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Energy and Exergy Analysis of Thermoelectric Generator Installed on Diesel Engine Exhaust Heat Recovery System

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ABSTRACT

Thermoelectric generators are a viable solution for capturing and producing power from the energy dissipated in vehicle exhaust. Exergy analysis facilitates the identification of irreversible losses during the transmission of exhaust energy. This research is essential for comprehending and developing methods for exhaust thermoelectric generators. This study provided a theoretical framework to analyse the operation of a thermoelectric generator exhaust utilizing the principles of thermodynamics. The practical and theoretical analysis assessed the energy and exergy of thermoelectric generator power generation utilizing the waste heat from diesel engine exhaust. Four TEG type 12706 units were mounted on the diesel engine exhaust muffler. The voltage, current, power output, and temperatures of the cold and hot sides were recorded at an engine speed of 2200 rpm and a brake-specific fuel consumption of 0.67 kg/hr. The peak voltage and current produced were 17.01 volts and 15.49 amperes, respectively. The largest temperature differential was 111℃, while the ambient temperature was 11℃. The analytical results indicate that conversion efficiency, exergy efficiency, and exergy destruction increased with rising temperatures on the hot side and ambient temperature. The conversion efficiency, exergy efficiency, and exergy destruction increased with the current and voltage output.

1. INTRODUCTION

Engines with internal combustion are extensively employed in decentralized power generation, marine transport, railroad transportation, and vehicles [1]. However, approximately thirty and forty per cent of the propellant energy is converted into useful mechanical energy output of labour [2]. Most fossil energy is squandered due to heat loss, including air charge, lowering water temperature, and exhaust emissions, so internal combustion engines' fuel consumption is exceedingly efficient [3]. Recovering waste heat is regarded as a highly - promising technical approach to enhance thermal efficacy and has become a prominent enterprise priority of research organizations [4, 5]. Numerous waste heat recovery devices have been studied to make fossil fuel use more efficient. The exhaust turbocharger has been extensively employed because it significantly enhances combustion and emissions [6, 7]. However, the energy contained in exhaust remains substantial and worthy and can be recovered practically [8, 9]. In recent years, thermoelectric generators have been implemented in numerous domains due to their exceptional dependability and lightweight [10]. Asaduzzaman et al. [11] found that the thermoelectric generator (TEG) system consisting of two commercially available bismuth telluride (Bi_2Te_3) TEG modules installed on an automobile engine's exhaust gas pipe produced a net output power of around 0.8 W. This power was created at an exhaust temperature of 155℃. Kanimba et al. [12] demonstrated that the TEG's power and effectiveness with two stages were 42 watts and 8.3%, respectively. In contrast, the power and the generator's efficiency have three stages, the thermoelectric generator's power output being 51 watts and using 10.2%. Despite this, it is less efficient than a three-stage TEG, which has a higher performance level and is highly recommended because it is expensive and heavy compared to the thermoelectric power generator with two stages. Sun et al. [13] concerning a single-stage TEG, a two-stage one connected in series results in a 10.9% rise in power output, a 12.4% conversion efficiency improvement, and a 12.5% improvement in exergy efficiency in a single-cylinder diesel engine exhaust heat recovery system. Chen and Chiou [14] have introduced a segmented structure for a TEG that achieves an efficiency of 14.05%, which is 21.94% more than that of an equivalent segmented TEG when used in an engine exhaust heat recovery system. Wang et al. [15] have suggested using a heated side heat exchanger with a dimpled surface in the SSTGS. This modification results in a 173.60% net power increase in production and a 20.57% decrease in the drop in pressure related to the SSTGS having a hot side heat exchanger inserted with fins. Imran and Hashim [16] investigated how temperature affected the hot side of power generation from the EWHR system, which uses TEG as a power generator. The four TEGs were used in the EWHR system. They found that the generated power from TEG increased as the hot side temperature of the TEG rose. It was installed on the external SI engine muffler of the single-cylinder engine.

