Experimental testing and applications of power obtained by thermoelectric generator using exhaust

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ABSTRACT

The internal combustion engine (ICE) does not efficiently convert chemical energy into mechanical energy. A majority of this energy is dissipated as heat in the exhaust which is about one-third of the total energy produced during combustion. To improve the efficiency of the engine indirectly by using a system to recover waste heat from the exhaust, the technology useful for this purpose is thermoelectric generators (TEGs). Thermoelectric generators are an environment friendly source of electric power which make use of the Seebeck effect to convert a difference in temperature between hot and cold side of thermoelectric generator into electricity. Heat pipes are used to reduce the thermal resistance in the system, as well as temperature regulation of the TEGs. TEGs have limitations, such as low temperature limits and relatively low efficiency, and heat pipes also have some limitations such as maximum rates of heat transfer and temperature limits. But both of TEG and heat pipe are durable and cost effective. This study presents TEGs experimental test to provide accurate TEGs performance data at the various range of temperature difference and design a heat dissipation setup for TEGs to analyse the efficiency obtained from heat dissipated in the exhaust. The present study also includes the applications of the experimental power obtained from the setup of TEGs.

**Key words**: Four stroke engine, camshaft, inlet valve, exhaust valve.

**Abbreviations**: TEGs, thermoelectric generators; IC Engines, internal combustion engine.

INTRODUCTION

In the last few years, the fluctuation in oil prices, change in environment due to hazardous gas expelled during combustion of IC engine and depletion of natural resources have drawn attention towards renewable energy technology and waste heat recovery technology. The current IC engines have efficiency of about 25-45% depending upon the engine type and working conditions. There are various waste heat recovery technologies such as the use of TEG’s, six stroke engine, regenerative braking etc. In comparison with other waste heat recovery technologies, the use of TEG’s has many advantages such as silence, small size, low in cost and durability (Orr et al., 2016). A TEG operates at approximately 20% of the Carnot efficiency over a range of temperature (Meisner, 2010).

Thermoelectric generators works on Seebeck effect for the direct conversion of heat into electric energy. For insulators, seebeck coefficient can be very high, but electrical resistance is very high. Electrical resistance is very low, seebeck coefficient is very low as well, but thermal conductivity is too high for metals. There are semiconductors of materials with adequate value of Seebeck coefficient, acceptable resistance range that can be
tuned by doping, and low thermal conductivity (Meisner, 2010). Therefore, TEG’s are made up of N and P type elements that are connected electrically in series and thermally in parallel (Goldsmid, 2014). The electric power is obtained by heating one side of the arrangement while keeping the other side cooled. The efficiency of a TEG is defined as the ratio of generated electric power and the heat input into the generator:

$$\eta = \frac{P_{\text{TEG}}}{Q_{\text{H}}}$$  \hspace{1cm} (1)

Figure 1 shows the schematic of a thermoelectric generator. When there is a temperature difference between two sides, a small voltage is generated. As all TEG’s are connected in series, these small voltages add up to generate usable voltage. The amount of voltage generated by the TEG is proportional to the temperature difference and the amount of electrical power produced is proportional to the square of temperature difference. The most common thermoelectric material is Bismuth Telluride (BiTe) but other thermoelectric materials are also available. For the purpose of classifying thermoelectric materials, three major parameters are considered: Electrical conductivity $\sigma$, thermal conductivity $K$, and Seebeck coefficient $S$. Their thermal efficiency typically peaks at around 5% (Al-Habahbeh et al., 2018).

This study focuses on the prospects of TEGs being used to produce power from waste heat sources. The possible use of a device consisting of numerous TEG’s in the wasted heat recovery of an internal combustion engine can considerably help the world effort for energy savings. Furthermore, the temperatures developed vary from high (about 900°C at exhaust manifold) to medium (about 100°C in the engine coolant fluid) and thus the efficiency of the thermoelectric elements could be sufficient. This study focuses on investigating the amount of power that could be recovered from the exhaust pipe of an IC engine with the use of thermoelectric generators and to examine whether such a solution could be beneficial in the automotive industry. However, the procedure used can also be applied for thermoelectric generators with a higher “figure of merit” ZT and respectively higher power output. A measurement method and a theoretical and experimental model have been developed to measure the power output and efficiency for different electric charges and temperature gradients. Figure 2 shows the thermoelectric generator module used in the experimentation.

