thermoelectric function. According to Aziz et al, thermoelectric is a tool for converting temperature differences into a potential difference and vice versa [3]. Thermoelectric Generator (TEG) is a small plate-shaped device that operates as a heating machine by converting heat directly into electricity [4], [5].

According to the configuration of thermoelectric generator, there are several model configurations of thermoelectric setting. One of them, Salim et al. has been characterized thermoelectric generator and thermoelectric cooler with variations in resistor loading and setting the temperature difference between the two sides of the element at 70 ° C, the value of the electric voltage is generated using a thermoelectric generator 1.48 V and a thermoelectric cooler 1.02 V [6][6]. Based on Reyanuargo et al., thermoelectric hot steam condenser AC can produce a voltage of 3.14 volts and 0.16 watts of power at an average temperature difference of 34°C [7]. In Mustakim et al. research to testing the cooling performance of the best cooling variation is water with the highest temperature difference of 48.3°C. While the air cooler has the highest temperature difference is 21.9°C [8]. So that by using water or cooling liquid, the optimal thermoelectric voltage will be obtained.

Based on the explanation of several previous studies, the aim of this study is to investigate the performance of the thermoelectric generator as energy conversion system by utilizing the residual heat of condenser as heat energy resource and water circulation as a cooling system. Performance testing is carried out with variations in temperature and resistance so that the voltage, current and power generated can be analyzed.

2. Methodology

2.1. Design of Energy Conversion System

The design of an energy conversion system based on a thermoelectric generator can be shown in Figure 1 and 2. The conductor is a component that functions as a medium for heat transfer from the condenser pipe to the hot side of the thermoelectric generator. The size of the conductor is adjusted to the size of the condenser pipe used as a heat source, which is 4.2 cm in diameter. The thermoelectric generator used is 5 pieces of TEG SP1848 which are connected in series. The cooling system functions to cool the cold side of the generator thermoelectric so that the temperature difference between the cold side and the hot side increases. The cooling system consists of water fluid, water block, pump, mini radiator and fan. The water in this generating system functions as a coolant in the thermoelectric in order to increase the temperature difference on the cold and hot thermoelectric sides. The water pump is used as a water line to the thermoelectric with a voltage source from the power supply. The radiator is used as a container for water as well as cools the water. Water block is used as a conductor between water and thermoelectric.

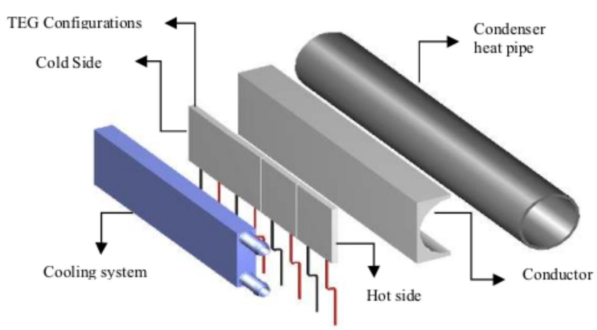

Figure 1. Part of the energy conversion system

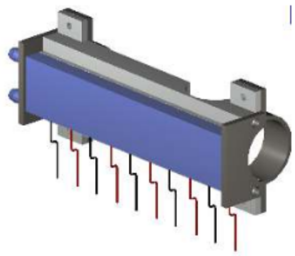

Figure 2. Design of energy conversion system based on thermoelectric generator

2.1.1. Energy Conversion System Performance Testing

The data was collected by using a condenser pipe as heat source which controlled the temperature. The temperature variations used are 40°C, 50 °C, 60 °C, 70 °C, 90 °C, 100 °C, and 110 °C. The variations in resistance used are 20 Ω, 22 Ω, 33 Ω, 39 Ω, 47Ω, 56 Ω, 68 Ω, 83 Ω, 90 Ω, 100 Ω, 110 Ω, 120 Ω, 130 Ω, 140 Ω, 150 Ω, 160 Ω, 170 Ω, 180 Ω, 190 Ω, and 200 Ω. The data were obtained include the voltage on the thermoelectric, current, temperature on the cold side, temperature on the hot side, and the thermoelectric resistance of the generator.