Shen et al. [17] discovered that introducing the cylindrical EHEX channel with a hollow cylinder inside may enhance the thermoelectric efficiency of the engine exhaust system for recovering heat. This improvement is seen when the diameter of the cylinder is more than 75 mm, and the maximum net electrical output of the system can be close to 122 W. Imran et al. [18] installed four TEGS at the outside surface of the muffler to collect heat from the waste exhaust of the diesel engine. The heat exchanger's working fluid was water to cool the TEG's cold side. The final experimental outcome shows that increasing the temperature difference between the TEG's two sides enhances the generation of TEG power. Lamba and Kaushik [19] created a trapezoidal thermoelectric module thermodynamic model. They examined the relationship between the hot and cold side area ratios and the external load to the internal resistance ratio influence performance. The results deliver a reference point for the development of modules of thermoelectric power with improved energy efficiency exhaust heat recovery of ICE.

Manikandan and Kaushik [20] developed analytical formulas employing reversible models of irreversible thermodynamics for a two-stage generator energy conversion and exergy efficiency. It was brought to their attention that lowering the total area linked to the hot and cold sides of the generator would decrease the exergy efficiency. Bai et al. [21] conducted a computational and experimental analysis to determine TEG's best exhaust heat exchanger solution. They used the thermoelectric material to simultaneously mimic six distinct types of heat exchangers. The car's exhaust gas serves as the system's source of heat. They discovered that heat transfer was enhanced by the seven baffles in the serial plate structure with a 1737 W heat transfer rate. Liu et al. [22] constructed a practical device to produce electrical energy from the automobile's exhaust. The system used (TEG) based on (Bi2Te3). A heat source was created using the exhaust gas. The cooling water cycled to keep the variation in temperature between the TEG's hot and cold sides. They tested their creation by building it into a car. The most significant power obtained in their experiments was 944 W. Kim et al. [23] proposed using heat pipes as heat sinks in TEG-EWHR systems. Most literature designs deliver a TEG cold stream via a pump or fan. They opted for a passive cooling system. The heat pipe used water and the thermoelectric component was a Bi2Te3-based TEG. The maximum energy recovery of 350 W was achieved.

Abdelkefi et al. [24] created an electro-thermal analytical model to analyse thermoelectric modules. They then utilized information from prior research to validate their model. An analysis was conducted on the impact of various factors: temperature disparities, load resistances, hot side temperatures, and clamping pressures on a single thermocouple's electrical output power. Friedrich et al. [25] created a mathematical model to investigate the effectiveness of a (TEG) employing thermoelectric modules made of lead telluride (PbTe) and bismuth telluride (Bi2Te3). An experimental TEG model, consisting of 24 Bi2Te3 HZ-20 thermoelectric modules, was successfully incorporated into an experimental car. This system's power output was determined to be around 200 W. Gou et al. [26] constructed a model of theoretical dynamics for (TEG) equipped using a finned heat exchanger. Analyzed in this study were the variations in temperature over time on the cold and hot surfaces of the semiconductor, as well as the system's maximum power production and efficiency. These changes were examined by implementing step changes in the temperatures of the mass flow rates and the heat reservoirs.

Hashim and Imran [27] studied the relationship between temperature, both the hot and cold sides and time on TEG voltage generation. They installed one TEG to recover waste heat from the system's outside. The outcome shows that the increase in temperature difference causes an increase in voltage generation. Orr et al. [28] examined the power-generating their 3.0 L V6 engine's TEG capabilities and utilized heat pipes to accomplish a further adaptable TEG design for automobiles. They reduced CO_2 emissions by 1.57%, equivalent to 2.46% of the TEG's waste heat recovery performance.

The gap between this study and previous studies is that earlier studies relied on theoretical analysis only, while this study focused on theoretical analysis based on practical results according to reference number [29]. In addition, previous studies in their theoretical analysis relied on theoretical results for one TEG. In contrast, this study obtained practical and theoretical results for four TEG installed along the heat return system. In the theoretical part of the research, both the exergy degradation and the exergy efficiency were calculated in addition to the conversion efficiency to know the amount of energy lost and the extent of its effect on both the voltage and current generated by the thermal generator.

