A Heat Recovery Method of Internal Combustion Engine Using a Thermoelectric Generator

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Abstract The means by which engines lose energy include losses such as friction between the moving parts and heat. The heat losses are larger than the friction losses, and the largest portion of heat loss occurs in the exhaust system. The recovery of heat losses represents a power gain by the process and reduction in engine fuel consumption. An experimental study was conducted for utilizing waste exhaust heat to generate electricity using thermoelectric generators. The test engine was a four-stroke, single-cylinder, air-cooled spark ignition (SI) engine. Four thermoelectric generators were installed at the upper surface of the engine silencer, with two aluminium heat sinks in order to decrease the cold side temperature. The experimental results showed that the generated voltage from the four thermoelectric generators went up with increase in the hot side temperature, and time. The maximum voltage generated was 11 volts under natural convection effect. The study was accomplished at engine speed 2200rpm with brake power 1473.77 W and fuel consumption of 0.83kg/hr.

Key Word: Waste Heat, Temperature Difference, TEG, SI Engine

1. Introduction

The scarcity of fuel and the CO₂ of emissions due to the combustion process of fossil fuel have forced engine researchers and manufacturers to find ways to reduce the waste thermal energy and increase engines’ thermal efficiency. The largest proportion of the heat lost from the engine transfers through the exhaust system. Researchers have suggested installing a thermoelectric generator (TEG) at the outer surface of the exhaust system to recover some of this heat [1]. The thermoelectric generator changes the heat energy into electrical energy, which can be used later to recharge the vehicle’s battery or for another purpose. The installation of a TEG rises the engine’s thermal efficiency due to reduction or elimination of the alternator load. Mohite et. al. [2], studied the effect of temperature on power recovery by TEG at different engine speeds. The experimental work was accomplished via placing two thermoelectric modules at the upper wall of a motorcycle engine silencer with the aluminum heat sink. The experimental results reveal that the high-power recovery was 11.837 watt with a hot side temperature of 398°C at an engine speed of 9000 rpm. Buchalik et. al. [3], studied the influence of the high temperature side on power recovery by TEG in a
small-sized petrol engine. Their experimental work was conducted at a constant speed with different values of engine torque. The test rig was provided with a heat flux control system, to allow the TEG to work under different engine operating conditions without damage. The maximum power recovered from single TEG was 11 watts at engine speed 2000 rpm. Khalil [5] experimentally investigated the influence of TEG use on SI engine pollution emissions. Ten TEG cells were installed on the upper wall of the square-shaped engine silencer in the opposite direction. The results showed that the heat recovery system reduced the exhaust gases’ opacity, due to the reduction in fuel consumption.

Ravi et. al. [6] installed the TEG at the upper surface of the cooling system to benefit from dissipated heat. Their TEG was set up at the outer surface of a two-stroke engine with cooling by fins. The maximum voltage generation was 3-4 V, which was stored in a supercapacitor for use in engine operation requirements. Gupta et al. [7] studied the effect of the temperature difference between the two faces of TEG on voltage generation. The heat recovered from the outer surface of the rail engine, in which the TEG was installed. The cooling side of the TEG was cooled via atmospheric air; the thermoelectric generator was fitted perfectly to receive the largest amount of heat to generate voltage. Dai et al. [8] studied the effect of using liquid metal in waste heat recovery systems as a working fluid with an electromagnetic pump. Fourteen TEGs were fitted at the upper wall of the silencer. The open circuit voltage from waste heat was 34.7 V.

R. Stobart et al. [9] studied the effect of heat exchanger design in heat recovery system on both diesel and gasoline engine performance. Their analysis was of the effect of back pressure development on both the heat exchanger behavior and the overall engine performance. The heat recovery system design included 18 TEGs. The experimental results revealed that the increased back pressure created by the waste heat recovery system design was insignificant, and had little effect on the overall engine performance. Orr et al. [10] reviewed the effect of the temperature difference between the TEG’s two sides on energy generation. The cooled side temperature was reduced by using heat pipe to prevent the thermoelectric generator damage. Kumar et al. [11] studied the effect of heat exchanger design on heat recovery system efficiency. The best design selection in their study depended on theoretical analysis using computational fluid dynamic and cad program. The theoretical results showed that the square section was more efficient for heat transfer in a heat recovery system, which was used in a spark ignition system. The number of TEGs used in the heat recovery system was 18, connected together in series to produce 25 W. The waste heat recovery process generated savings in fuel and decreased engine emissions.