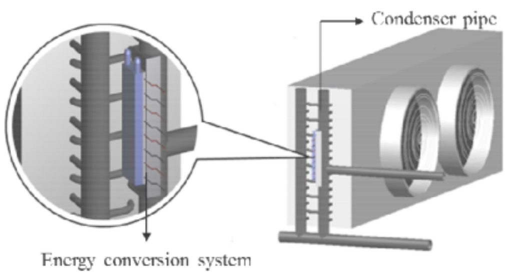

Figure 3. Energy Conversion System Testing on Cold Storage Condenser Pipes

To determine the potential of electrical energy generated by the exhaust heat of cold storage condensers, a test was carried out without stabilizers and with stabilizers. The test was carried out with three repetitions and the data obtained were the voltage on the thermoelectric generator, external resistance, current in the thermoelectric, heat source temperature, cold side temperature, hot side temperature, voltage on the voltage stabilizer, current on the voltage stabilizer and time.

Data analysis was carried out in a descriptive quantitative manner by processing primary data into power and efficiency. Data analysis is using equations 1 – 6 [9].

$$P = V \times I \quad (1)$$

The thermoelectric efficiency of the generator can be shown in equation 2.

$$\eta = \frac{P}{Q_h} \times 100\% \quad (2)$$

Heat absorbed is calculated by using equation 3.

$$Q_h = n\,(\alpha . T_h . I - 0{,}5 . I^2 . R + K\Delta T) \quad (3)$$

Seebeck coefficient is calculated by using equation 4.

$$\alpha = \frac{V}{\Delta T \; x \; n} \quad (4)$$

Thermal conductance is calculated by using equation 5.

$$K = k.\frac{A}{L} \quad (5)$$

The resistance is calculated by using equation 6.

$$\Sigma\varepsilon + \Sigma I(R_L + R_{int}) = 0 \quad (6)$$

Nomenclature:
P = Power (Watt)
V = Voltage (Volt)
I = Current (Ampere)
η = Efficiency of the thermoelectric generator (%)
P = Power produced by the thermoelectric generator (W)
Q_h = Heat absorbed by the thermal side of the thermoelectric (W)
k = Thermal conductivity (W/mK)
K = Thermal conductance (W/K)
A = Cross-sectional area (m^2)
L = Thickness (m)
T_o= Temperature at condenser heat pipe (K)
T_h= Thermoelectric hot side temperature (K)
T_c = Thermoelectric cold side temperature (K)
ΔT = Temperature difference between the hot and cold sides (K)
α = Seebeck coefficient (V/K)
x = Number of thermoelectric modules
n= Number of thermoelectric thermocouples
R_L= External resistance (Ω)
R= Internal resistance (Ω)

3. Results and discussion

3.1. *Effect of resistance value on current and voltage*

Figure 3 shows the relationship between resistance with voltage and current in series configuration of thermoelectric generator at a temperature of 110°C on the hot side. In the test for the smallest resistance of 10Ω, the smallest voltage is 3.8V, if the resistance is increased to 200Ω, the voltage increase is 12.2V. These results indicate that the relationship between resistance and voltage is comparable, such as research conducted by Widjaja which tested a thermoelectric generator with a temperature difference of 25 K and a variation of resistance from 0.39Ω to 15Ω, there was an increase in voltage from 0.04 V to 0 , 24 V [10]. By using exponential fitting analysis, an exponential equation

is obtained $y = -10.10\, e^{(-\frac{x}{43.69})} + 12.01$ with $R^2 = 0.993$.

The test results using the smallest resistance of 10 Ω, the current value is obtained in the series of 0.4 A. Furthermore, in the 200 Ω resistance test, the current value is 0.05 A. These results are in line with study by Widjaja that in the thermoelectric generator test with a temperature difference of 25 K and a resistance variation of 0.39Ω - 15 Ω, a decrease in current occurs from 0.07A to 0.01 A [10]. Similar to the research of Cai et al., that testing a thermoelectric generator with a resistance variation of 0 Ω to 150Ω results in a current decrease from 1.2 A to 0.4 A [11]. These results indicate that the relationship between resistance and current is inversely proportional. The greater the resistance value, the smaller the current value. By using exponential fitting analysis, an exponential equation is obtained $y = 0.42\, e^{(-\frac{x}{41.06})} + 0.06$ with $R^2 = 0.996$. The results of this study are linear with Ohm's law which states that the voltage across the conducting material is directly proportional to the current and inversely proportional to the resistance (*V* = *I.R*). So that to obtain a high voltage, it is necessary to use a high resistance, which is 200 Ω and to obtain a high current it is necessary to use a small resistance, which is 10 Ω.