2. HEAT TRANSFER MODELING

Let Q_{hot} represent the rate at which the exhaust gas transmits heat to the TEGs, and let Q_{cold} represent the heat ejected from the TEGs' cold side. The relationship between The Conduction of Heat by Joule heating, Fourier Law, and the impact of Peltier heating on a given number of semiconductors may be expressed in this manner [11]:

$$Q_{hot} = N[K_{th}(T_{hot} - T_{cold}) - \frac{1}{2}I^2R_{int} + \alpha IT_{hot} \quad (1)$$

$$Q_{cold} = N\left[K_{th}T_{hot} - T_{cold} - \frac{1}{2}I^2R_{int} + \alpha IT_{cold}\right] \quad (2)$$

The symbol K_{th} represents the material's thermal conductivity. The symbol I represent the current passing from the p-type to the n-type semiconductor. T_{hot} represents the temperature on the hot side, while T_{cold} represents the cool side temperature. R_{int} represents the intrinsic opposition to the flow of electric current inside a conductor, whereas α (Eq. (3)) represents the Seebeck coefficient of a thermoelectric material, which may be mathematically expressed as [11]:

$$\alpha = \alpha_p - \alpha_n \quad (3)$$

where, α_p and α_n represent the semiconductors' respective Seebeck coefficients for p-type and n-type materials.

3. ELECTRICAL MODELING

The difference in the rate at which the voltage difference produces the power is equivalent to moving from the heated to the cooled side; heat is transferred. The output of electric power may be expressed as [30]:

$$P_{TEG} = Q_{hot} - Q_{cold} \quad (4)$$

And

$$P_{TEG} = I * V \quad (5)$$

4. EXERGY ANALYSIS AND ENERGY

The thermoelectric model and system equations used in this study's energy analysis are covered in-depth in a different publication [31]:

$$P_{TEG} = N\alpha I(T_{hot} - T_{cold}) - I^2 R_{int} \quad (6)$$

While N equals 127 p-n semiconductor pairs, for a single TEG, the temperature-dependent Seebeck coefficient element is denoted as α_{TEG} (V/K). This value is determined using the correlation [17]:

$$\alpha_{TEG} = 2 \times 10^{-9}(22224 + 930.6\, T_m - 0.9905 T_m) \quad (7)$$

$$T_m = \frac{T_{hot} + T_{cold}}{2} \quad (8)$$

We assumed that the temperature is evenly distributed throughout the whole.

$$R_{int} = N \times \left(\rho_p \frac{L_p}{A_p} + \rho_n \frac{L_n}{A_n}\right) \quad (9)$$

The p-n semiconductor components' cross-sectional lengths and sizes in the Bi_2Te_3-based TEG module are as follows [31]:

The area of A_p is equal to A_n and is measured at 1.96 mm^2. The length of L_p and L_n is equal and measures 1.6 mm.

The resistance to electricity of a single Bi_2Te_3 semiconductor leg was determined as [31], with its value depending on temperature and measured in ohms per meter (Ω/m).

$$\rho_n = \rho_p = \left(5512 + 163.4 T_m + 0.6297\, T_m{}^2\right) \times 10^{-10} \quad (10)$$

where: The definition of a single thermoelectric element's thermal conductance K_{th} (W/K) is as follows [31]:

$$K_{th} = K_p \frac{A_p}{L_p} + K_n \frac{A_n}{L_n} \quad (11)$$

where: The thermal conductivities k_p and k_n (W/ m·K) are regarded as [31]:

$$K_p = K_n = (62605 - 277.7 T_m + 0.4131 T_m^2) \times 10^{-4} \quad (12)$$

The energy analysis was derived based on energy conservation, a fundamental principle of thermodynamics, can be computed by [32]:

$$\eta_{th} = \frac{P_{TEG}}{Q_{hot}} \quad (13)$$

However, it does not deliver valuable insights into the best conversion of power [33]. The evaluation of the quality and extent of energy deterioration throughout a thermodynamic process may be done using the idea of exergy [34]. It is important to remember that the energy transfer system has thermodynamic irreversibility. Thermoelectric devices are especially vulnerable to exergy destruction problems caused by these losses. Thermal conductivity in thermoelectric legs, Joule heating, and heat transfer to the filler substance (structural support) are all internal irreversibilities that we confront.

