Development of Thermoelectric Generator for Energy Saving Device Using Exhaust Waste Heat in Patrol Boat

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***Abstract*— This study describes the energy wastage of diesel engines on patrol boats. Patrol boats typically have high speeds and large engines that waste a lot of heat. This research focuses on research on diesel engines as main engines and generators. Diesel engine combustion results in only about 30~40% available as mechanical energy. Waste heat energy from combustion that is not used as mechanical energy is released to the environment in the form of exhaust gases. The thermal energy of the exhaust gas from engine combustion inside the patrol boat is wasted and cannot be used. The thermoelectric generator concept converts unusable thermal energy from the exhaust gases into electrical energy that can be used by the patrol vessel. The device setup with series and parallel connections was tested on a patrol boat diesel generator engine. Exhaust heat causes an average engine temperature of 110°C and can produce a voltage of 12.85 volts DC and 5.88 watts of electrical energy when connected in series and a voltage of 1.5 volts when connected in parallel. Produces DC and power with 1.44 watts of energy. By utilizing hitherto neglected engine waste heat, thermoelectric generators are a potential alternative energy harvesting technology with the concept of waste heat energy recovery systems.**

Keywords—*Energy saving device, Diesel Engine, Patrol Boat, Thermoelectric Generator, Waste Heat Recovery System*.

I. INTRODUCTION

Patrol boat design prioritizes speed as the main factor[1][2][3][4][5]. This speed is needed when pursuing or pursuit when carrying out patrols at sea. The Patrol Boat uses 2 diesel engines as the main propulsion engine and a generator set for the ship's electricity needs. Combustion occurs in diesel engines with a very large amount of heat energy produced by the combustion process, not all of which is available as mechanical energy. [6][7]. Unused thermal energy is wasted into the atmosphere in the form of exhaust gases. Combustion in a diesel engine results in only about 30~40% being usable as mechanical energy, the remaining unused thermal energy from combustion being released to the environment in the form of exhaust gases. [8]. From these conditions, the thermal energy from the exhaust gas of the diesel engine of the patrol boat is energy that can be used as electrical energy for the patrol boat using the principle of thermoelectric technology. [9][10]. Thermoelectric generators work by converting heat energy directly into electricity. The concept of the Seebeck effect states that if two metallic materials (usually semiconductors) are exposed to two different temperatures, then these materials will flow an electric current or electromotive force. Applying this concept to the exhaust of an internal combustion engine produces a source of electrical energy that can be used on patrol vessels. The analysis in this paper uses experimental and computational methods to determine the design performance of series or parallel thermoelectric circuits. The benefits of this research are expected to be used as literature in the use of free alternative electricity using engine exhaust heat.

Based on research that has been done before, no research has been done by applying the thermoelectric generator directly on the ship, therefore the author will conduct research in an applicative manner with direct application on the patrol boat. In this study, the author uses heat from the engine exhaust of a patrol boat. The engine used is a Patrol class He Deutz Marine Engine Diesel Generator BF 6 M 1013 MC. The maximum exhaust gas temperature of the engine reaches 383ºK and the ambient temperature in the engine compartment is about 311ºK. A heat sink is used on the cold side of the module. The generated electrical energy will be used for operational purposes at Patrol Boat. Specimen test results are used to calculate suitable design parameters for thermoelectric generators. This paper is organized into several parts, the second part is the basic concept of a thermoelectric generator, the third part is the research results, the fourth part is a discussion of the application of a thermoelectric generator and the fifth part is the conclusion.

The patrol boat in this research has a length of 45 meters, a width of 8 meters, a maximum speed of 24 knots, and a displacement of 150 tons. The main diesel engines are 2 units with a capacity of 2500 Hp each. The ship has 2 diesel generators with a capacity of 180 kW. This paper consists of 4 parts. The first part discusses why this research was conducted. The second part describes the method used. the next section discusses the

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results of the data and discussion. The final part is the conclusion and future research of this study.