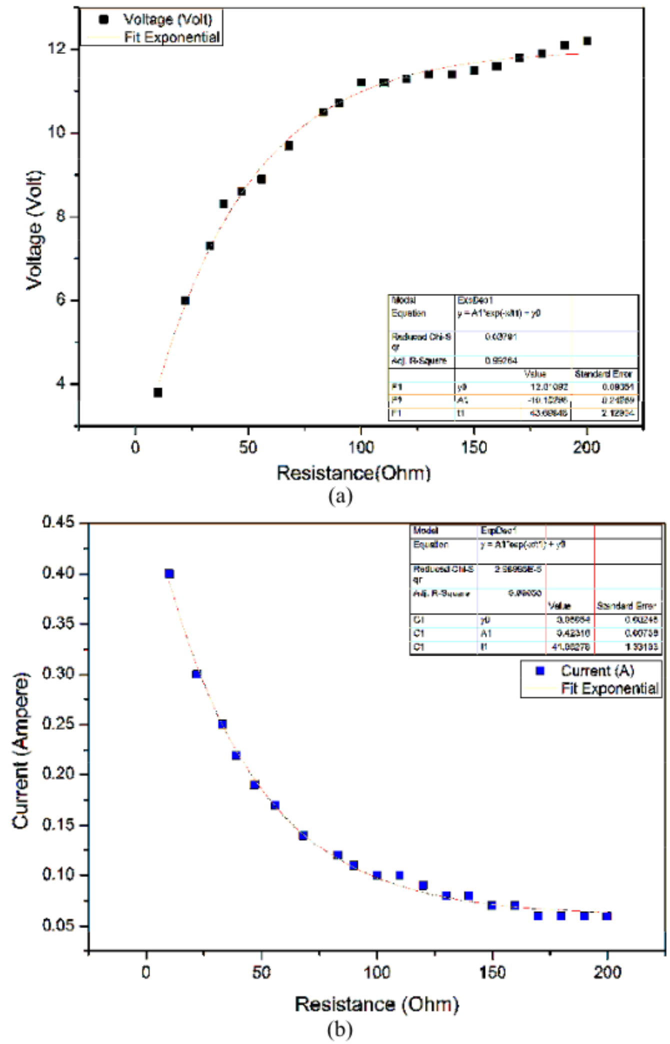

Figure 4. The effect of resistance value on voltage (a) and current (b)

3.2. The Effect of Resistance Value on Power

Figure 4 is a graph of the results of testing the relationship between resistance and power at a temperature of 110 ° C. The test results show that in the resistance range of 40 Ω to 190 Ω there is a decrease in power up to 0.61 W. The results show that in testing the series thermoelectric generator circuit with various kinds of resistance can produce maximum power at resistance of 39 Ω and then

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the power decreases as the resistance value increases. This is relevant to research conducted by Cai et al., (2013) that in testing 6 thermoelectric modules connected in series with a resistance variation of 1.5Ω to 150 Ω, there is an increase in maximum power of 25 W on an external resistance of 60Ω and a drop of up to 20 W at a resistance of 150Ω [11]. The study also says that the system will reach maximum power when the internal resistance is close to or equal to the internal resistance. So that to produce maximum power in the thermoelectric generator system is necessary to use an external resistance with the same resistance as the internal resistance in the thermoelectric generator. By using polynomial fitting analysis, an polynomial equation is obtained $y = 2.29 - 0.02x + (3.69 \times 10^{-5})x^2$ with $R^2 = 0.98$.