Also, heat source, heat transfer at the heat sink, and fluid supply levels are examples of external irreversibility [35]. In general, the exergy balance can be used to calculate the energy destruction as shown [36]:

$$Ex_{hot} - E_{cold} = Ex_{dest,TEG} \quad (14)$$

It was demonstrated that the heat transfer between the cold and hot plates of the TEG modules, $Ex_{dest,\ TEG}$, results in the exergy destruction can be expressed as [35]:

$$Ex_{dest,TEG} = \left(1 - \frac{T_a}{T_{hot}}\right) . Q_{hot} - \left(1 - \frac{T_a}{T_{cold}}\right) . Q_{cold} - P_{TEG} \quad (15)$$

It is understood that the electrical power that is useful and produced by TEG can be computed using Eq. (4) and Eq. (15) became:

$$Ex_{dest,TEG} = T_a . \left(\frac{Q_{cold}}{T_{cold}} - \frac{Q_{hot}}{T_{hot}}\right) \quad (16)$$

To calculate the reversible work can be used the following relationship [37]:

$$W_{rev} = P_{TEG} + T_a\, S_{gen} \quad (17)$$

Lastly, the second law efficiency, commonly referred to as energy efficiency, was assessed using the expression [38]:

$$\eta_{ex} = \frac{P_{TEG}}{W_{rev}} \quad (18)$$

5. EXPERIMENTAL SETUP

Figure 1 displays the trial setup that works a single-cylinder diesel engine with four strokes, natural aspiration, and air cooling for the test apparatus. An electric swing dynamometer was connected to the engine to evaluate the engine's brake power and torque. By adjusting the swing dynamometer's speed, the engine was loaded throughout. A stopwatch and graduated cylinder may measure the engine's fuel consumption. A speed sensor was attached to the dynamometer shaft to measure the engine's speed. A type (k) thermocouple was inserted into the exhaust pipe to measure the temperature. To collect the hot exhaust gases, the heat recovery system was directly linked to the engine's exhaust port, which has a square cross-section of 280 mm in width and 8 cm in length; the silencer was constructed from cast iron to endure the exhaust gasses' extreme heat. On top of the engine silencer were attached four TEG type 12706. The TEG was positioned between two perforated copper blocks, one touching the heat source (engine exhaust) and the other with the heat sink (aluminum fins). The thermocouples are inserted through the grooves in the two-copper shim to determine the TEG's two sides' respective temperatures. The thermal interaction resistance between the connection surfaces of the heat recovery system is reduced by covering the contact point between the TEG, two copper blocks, and the silencer surface with thermal paste. The aluminum heat sink's measurements are (14×27×3.4) cm and contain 14 vents to lower the TEG's low-temperature side. The heat is transferred from the upper surface of the aluminum heat sink through a natural convection effect. Figure 2 illustrates the heat recovery system in a graphic format, while Figure 3 illustrates it in a schematic format. A voltmeter was used to measure the generated voltage.