II. METHOD

A. *Concept Energy*

A waste heat recovery system is the concept of utilizing heat from a work process in gaseous or liquid form for reuse in the form of electrical or mechanical energy [11][12][13][14][15]. The utilization of wasted heat or heat loss can be through the processes of conduction, convection, and radiation. Heat loss can be classified into several levels, namely high temperature (>400 °C), medium temperature (100~400 °C), and low temperature (<100 °C)[16]. Typically, most of the waste heat comes from direct combustion processes in the high temperature range, from combustion equipment exhaust gases in the mid-range, and from components, products and process equipment in the low temperature range. Global Ocean Trend Technology (GMTT In 2030)[17][18], Waste Heat Recovery (WHR) is a technological issue that is under the spotlight in the maritime technology sector[19][20][21][22]. In the WHR system, the energy source used is thermal energy (heat). Thermal energy is one of the energy classifications where the term thermal energy efficiency is known by the equation defined by the equation :

$$\eta_{th} = \frac{Energy\ output}{Energy\ input} \quad (1)$$

Thermal energy can be directly converted into electrical energy with a thermoelectric converter, also known as a thermoelectric generator.

Heat transfer is defined as the process of transferring energy from an object with a high temperature (having large energy) to an object with a low temperature (having small energy) and heat will stop flowing when the two objects reach the same temperature (thermal equilibrium) [23]. This heat transfer process can take place by conduction, convection, or radiation. In thermoelectric generators, the heat transfer process that occurs is conduction and convection. Conduction occurs in the internal components of the thermoelectric module, while convection occurs in the outer sides of the thermoelectric.

B. *Thermoelectric*

Thermoelectric Generator was influenced by Thomas Johan Seebeck's experiment in 1821[24][25][26]. This experiment led to the concept known as the Seebeck effect. This means that when two dissimilar metals are connected at one end and measured, the other end is given a different temperature, creating a potential difference across both metals. The resulting potential difference is proportional to the temperature difference between the two metal ends. The greater the temperature difference, the greater the potential difference across them. At the atomic level, the temperature difference causes carrier charges to diffuse from the hot surface to the cold surface. This creates a potential difference across the two metal ends, as shown in Figure 1. Several types of modules are offered in the market. The ability of modules depends on the type of each module that has its module specifications. In this research, using Thermo Electric Module (TEM) type TEC1 12706 as shown in Figure 2.

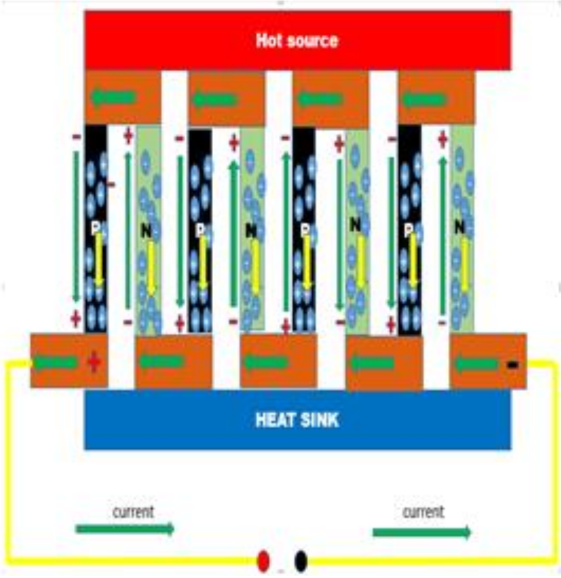


Figure 1. Seedback effect

C. *Servo Motor Mechanical Device*

Calculation of the efficiency of the thermoelectric module is obtained from the thermoelectric parameters using equations 2~7:

a. Coefficient Seebeck

$$\alpha_m = \frac{U_{max}}{\Delta T} \quad (2)$$

b. Thermal Resistance Thermoelectric module

$$Rthm = \frac{\Delta T_{max}}{U_{max}\, I_{max}} \frac{2T_h}{(T_h - \Delta T_{max})} \quad (3)$$