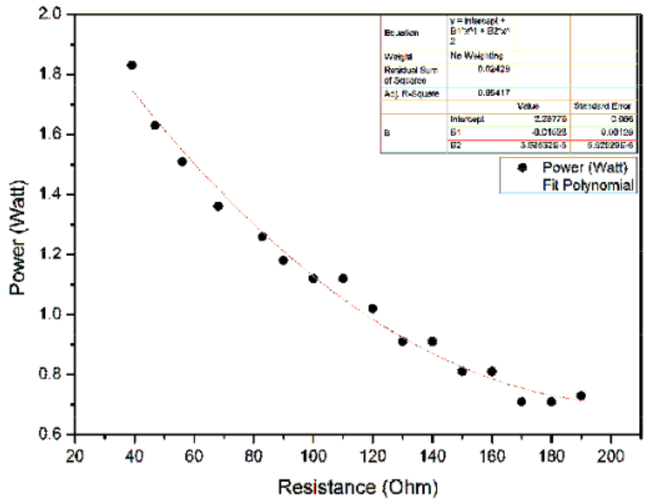

Figure 5. The relationship between resistance and power

3.3. *Stability test of hot side temperature (T_h), cold side temperature (T_c), temperature difference (ΔT)*

Based on Figure 5, it is known that the temperature on the hot side, the cold side, and the temperature difference of thermoelectric generator are quite stable until 30 minutes. Although it is not completely stable, the temperature fluctuation range is not too far away so that it does not really affect the temperature of the thermoelectric generator performance. The temperature difference (ΔT) is the temperature difference between the hot and cold sides of the thermoelectric generator. So that when the temperature on the hot side is stable and the temperature on the cold side rises, the temperature difference decreases. While the cold side temperature decreases, the temperature difference increases. Whereas in the 3rd and 22nd minutes the temperature on the hot side in the same conditions of 62.77 °C. While the cold side temperatures were 38.67 °C and 39.33 °C, the difference in temperature in the second minute was 23.47 °C and at the 22nd minute it was 23.43 °C. In the test for 30 minutes the temperature of the cold side of the thermoelectric was quite high, which was around 38 °C. The temperature was high because it received continuous heat and the ambient temperature was also quite high. However, in testing for 30 minutes the temperature on the cold side of the thermoelectric is quite stable so that it can be said that the cooling system is functioning properly.

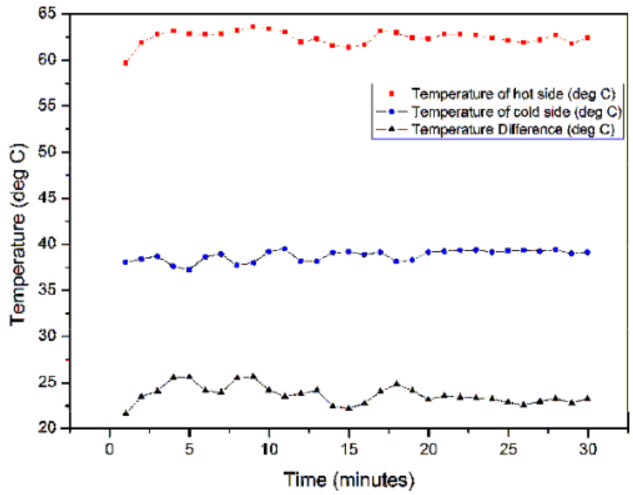

Figure 6. The stability of hot side temperature (T_h), cold side temperature (T_c) and the temperature difference (ΔT) in 30 minutes

3.4. Effect of temperature difference (ΔT) on power (P) and efficiency (η)

Based on Figure 6, it can be seen that there is no significant change in power and efficiency to changes in temperature differences because in testing the temperature increase is not significant. However, the effect of temperature differences on power can be attributed to previous tests where the hot side temperature was proportional to the power produced. Thus, the temperature difference can be said to be linear with power and efficiency. The greater the temperature difference, the greater the power to be generated and the system the more efficient. The test results show that power and efficiency are directly proportional. The greater the power produced, the efficiency will also increase. In this test, an efficiency of 2.3% is obtained when the power is 0.133 W and an efficiency of 2% is obtained at the resulting power condition of 0.114 W. As in the theory that efficiency is the ratio between the heat absorbed by the thermoelectric (Q_h) and the power (P) generated by the thermoelectric. So that to increase the thermoelectric efficiency is necessary to increase the power of the thermoelectric. Meanwhile, to increase the thermoelectric efficiency, it is necessary to increase the value of the temperature difference between the cold side and the hot side.