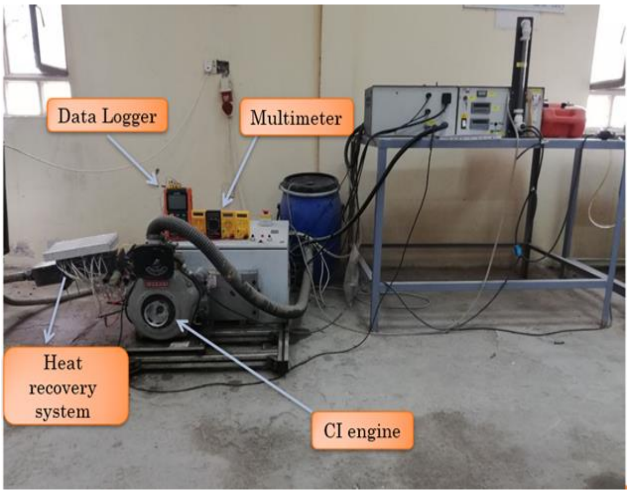

Figure 1. ICE test rig

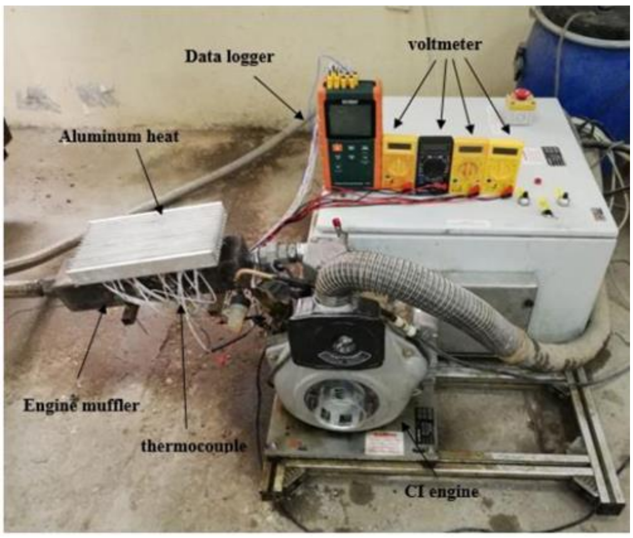

Figure 2. Heat recovery system

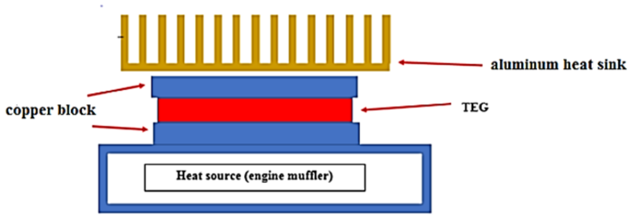

Figure 3. Heat recovery system schematic diagram

6. RESULTS AND DISCUSSION OF EXERGY AND ENERGY ANALYSIS

A program was used to perform the energy analysis for the exhaust system's heat recovery system. The calculations were based on the hot surface temperature, current, voltage and ambient temperature. The values were taken from practical experiments according to the reference [29]. The analysis results were as follows.

6.1 The analysis of energy and exergy efficiency with hot side temperature

Figures 4 and Figure 5 show that the energy efficiency and exergy efficiency increased with hot side temperature for the four TEGs placed at different positions on the surface of engine mufflers. The increase in both conversion and exergy efficiency with hot temperature is attributed to the rise in the speed of electron movement and its transfer from the heated to the cooled end. In this case, the chances of the electron falling into the gap will increase to form an electrical chain, which leads to an improvement in exergy and conversion efficiency [11].

Figure 6 shows the exergy distraction increased with hot side temperature. This increase was because the heat losses from the engine muffler's outer surface increased with increasing hot side temperature by convection and radiation heat transfer effect [8].

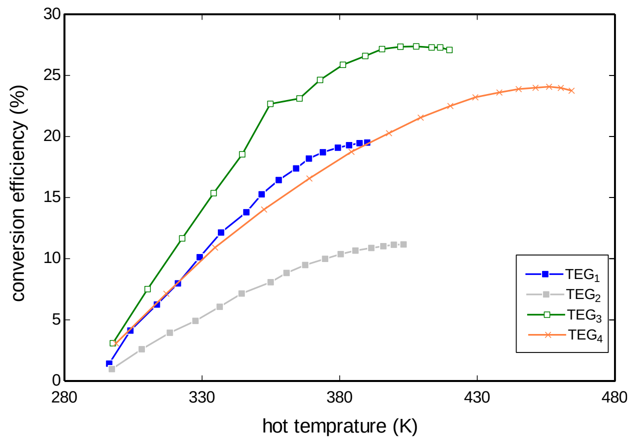

Figure 4. The relationship between hot side temperature and conversion efficiency