**EXPERIMENTAL SETUP**

The experimental setup consisted of a high precision response controlled hot plate where the TEG being tested was placed on top with the hot side of the TEG on the hot plate (Figure 3). K-Type thermocouples were used on both hot and cool sides of the TEG to measure the actual temperature of each side. Aluminum heat sink with copper core was used to cool down the cold side of the TEG by forced convection using an electric axial fan. Thermal paste having thermal conductivity of 0.925 W/m-k was used.
between all the different layers to ensure proper heat transfer, and at last, the setup was attached to the hot plate to maximize the accuracy of the results.

The K-Type thermocouple was placed between the TEG and the hot plate to measure the temperature of hot side, thermal paste was used to ensure thermal conductivity from the plate to the TEG. The second thermocouple was placed on top of the TEG and fastened to the cold side of it, and thermal paste was used to ensure thermal conductivity. The heat sink was then placed on top of the cold side of TEG.

The complete setup was then held to the hot plate as any movement will affect the accuracy of the measurement. Both thermocouples were attached to temperature data logger, and a digital multimeter was used to measure the TEG opencircuit voltage, or short circuit current. The hot plate temperature was then varied to measure TEG output at various temperature difference. The TEG was set up, allowing enough time between changes for the TEG temperature to reach steady state and the generated voltages to stay at a constant level. The readings were recorded, and a next setting at different temperature was applied (Figure 4).

**TEG efficiency calculation**

The efficiency of a thermoelectric generator can be calculated using various methods. It depends upon seebeck coefficient, thermal conductivity and electrical resistivity. Figure of merit also depends upon these three factors and efficiency can be measured in terms of figure of merit (Z).

Figure of Merit:

\[ ZT = \frac{S^2 T}{K \rho} \quad (2) \]

Efficiency of a TEG:

\[ \eta = \frac{\left[(T_H - T_C) / T_H\right] \times \left[(\sqrt{1 + ZT}) - 1 / (\sqrt{1 + ZT}) + T_H / T_C\right]}{1 + ZT} \quad (3) \]

Here, \( T_H \) and \( T_C \) indicate temperature of hot side and cold side, respectively.

Four basic physical phenomena are associated with the functioning of thermoelectric generators, namely, the Seebeck effect, the Peltier effect, the Thomson effect and Joule effect. Under steady state conditions, the impact of these four factors to energy flow, through a unit volume is expressed as follows:

\[ T J \frac{dS}{dx} + \Gamma J \frac{dT}{dx} - \rho J^2 - \frac{d}{dx}(K \frac{dT}{dx}) \quad (4) \]

Where, \( T \) is the temperature, \( J \) is the electrical current density, \( \alpha \) is the Seebeck coefficient, \( \tau \) is the Thomson coefficient, \( \rho \) is the electrical resistivity and \( K \) the thermal conductivity of the material. Neglecting the effect of Thomson effect, as small, the equation that directs the heatflow at the hot side is:
The experimental setup consists of TEG, hot plate and heat sink with temperature indicator and digital multimeter (Musleh et al., 2017).

\[ Q_H = K_{TEG}(T_H - T_C) + S_{TEG}T_HI - \frac{1}{2}I^2R_{TEG} \]  
(5)

Where \( K_{TEG} \) is the total thermal conductance, \( S_{TEG} \) is the total Seebeck coefficient and \( R_{TEG} \) is the total resistance. Similarly, the heat flow from the cold side is:

\[ Q_C = K_{TEG}(T_H - T_C) + S_{TEG}T_CI + \frac{1}{2}I^2R_{TEG} \]  
(6)

Thus, power produced by the module is expressed as:

\[ P_{TEG} = Q_H - Q_C = S_{TEG}(T_H - T_C)I - I^2R_{TEG} \]  
(7)

\[ P_{TEG} = V_{TEG}I \]  
(8)

Therefore, the voltage produced by thermoelectric generator is:

\[ V_{TEG} = S_{TEG}(T_H - T_C) - IR_{TEG} \]  
(9)

Hence, for a thermoelectric generator \( P_{TEG}, V_{TEG} \) and \( \eta \) can easily be calculated, if the material properties are known. TEGs are connected in series to add up the voltages produced by individual module, this will help us to use TEGs in various applications. According to the voltage required for the operation of a particular component, the number of TEGs are selected on this basis.