In our previous work, the effect of hot side temperature, temperature difference, and cold side temperature with respect to time on the voltage generated by TEG was studied. A single TEG type (12706) was fitted at the outer wall of the engine silencer [1]. The maximum voltage generation from TEG was 5 V, with hot side temperature and the temperature difference of 195°C, 121°C respectively. In the present work, the number of TEGs has increased and the design of the heat recovery system has been improved. The experimental work was accomplished at a lab room temperature of 33°C and relative humidity of 60%, with maximum temperature difference of 75.3°C to produce more voltage.

2. Basic Theory of Thermoelectric Generator

The thermoelectric generator represents a free energy resource that operates on the Seebeck effect, which was identified by Thomas Seebeck in 1821[13]. The change in temperature between high and low temperature junctions of two different metals or semiconductors causes voltage generation [14]. The
heat energy transfers from the hot engine muffler surface to the hot side of the TEG surface activates the motion of electrons and holes, which later form electrical series when electrons meet holes. The electrons and holes transfer between the hot and cooled sides due to the difference in temperature between both sides. Figure 1 is a photograph of the thermoelectric generator.

![Figure 1 Thermoelectric generator components.](image)

3. Experimental Work

The specifications of the engine used in the experimental work were four-stroke, air-cooled (S. I. Engine), single cylinder, swept volume of 175 cm$^3$. The engine was coupled to an electrical dynamometer via a belt to measure the brake torque. Figure 2 shows the experimental rig, and the main technical specifications of the engine are listed in Table 1. The speed of the dynamometer can be controlled or adjusted by the control system. The control system comprises software and hardware, which operate according to the information received from the speed sensor and torque sensor.

The speed of the dynamometer can be adjusted by a switch fitted at the lid of the dynamometer box. The combustion system test rig includes an air measuring system, which comprises a special air box and manometer, calibrated by the Armfield Company. The combustion system test rig includes a liquid fuel supply system, which is provided with fuel measuring system used to measure the fuel consumption during engine operation. There is also a waste heat recovery system, designed and fabricated in the lab. The waste heat recovery system in Figure 3 consists of four commercial TEGs which were installed on the upper wall of the square section engine which has dimensions of 8cm×8cm×70cm. The thermoelectric generator was fitted between the two aluminum small blocks, which have dimensions of 50×50×10 mm. The aluminum block includes a hole to fix the thermocouple to when measuring the temperature of cold and hot face of the thermoelectric generator. The contact surfaces of the two aluminum blocks, thermoelectric generator, source of heat, and aluminum fins are coated with a very thin layer of thermal paste which has a thermal
conductivity of 2.5 W/m.k, to reduce the thermal contact resistance. The generated voltage (open circuit voltage) from the heat recovery system is measured using a multimeter.

The aluminum heat sink, which has dimensions of 20cm×15cm×6cm, was fitted at the upper wall of the thermoelectric generator in order to create temperature difference across the TEG.
The generated voltage value depended on the temperature difference between the hot and cold sides of the TEG. The temperatures of the hot and cooled side of the TEG were measured by using eight thermocouples type (k) and data logger. All of the measurements were taken at constant engine speed; the temperature of the lab was 33°C and relative humidity was 60%.