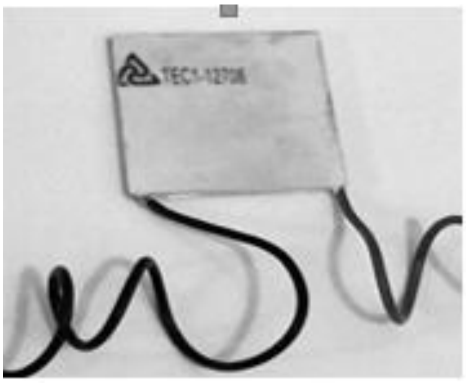


Figure 2 TEM Type TEC1 12706

c. Electricity Thermal Thermoelectric Module

$$R_m = \frac{U_{max}}{I_{max}} \frac{(T_h - \Delta T_{max})}{T_h} \quad (4)$$

d. Thermal Power Thermoelectric Module

$$q_h = \alpha_m T_h I_{out} + \frac{1}{2} R_m I_{out}{}^2 + \frac{(T_h - T_c)}{Rthm} \quad (5)$$

$$q_c = \alpha_m T_c I_{out} - \frac{1}{2} R_m I_{out}{}^2 + \frac{(T_h - T_c)}{Rthm} \quad (6)$$

e. Electrical Heat Power Output

$$P_o = (q_h - q_c)$$

III. Results and Discussion

This study uses experimental methods and numerical calculations with the Excel program. Some of the stages carried out in this study include the first stage of data collection used for experiments such as research object specifications, TEM specifications, heatsink technical specifications, and tool technical specifications. The next stage is testing tools and materials, if the tools and materials are considered good then the research continues to the next stage. The next phase is to construct a thermoelectric generator circuit. The design in this study uses a cooling method on the thermal side of the Thermoelectric Module (TEM) by natural convection using a heatsink[27][28] [29][30][31]. In this research, experiments were carried out using 12 TEC1 12706 type thermoelectric modules arranged in series and parallel. The next stage was to experiment on a patrol boat as shown in Figure 3.

The experiment was carried out for 60 minutes. Furthermore, the parameter values obtained from the experimental results are calculated using a numerical method with the Excel program to determine the value of the electric power generated by the Thermoelectric Generator.

A. Specifications Data

1) Thermoelectric Module (TEM)

Using thermoelectric module type TEC1-12706: dimensions 40 mm x 40 mm x 3 mm, maximum working temperature 135 C, Vmax 16.1 volts, Imax 6.1 A, Resistance 2 ohms.

2) Heatsink

Using aluminum material, dimensions 300 mm x 120 mm x 30 mm, a thickness of 2 mm, and the number of fins is 12 fins.

3) Engine

Using Deutz engine type BF6M 1013 M, 180 kW power, 1800 rpm engine speed, 440-volt voltage, maximum exhaust gas temperature average 382 K, exhaust pipe diameter 250 mm. The tools used in this research are a multimeter, digital thermometer, mercury thermometer, aluminum plate holder, thermal paste, clamps, bolt nuts, pliers, screwdrivers, drills, and grinders.


Figure 3 Experimental and Measurement of Thermo Electric Generator

B. *Experiment test*

This experiment occurred for 60 minutes by measuring the temperature of the hot side (Th), Temperature cool side (Tc), DC Voltage (V), and Current (A). Furthermore, the result of parameter values are used to calculate the Coefficient Seebeck value (α), Thermal Resistance ($Rthm$), Electrical thermal resistance (R_m), Thermal power (q dan Power output (P_o) is shown in table 1 and 2. The experiment of the Parallel Circuit is shown in Table 2.

TABLE 1.
EXPERIMENT OF SERIES CIRCUIT

Variable	Value							Units
Time	0	10	20	30	40	50	60	Minute
Th	303.9	330.8	353.0	366.4	382.1	384.2	387.0	K
Tc	303.8	314.0	323.7	328.1	338.8	339.1	340.2	K
ΔT	0.1	16.8	29.3	38.3	43.3	45.1	46.8	K
Voltage	0	5.12	8.59	10.74	11.88	12.34	12.85	V
Current	0	0.24	0.36	0.41	0.46	0.48	0.49	A
αm	0	0.30	0.29	0.28	0.27	0.27	0.27	V/K
Rm	0	0.66	1.13	1.42	1.59	1.65	1.73	Ω
Rthm	1.86	1.82	1.79	1.77	1.75	1.75	1.75	˚K/W
qh	0	27.13	45.98	56.50	66.36	70.10	73.32	W
qc	0	25.94	43.03	52.34	61.23	64.56	67.44	W
Po	0	1.19	2.95	4.16	5.13	5.54	5.88	W