**Automotive waste heat recovery systems using TEGs**

Large multinational car companies such as BMW (Lagrandeur, 2006), Ford (Hussain et al., 2009), Renault (Espinosa et al., 2010) and Honda (Mori et al., 2011) have showed their interest in exhaust heat recovery, developing systems that make use of TEGs. All of their designs are relatively similar. The TEGs are placed on the exhaust pipe surface (shaped as a rectangle, hexagon, etc.) and they are cooled with cold blocks using engine coolant. Examples of a rectangular shaped and hexagonal shaped heat exchanger can be seen in Figures 5 and 6, respectively (Saqr et al., 2008). This technology has not yet been installed in present production cars and is still in the concept stages.

The BMW system uses a shell and tube heat exchanger. High temperature TEGs are used and the system is rated to produce 750 W from a number of 20 W rated TEGs. The Ford system heat exchanger uses many small parallel channels lined with thermoelectric material for the exhaust gases to pass. The Renault system is to be used on a diesel truck engine. It has dimensions of 10 cm × 50 cm × 31 cm.
Figure 5: Rectangular exhaust heat exchanger using TEGs.

Figure 6: Hexagonal exhaust heat exchanger using TEGs (Orr et al., 2016).
This system uses a counter flow heat exchanger arrangement using liquid cooling. A combination of high temperature TEGs at the high temperature end and low temperature TEGs at the low temperature end were used. The modelled system is assumed to produce approximately 1 kW.

A model of a system of a number of TEGs arranged in series can be developed in various shapes such as rectangular and hexagonal exhaust heat exchanger. A rectangular exhaust heat exchanger consists of exhaust gas inlet through which gas enters, exhaust gas exit through which gas leaves, cold plate, cooling water inlet and exit port, hot box and assembly of TEGs. Thermoelectric generators are arranged in series connection to form a set. A number of sets are also placed parallel to one another to increase the output power. The model is surrounded by cooling water which is flowing above the cooling side of thermoelectric generator. The cooling water enters through one end above the cold plate and after circulating throughout the exchanger over the cold side of module, it leaves from other end above cold plate. The exhaust gas is directed to a path as shown in Figure 5. This will increase the temperature of hot side of thermoelectric generator and thus maintain an appropriate temperature difference between the two sides of the module. The exhaust gas leave from the other side of the heat exchanger.

Other type of model is hexagonal exhaust heat exchangers. It has support structure, hot box, cold plate, springs and adjusting screws (Figure 6). Thermoelectric modules are arranged in a hexagonal shape around the hot box with hot and cold side of the module placed at inside and outside of box, respectively. The exhaust gas flow inside the hot box resulting in increasing temperature of hot side of thermoelectric generator and cold plate is placed outside the hot box on the opposite side of the module, that is, cold side. The whole system is supported by a support structure with the help of springs and adjusting screws.

The Honda system used a simple design of a thin flat rectangular box with TEGs placed on the top and bottom surfaces. Liquid cooling was used in this design. The system consisted of 32 30 mm × 30 mm TEGs and produced a maximum of approximately 500 W. The fuel consumption reduction is 3%. An image of the prototype from Honda can be seen in Figure 7.

Other heat exchanger designs have been discovered such as that designed by Dai et al. (2011) which used finned air cooled aluminium heat sinks. This system used 24 BiTe TEGs and generated a maximum of 12.41 W with an average temperature difference of 30°C.

**ANALYSES AND RESULTS**

The parameters used in the calculations are seebeck coefficient, thermal conductivity and electrical resistivity as shown in Table 1. The Seebeck coefficient of a material is a measure of the magnitude of thermoelectric voltage developed due to a temperature difference across that module, as induced by the Seebeck effect. Thermal conductivity is the rate at which heat passes through a specified material; the lower the value of thermal conductivity, the greater will be the temperature difference across two sides. Electrical resistivity is the ability of a material to oppose the electric current, normally semiconductors have lower value of resistivity. Thus, they give large value of ZT.

Figure 8 shows the measured and calculated values for the output power $P_{TEG}$ for various values of voltage developed across the two sides of TEG. From the figure, it can be seen that the power is increasing with increase in voltage developed due to temperature difference across thermoelectric generator. When several thermoelectric generators are arranged in series, the voltage developed will also increase and result in increase in power significantly which can be efficiently used.

Figure 9 shows the measured and calculated values for the efficiency of TEG, for various values of voltage developed. From Figure 8, it can be seen that the power increases and accordingly the maximum efficiency increases with the increase voltage developed due to the temperature difference across the two side of TEG module.

Figure 10 shows the measured and calculated values for the output power $P_{TEG}$ for various values of temperature difference across the TEG. From the figure, it can be seen that the power increases with increase in the hot-side temperature with temperature of the cold side held constant. Temperature of the cold side is held constant with the help of coolant and the temperature of the hot side of the TEG module is raised and the output power is measured.