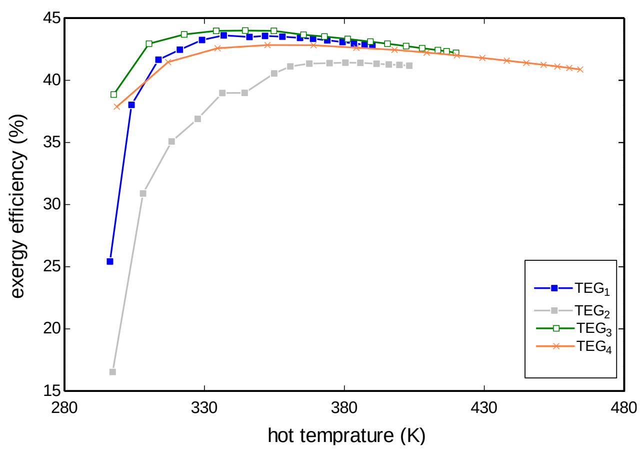

Figure 5. The relationship between hot side temperature and exergy efficiency

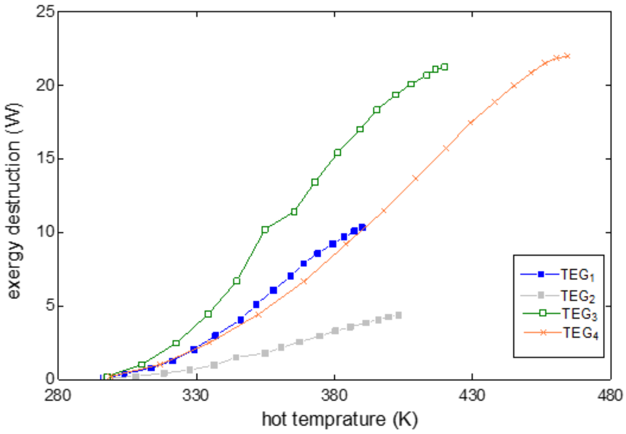

Figure 6. The relation between hot side temperature and exergy destruction

6.2 The analysis of energy and exergy with current generation

Figure 7 and Figure 8 show that the energy and exergy efficiency increased with the current generation for the four TEGS, which were placed at different positions on the surface of engine mufflers. This attitude of rising in the current generation is attributed to increasing hot side temperature, which plays an essential role in electron speed of motion and the time of electrical chain formation [11]. Figure 9 shows that exergy distraction has increased with the current generation. This analysis results attributed that the current generation grew when the hot side temperature rose as a result of an increase in electron speed to lessen the variation in temperature between the TEG's two sides as a result of heat losses to the atmosphere through convection and radiation as well as heat transfers from the hot to the cold side [14].

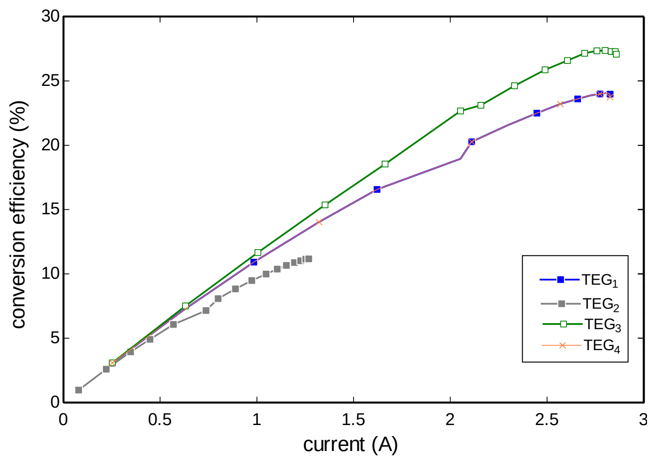

Figure 7. The relation between conversion efficiency and current generation

6.3 The analysis of energy and exergy with voltage generation

Figures 10 and 11, for the four TEGs, demonstrate how conversion energy efficiency and exergy efficiency increased with voltage generation., which were placed at different positions on the surface of the engine mufflers. The main reason behind the increase in the voltage that the thermal generator produces is the increase in the hot surface's temperature, and this is crucial in accelerating the flow of electrons from the heated surface to the cooled surface, which falls into a gap to form an electrical chain, which in turn is considered a generator of electrical energy [17]. Figure 12 shows the exergy distraction increased with voltage generation. According to the findings of this analysis, the voltage generation increased as the temperature on the heated side rose. This was attributed to the fact that the speed of the electron increased, which led to an increase in the amount of heat lost to the environment through radiation and convection. Furthermore, less heat was transferred from the hot to the cold side by conduction, which decreased the variation in temperature between the TEG's two sides [16].