TABLE 2.
EXPERIMENT OF PARALLEL CIRCUIT

Variable	Value							Units
Time	0	10	20	30	40	50	60	Minute
Th	303,9	330.8	353.0	366.4	382.1	384.2	387.0	K
Tc	303,8	314	323.7	328.1	338.8	339.1	340.2	K
ΔT	0.1	16.8	29.3	38.3	43.3	45.1	46.8	K
Voltage	0	5.12	8.59	10.74	11.88	12.34	12.85	V
Current	0	0.24	0.36	0.41	0.46	0.48	0.49	A
αm	0	0.3	0.29	0.28	0.27	0.27	0.27	V/K
Rm	0	0.66	1.13	1.42	1.59	1.65	1.73	Ω
Rthm	1.86	1.82	1.79	1.77	1.75	1.75	1.75	˚K/W
qh	0	27.13	45.98	56.5	66.36	70.1	73.32	W
qc	0	25.94	43.03	52.34	61.23	64.56	67.44	W
Po	0	1.19	2.95	4.16	5.13	5.54	5.88	W

C. *Calculation for Power Generated*

The calculation of the power generated by the thermoelectric generator is carried out. The calculation process presented takes an example of series and parallel data at minute 60th. To get the electrical power value needs to know the value of coefficient Seebeck (α), Thermal Resistance ($Rthm$), Electrical thermal resistance (R_m), Thermal power (q dan Power output (P_o).

1) Coefficient Seebeck (α_m)

Based on Formula 2 : $\alpha_m = \frac{V_o}{\Delta T}$

The results Series circuit :

$$\alpha_m = \frac{12{,}85\ V}{46{,}8\ K}$$

α_m = 0.2746 (V/K)

The results obtained Parallel circuit :

$$\alpha_m = \frac{1{,}502\ V}{47{,}9\ K}$$

α_m = 0.0314 (V/K)

2) Thermal Resistance ($R_{th}m$)

Based on Formula 3 :

$$R_{th}m = \frac{\Delta T_{max}}{V_{max}\,I_{max}}\frac{2T_h}{(T_h-\Delta T_{max})}$$

The results Series circuit :

$$R_{th}m = \frac{70K \times (2 \times 387K)}{16\ V\ x\ 6{,}1\ A\ x\ (387K-70K)}$$

$R_{th}m$ = 1.7512 W/K

The results obtained Parallel circuit :

$$R_{th}m = \frac{70K \times (2 \times 387{,}8K)}{16\ V\ x\ 6{,}1\ A\ x\ (387{,}8K-70K)}$$

$R_{th}m$ = 1.7504 W/K

3) Electrical Resistance (R_m)

Based on Formula 4 :

$$R_m = \frac{V_{max}}{I_{max}}\frac{(T_h-\Delta T_{max})}{T_h}$$

The results Series circuit :

$$R_m = \frac{12{,}85\ V\ x\ (387K-70K)}{6{,}1\ A\ x\ 387K}$$

R_m = 1.73 Ω

The results obtained Parallel circuit :

$$R_m = \frac{1{,}5\ V\ x\ (387{,}8K-70K)}{6{,}1\ A\ x\ 387{,}8K}$$

R_m = 0.2 Ω

4) Thermal power input (q_h)

Based on Formula 5 :

$$q_h = \alpha_m T_h I_{out} + \frac{1}{2} R_m I_{out}{}^2 + \frac{(T_h-T_c)}{R_{th}m}$$