Figure 11 shows the measured and calculated values for the efficiency of thermoelectric generator, for various values of temperature difference across it. From Figure 10, it can be seen that the maximum power and accordingly the maximum efficiency increase with increasing change in temperature. For the measurement of change in temperature, the hot-side temperature of the thermoelectric generator increases within the range of TEG module to obtain the maximum efficiency with the temperature of the
The experimentsetup was tested for different values of input heater voltage. Due to different value of input heater voltage, different temperatures were developed at hot side of TEG. Due to this, a temperature difference was developed between hot side and cold side of thermoelectric generator, which result in development of voltage and hence power. Voltage produced by TEG is depended upon temperature between hot and cold side of module. These results clearly show that value of power produced by TEG increases with increase in temperature difference. The same trend goes with the efficiency of thermoelectric generator. The maximum efficiency obtained in this experiment was 2.25%. It can be increased using thermoelectric generator of improved properties such as higher seebeck coefficient, lower thermal conductivity and lower value of electrical resistivity. When large number of TEGs are assembled in series, the output voltage, power and efficiency are much higher than those obtained from a single thermoelectric generator.
Figure 8: Power vs Voltage Graph for a TEG module.

Figure 9: Efficiency vs Voltage Graph for a TEG module.
Figure 10: Power vs Temperature difference graph for a TEG module.

Figure 11: Efficiency vs Temperature difference graph for a TEG module.
Conclusions

This study describes an experimental setup for measuring the instantaneous power generation and efficiency of a thermoelectric generator. The power generation and efficiency were calculated and plotted for different values of temperature difference and input heater voltage. The maximum temperature difference tested was 70.2°C and this produced an efficiency of 2.25% and an output power of 1.21 watts. While this efficiency might seem low, thermoelectric generators are known for their relatively low conversion efficiency. Also, the maximum temperature difference tested in this experiment is fairly ordinary, higher temperature differences would result in higher efficiency. Typical thermoelectric devices require a temperature difference of approximately 500°C to achieve an efficiency of 10% (Rowe, 2006; Allen et al., 2002). In future, testing should be planned with higher temperature differences, but the current testing has been successful for the conditions tested.

The use of thermoelectric materials in vehicle engines for wasted heat recovery can help effectively in the world need for energy saving and reduction of pollutants. The allocated power and the temperatures that exist in the exhaust pipe of anormal size car are satisfactory enough for the efficient application of a thermoelectric generator. The most advisable place appears to be exactly after the catalyst, where high temperatures exist (Liu et al., 2014). The output power and the efficiency of the device depend on the operational conditions of the engine and on the effective designing and modelling of the heat exchanger. Even with conventional thermoelectric elements, a thermoelectric device with an output power of around 300 W would be feasible, with a corresponding fuel saving of around 5% (Zorbas et al., 2007).

The devices have no moving parts and can have a relatively long life which is a benefit. However, thermoelectric generators have lower efficiency when compared with many other power generation devices. Thermoelectric generators can be used in engineering applications ranging from automotive waste heat recovery (Zorbas et al., 2007) to powering a small wristwatch (Leonov and Vullers, 2007). The devices offer the advantage of relatively low cost and small size, while still providing an excellent thermodynamic example of power generation (Allen et al., 2009).

Further improvements in the efficiency of the thermoelectric materials, particularly for high temperature operation, are expected to give a radical inclination in their application in the automotive industry.

It has been found that the wasted heat from exhaust can be used by combination of two technologies identified of TEGs and heat pipes. It was found that:

- Both TEGs and heat pipes are solid state, passive, silent and accessible.
- TEGs have relatively low efficiency and maximum surface temperatures
- Heat pipes have maximum rates of heat transfer and working temperature ranges.

These can be overcome using thermoelectric modules of better elements and by operating it under high temperature difference.

The result and the TEG model discussed in this work allows performing this experimental work on large scale and with the use of heat pipes. Moreover, this work has identified a strong need for research on advance TEG materials, heat transfer materials, and heat exchanger technologies. Since, the performance gain from advancement in one TEG component is limited by advances in other TEG components, all TEG system components must be developed in tandem to maximize the conversion efficiency. Overall, the current work has identified an optimum design for a large TEG system, which can compete with existing technologies. The next step will be to build a prototype of the TEG system so as to maximize the application of this promising renewable energy source.

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