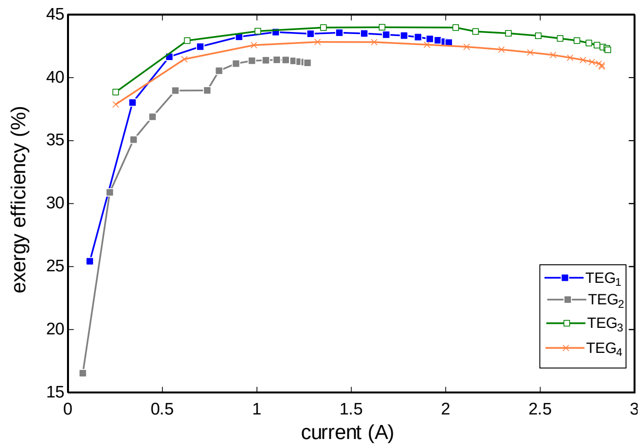

Figure 8. The relation between exergy efficiency and current generation

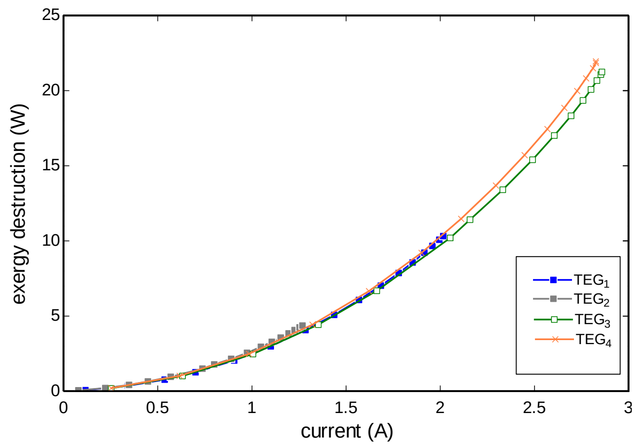

Figure 9. The relation between current generation and exergy destruction

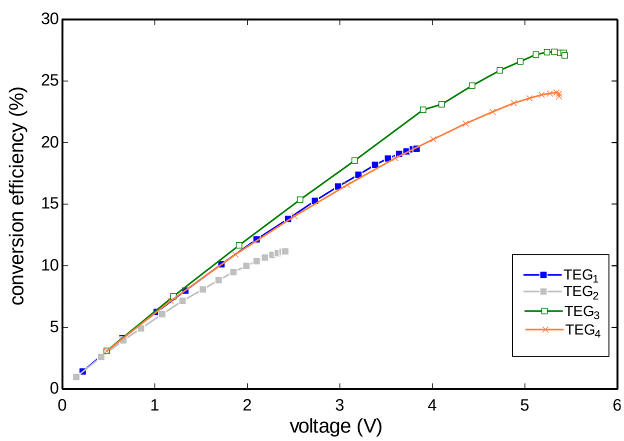

Figure 10. The relation between conversion efficiency and voltage

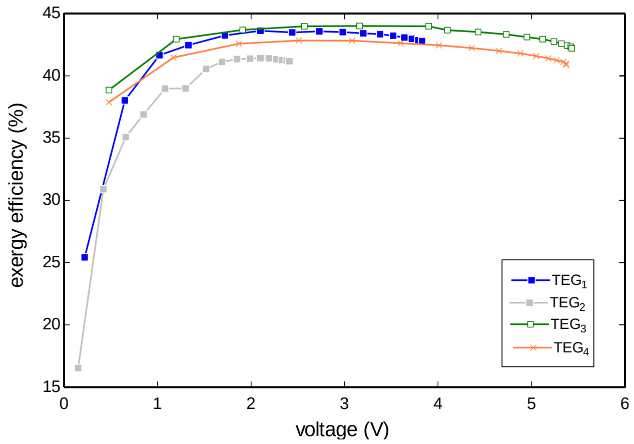

Figure 11. The relation between exergy efficiency and voltage generation

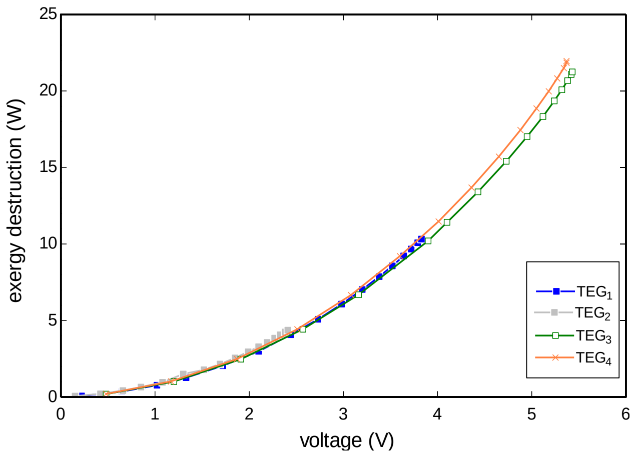

Figure 12. The relation between exergy destruction and voltage generation

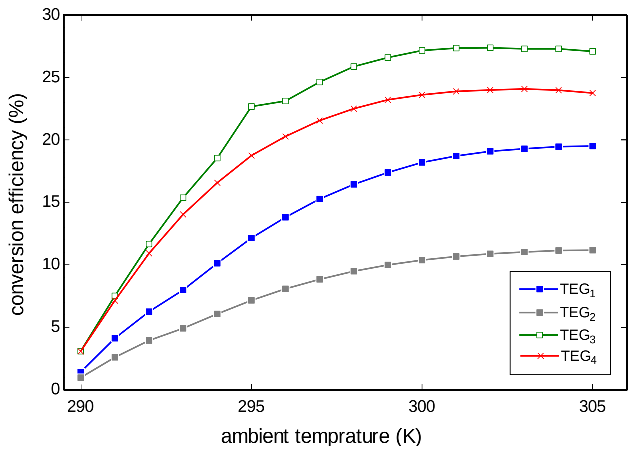

Figure 13. The relation between conversion efficiency and ambient temperature

6.4 The analysis of energy and exergy efficiency with ambient temperature

Figures 13 and 14, for the four TEGs, demonstrate how energy efficiency and exergy efficiency increased with ambient air temperature for different TEG which were placed at different positions on the upper surface of the engine mufflers. The main reason behind the increase in energy efficiency and exergy efficiency of TEG with increase in the ambient air temperature, attributed to that the electrons motion from the heated surface to the cooled surface will accelerated due to reduce the heat transfer between the outer surface and ambient because lowering the temperature difference between the ambient and muffler surface [21].

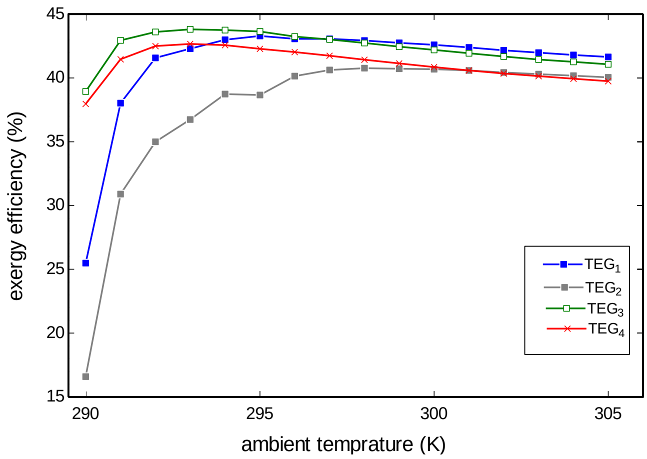

Figure 14. The relation between exergy efficiency and ambient temperature

7. CONCLUSION

After conducting the energy and exergy analysis using a program for the system of heat recovery from exhaust gasses emitted from a single-cylinder diesel engine, the tests were performed on it as found in the source, where the data from that source was adopted in calculating the energy conversion efficiency, exergy efficiency and exergy degradation. Among the data that was adopted are the hot and cold surface temperatures, voltage, and current for the thermal generator, where we reached a set of conclusions that will be enumerated as follows:

1. The conversion efficiency, exergy efficiency, and exergy destruction grew as the temperature on the hot side rose.
2. The current generation has improved conversion efficiency, exergy efficiency and destruction.
3. The conversion efficiency, exergy efficiency and destruction increased with the increase in voltage generation.
4. The energy efficiency and exergy efficiency increased with ambient air temperature for different TEG.
5. The reasons that control all the previous results mentioned in the first, second and third paragraphs can be summarized as the increase in the temperature of the hot surface has a direct effect on the speed of electron movement between the hot and cold sides, which increases the chance of the electron falling into the gap and forming an electrical chain quickly, in addition to the factor of heat loss to the surroundings by radiation and convection, as well as heat transfer between the two sides of the thermal generator by conduction.

8. FUTURE WORK

The future plan of action is to analyze all the factors analyzed in this research paper using other types of heat generators or using another design of heat exchanger in which the exhaust gases flow. In addition to using another cooling method by which the cold end can be cooled in order to increase the generated voltage.

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NOMENCLATURE

TEG	thermoelectric generator
SSTGS	single stage thermoelectric generator
Bi_2Te_3	bismuth telluride
EHEX	exhaust heat exchanger
ICE	internal combustion engine