The results Series circuit :

$$q_h = 0{,}2746\ \frac{V}{K}\ x\ 387K\ x\ 0{,}49\ A + (0{,}5\ x\ 1{,}73\ \Omega\ x\ (0{,}49\ A)^2 + \frac{(387K-340{,}2\ K)}{1{,}7512\ {K}/{W}}$$

q_h = 73.32 Watt

The results obtained Parallel circuit :

$$q_h = 0{,}0314\ \frac{V}{K}\ x\ 387{,}8K\ x\ 0{,}86\ A + (0{,}5\ x\ 0{,}2\ \Omega\ x\ (0{,}86\ A)^2 + \frac{(387{,}8K-339{,}9\ K)}{1{,}7504\ {K}/{W}}$$

q_h= 37.90 Watt

5) Thermal power output (q_c)

Based on Formula 6 :

$$q_c = \alpha_m T_c I_{out} - \frac{1}{2} R_m I_{out}{}^2 + \frac{(T_h-T_c)}{R_{th}m}$$

The results Series circuit :

$$q_c = 0{,}2746\ \frac{V}{K}\ x\ 340{,}2K\ x\ 0{,}49\ A - (0{,}5\ x\ 1{,}73\ \Omega\ x\ (0{,}49\ A)^2 + \frac{(387K-340{,}2\ K)}{1{,}7512\ {K}/{W}}$$

q_c = 67.44 Watt

The results obtained Parallel circuit :

$$q_c = 0{,}0314\ \frac{V}{K}\ x\ 339{,}9K\ x\ 0{,}86\ A - (0{,}5\ x\ 0{,}2\ \Omega\ x\ (0{,}86\ A)^2 + \frac{(387K-340{,}2\ K)}{1{,}7512\ {K}/{W}}$$

q_c = 36.46 Watt

6) Electrical Power Output Thermoelectric (P_o)

Based on Formula 7 :

$$P_o = (qh - qc)$$

The results Series circuit :

P_o =(73.32 Watt – 67.44 Watt)

P_o = 5.88 Watt

The results obtained Parallel circuit :

P_o = (37.9 Watt – 36.46 Watt)

P_o = 1.44 Watt

D. Discussion

Result of measurement research on the patrol boat, the graph of temperature to the time in a series circuit is shown in Figure 4.