4. Mathematical Model of the Engine Performance
The engine parameters can be calculated according to the following function:

\[
\dot{m}_f = \frac{V_F}{\text{time}} \times \rho_F \left(\frac{\text{kg}}{\text{sec}}\right) \quad \text{……………….} \quad (1)
\]

and the brake power as:

\[
bp = \frac{2\pi N T_b}{60+1000} \left(\frac{\text{kW}}{\text{sec}}\right) \quad \text{……………….} \quad (2)
\]

The Brake specific fuel consumption

\[
\text{bsfc} = \frac{\dot{m}_f}{\dot{b}p} \times 3600 \left(\frac{\text{kg}}{\text{kw.hr}}\right) \quad \text{……………….} \quad (3)
\]

and the air consumption (S.I. engine)

\[
\dot{m}_{a,act} = 2.056 \times 10^{-4} \times \sqrt{\frac{V_F}{\text{sec}}} \left(\frac{\text{kg}}{\text{sec}}\right) \quad \text{……………….} \quad (4)
\]

Finally, brake thermal efficiency

\[
\eta_{b\text{th}} = \frac{bp}{\dot{m}_f + \dot{L} C_V} \quad \text{……………….} \quad (5)
\]

5. Methodology

The engine was filled with sufficient fuel to run the engine for at least one hour. The thermocouples were inserted inside the holes, which were drilled inside the aluminum block to measure the temperatures across the two thermoelectric generators. The thermocouples were fixed perfectly, to avoid the thermocouples’
separation from the holes due to engine vibration during operation. Thermal paste was used to fill the gaps between thermoelectric devices and the cold and hot sides. The thermocouple wires were connected to the data logger. Finally, the experimental results, such as; hot temperature, cold temperature, output voltage and time, were collected using a mobile camera.

6. Results and Discussion

The experimental results were presented to confirm the process of converting the waste heat to the electrical energy. The conversion of energy was accomplished via using TEG. The engine silencer was used to heat the hot side of TEG, while the cold side of the TEG was cooled by natural convection. The experimental results demonstrated that the hot face temperature increased with respect to time, as shown in Figure 4, at the engine speed of 2200rpm. The brake power was calculated based on the equation (2) and it was 1473.77 W, while the fuel consumption was 0.83kg/hr based on equation (1).

![Figure (4) the relation between the time and hot side temperature.](image)

The voltage output from each TEG increased with time due to increasing temperature on the hot side as shown in Figure 5. Also, the total generated voltage when connected the four thermoelectric generators in series raised with the time as shown in Figure 6, the higher voltage generated by the heat recovery system was 11.01 volt. The voltage generation in each thermoelectric generator increased with raised the hot face temperature as shown in Figure 7.

The generated voltage from each thermoelectric generator increased with the increasing difference in temperatures between the hot and cold faces of the TEG, as shown in Figure 8. The temperature difference increased over time as shown in Figure 9. This behavior, of increasing voltage generation with the hot side temperature or temperature difference and time, can be attributed to the increase in hot side temperature increasing the electron speed of motion through which can be increased the probability of uniting electron
with hole to form an electrical series. A comparison between previous studies and the present work is given in Table 2, which summarizes the experimental results such as engine speed, output power, output voltage numbers of TEGs and hot side temperature.

Figure 5. The relationship between the time and voltage generation in each thermoelectric generator.
Figure 6. The relationship between the total voltage generation and time.

Figure 7. The relationship between the voltage generation in each TEG and hot face temperature.
Figure 8. The relationship between the voltage generation in each thermoelectric generator and temperature difference.

Figure 9. The relationship between the temperature difference and time.
7. Conclusions

The waste heat recovery process from an SI engine at a constant speed via use of a heat recovery system, which includes a TEG, yields the following conclusions:

1- The wasted heat has been successfully recovered by the TEGs and recovery system.

2- The voltage generated from the TEG was increased with increase in the temperature difference between the hot and cold sides of the thermoelectric heat generator. The total maximum voltage generated was 11.01 volts, with maximum temperature difference 75.3°C. The hot face temperature, cold face temperature, and temperature difference increased with respect to time.

3- The brake power was calculated based on the equation (2) and all the measurements were done at 1473.77 W.

4. Increasing the numbers of TEGs resulted in increasing the voltage output.

5- Future work could helpfully measure the fuel that can be saved due to electrical power that may be generated by a TEG.

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