The test results of using condenser exhaust heat as an energy conversion system based on thermoelectric generator obtained an average power and efficiency of 0.129 W and 2%. The average voltage generated in the test is 1.578 V. If it is assumed that the voltage for each TEG is the same, then each TEG produces a voltage of 0.3 V. This voltage is higher than previous research, 0.174 V conducted by 12]. While the power and efficiency produced are relatively the same when compared to the research of Kumar et al., namely 2.21%. The value of this efficiency value is influenced by several factors, especially at a high enough ambient temperature, which causes the cold side temperature to not be maximized and affects the value of the difference in temperature and power generated [13]. However, the test results show that the condenser exhaust heat has the potential to be a thermoelectric generator based power plant if it is designed on a large scale and has good prospects as an alternative energy that utilizes exhaust heat and is environmentally friendly.

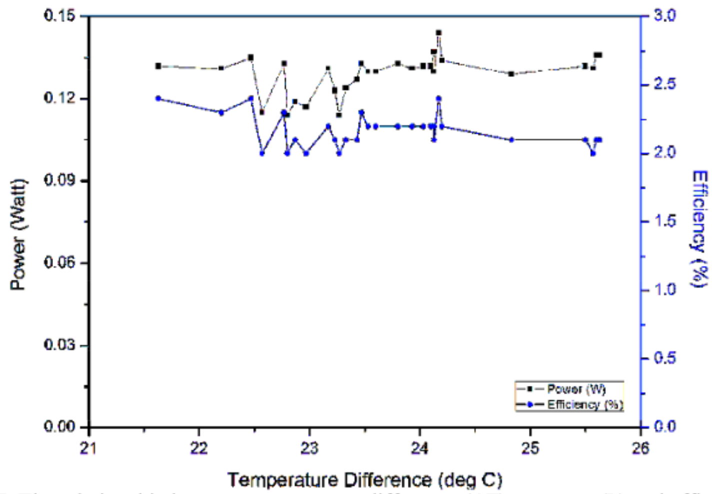

Figure 7. The relationship between temperature difference (ΔT) to power (P) and efficiency (η)

3.5. Effect of voltage stabilizers on the output voltage

Tests carried out using a voltage stabilizer obtained a thermoelectric output voltage of 2 volts. After being given a voltage stabilizer, the resulting voltage increased by 4.8 volts. However, along with the increase in voltage, the current value drops from 0.05 A to 0.015 A. The resulting DC current is also unstable so that when connected to the battery it cannot fully charge but the current fluctuates or is unstable. So that it cannot be done continuously on the battery or power bank because it can damage the components on the battery. Therefore, to be used as a source of charging energy, it is necessary to add a filter so that the current can be stable and at least can produce a power of 5 W because the majority of DC loads have input specifications of 5 V and 1 A. Thus, to produce 5 Watts of power it is necessary to assemble about 38 systems in series or increase the temperature difference by conditioning the temperature on the cool side.

4. Conclusion

The energy conversion system based on a thermoelectric generator consists of thermoelectric generator configurations, conductor and cooling system. The performance testing has been done by using series configuration of thermoelectric generator and varying the temperature of 40°C -110°C and the resistance of 10Ω-200Ω. The results show that the relationship between resistance and voltage is in the form of an exponential curve, as is the relationship between resistance and current. The greater the resistance, the greater the resulting voltage value, but inversely proportional to the current, the greater the resistance the smaller the current value. The relationship between resistance and power is in the form of polynomial curve, the power decreases as the resistance value increases. The temperature on the hot side, the cold side, and the temperature difference of thermoelectric generator are quite stable until 30 minutes. The test results of using condenser exhaust heat as an energy conversion system based on thermoelectric generator obtained an average power and efficiency of 0.129 W and 2%, respectively.

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