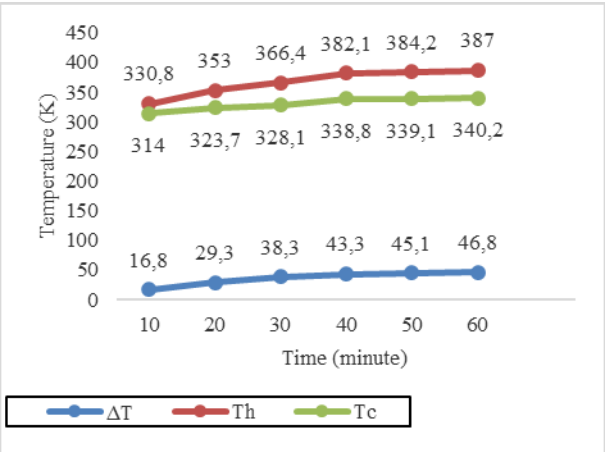


Figure 4. Graphic temperature to Time Circuit

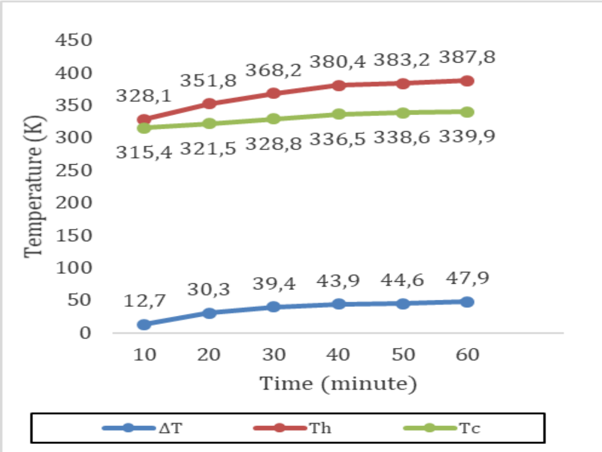


Figure 5. Graphic Temperature to Time Series Circuit

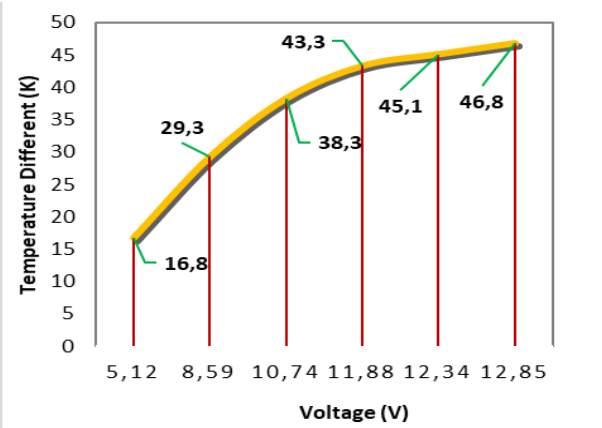


Figure 6. Graphic Temperature to Voltage Series Circuit

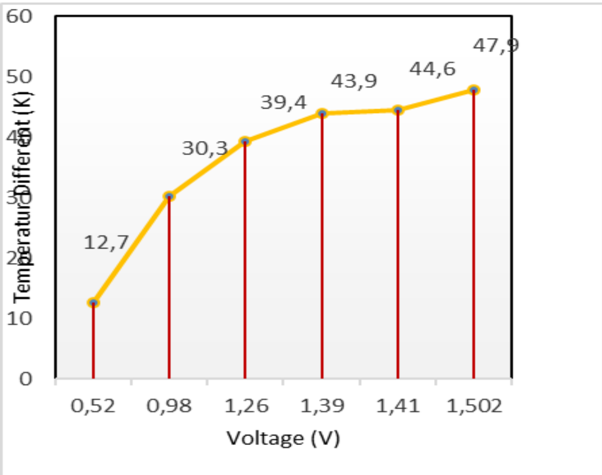
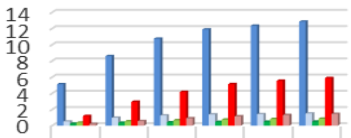


Figure 7. Graphic Temperature to Voltage Parallel Circuit

The graph of the temperature to the time in a parallel circuit is shown in Figure 5. Figures 4 and 5 show that the relationship between temperature to time is proportional if time increases make the temperature increase.

The difference in temperature (ΔT) graph to the time in a series circuit is shown in Figure 6. The difference in temperature (ΔT) graph to the time in a parallel circuit is shown in Figure 7. Figures 6 and 7 show that the relationship between the difference in temperature to voltage is proportional if the difference in temperature increases making voltage increase. A Diagram Comparison of series and parallel circuit diagrams is shown in figure 8. Figure 8 shows the comparison of voltage, current, and power produced in series and parallel circuits. The voltage generated by a series circuit is greater than the voltage generated in a parallel circuit. The current generated by a parallel circuit is greater when compared to the current generated in a series circuit. The power generated by the series circuit is greater when compared to the power generated in parallel circuits.



	10	20	30	40	50	60
Voltage series (V)	5,12	8,59	10,74	11,88	12,34	12,85
Voltage parallel (V)	0,52	0,98	1,26	1,39	1,41	1,50
Current series (A)	0,24	0,36	0,41	0,46	0,48	0,49
Current parallel (A)	0,38	0,54	0,66	0,75	0,83	0,86
Power series (W)	1,19	2,95	4,16	5,13	5,54	5,88
Power parallel (W)	0,21	0,57	0,90	1,15	1,30	1,44

Figure 8. Comparison Series to Parallel

CONCLUSION

Based on the experimental results obtained an electric voltage of 12.85 Volt DC and electrical energy of 5.88 Watt for a series circuit and produces an electric voltage of 1.5 Volt DC and 1.44 Watt electrical energy for a parallel circuit. It is known that the power produced by a series circuit is greater than the power generated in a parallel circuit. The proven thermoelectric generator can be applied on Patrol Boat.

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