Technical Feasibility Evaluation on The Use of A Peltier Thermoelectric Module to Recover Automobile Exhaust Heat

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Abstract. A thermoelectric module composes of integrated p-n semiconductors as hot and cold side junctions and uses Seebeck effect between them to function as a thermoelectric generator (TEG) to directly convert heat into electrical power. Exhaust heat from engines as otherwise wasted to the atmosphere is one of the heat sources freely available to drive the TEG. This paper evaluates technical feasibility on the use of a Peltier thermoelectric module for energy recovery application of such kind of waste heat. An experimental apparatus has been setup to simulate real conditions of automobile engine exhaust piping system. It includes a square section aluminium ducting, an aluminium fin heat sink and a TEC1 12706 thermoelectric module. A heater and a cooling fan are employed to simulate hot exhaust gas and ambient air flows, respectively. Electrical loading is controlled by resistors. Dependent variables measured during the test are cold and hot side temperatures, open and loaded circuit output voltages and electrical current. The test results revealed a promising application of the Peltier thermoelectric module for the engine exhaust heat recovery, though the loaded output power produced and loaded output voltage are still far lower than the commercially thermoelectric module originally purposed for the TEG application.

1. INTRODUCTION

In automotive sector, more efficiently use of non-renewable fuel energy resources has been great interest in the present days as well as conserving environmental issues, such as air pollution and global warming. Internal automotive combustion engines (IACEs) are prominent fossil fuel consumer, which involved irreversibility energy conversion process through discharging a by-product in the form of waste heat to the environment. Beside the useful mechanical work gained, the waste heat contributes a significant amount on the IACEs energy balance as shown in Table 1 [1-3]. Up to 45% and 35% of fossil fuel combustion energy is lost from exhaust system for Otto and Diesel engines, respectively, which seems good potential to reuse it as otherwise wasted.

| Engine Type | Shaft power (%) | Cooling (%) | Exhaust (%) | Miscellaneous (%) |
|-------------|-----------------|-------------|-------------|-------------------|
| Otto engine | 25-28           | 17-26       | 34-45       | 5-15              |
| Diesel engine | 34-38      | 16-35       | 22-35       | 3-8               |

Table 1. Energy balance for Otto and Diesel engines [1-3]
Various researchers developed the way to reuse the waste heat using heat recovery method from heat rejection through radiator with temperature distribution range from 90 °C to 95 °C using a coolant [4] or through exhaust gas system [5-7]. The temperature distribution of the exhaust gas for Diesel engine is illustrated in Figure 1. The exhaust gas temperature near the engine manifold is as high as 600 °C at full load and 100 °C at part load. Meanwhile, the Otto engine exhaust temperatures are approximately 200 °C higher than the Diesel engine at full load and approximately 100 °C higher at part load [8].

![Figure 1. Temperature distribution along exhaust system for a typical automobile Diesel engine](image)

Green technology applying thermoelectric generator (TEG) modules to recover energy lost from dispersed heat is considered useful on an automobile. Through the effect of temperature difference between the two of heat source and heat sink, thermal waste energy can be directly converted into electricity from the exhaust pipe and radiator [9]. TEGs theoretically may offer many advantages such as being highly reliable, having no moving parts, and being environmentally friendly, when compared with conventional electric power generators [10].

Several researchers have experimented and reported on the TEG applications in automotive field. Kim et al. [4] adopted engine water coolant as heat source and employed 72 bismuth telluride (Bi$_2$Te$_3$) TEG modules in which delivered maximum power output of 75 W and the calculated thermoelectric module efficiency of 2.1%. Thatcher et al. [11] applied HZ-20s (Bi$_2$Te$_3$) TEG module to a light truck engine and vehicle fuel efficiency on the order of 1-2% was typically improved depending on the engine speed. Ikoma et al. [12] attached 72 units of SiGe TEGs on exhaust pipe capable of generating electricity of 35.6 W when the exhaust gas was introduced into the generator under the condition corresponding to the 60 km/hr hill climb mode of 3000 cc gasoline engine vehicle. Crane et al. [13] integrated a high-temperature TEG (up to 500 °C) into two passenger vehicles: a BMW X6 and Lincoln MKT with 600 W power output generated in vehicle test and over 700 W produced over bench test.

In this paper, a commercial thermoelectric element (TEC 12706) which originally used for cooling but now investigated as TEG function is tested experimentally to identify its potential for engine exhaust waste heat recovery applications. Though maximum allowable operating temperature of the proposed TEG module as high as 138 °C, it is expected to be applied for the low temperature exhaust heat for the Diesel engine with the TEG located near the rear muffler.
2. WORKING PRINCIPLE OF THE TEG

Figure 2 shows schematic of an operating principle of TEG. The basic operating principle of the TEG based on Seebeck effect, which states that an electrical potential is generated in an open circuit formed by two dissimilar conductors when their junctions are bounded at two places with different temperatures [1]. Typically, the structure of the TEG module is consisted of a thermoelectric element (which composed of ceramic substrates, electrical insulators, electrical conductors and N-type/ P-type semiconductor block), a heat source and a heat sink [9,14]. By applying different temperature on both sides in which one side was heated (as heat source) while the other side was kept at a lower temperature (as heat sink), electric current is induced because of the thermoelectric effect [9, 15].

The indicator parameters to evaluate the technical performance of the TEG module in this paper include loaded output power, loaded current and open circuit voltage as given by Eq. 1-3[16] below:

\[ P_o = \frac{V_o^2}{R_L} \]

(1)

\[ I = \frac{P_o}{V_o} \]

(2)

and

\[ V_o = \frac{V_{oc}}{2} \]

(3)

where \( P_o \) is loaded output power in watt, \( V_o \) is loaded output voltage in volt, \( R_L \) is load resistance in ohm, \( I \) is load current in ampere and \( V_{oc} \) is open circuit voltage in volt.

![Figure 2. Schematic of an operating principle of TEG [9]](image)

3. METHODOLOGY

3.1. Experimental Setup

Figure 3 shows schematic arrangement of the TEG experimental apparatus. A Peltier thermoelectric module (TEC 12706) composed of 127 couples BiSn (bismuth tin) semiconductor and Al₂O₃ (alumina) ceramic cover materials and 40 mm x 40 mm x 3.8 mm size was employed in this experiment. The TEG module was attached on the top surface of a square section aluminium ducting. A thermal paste was used to maintain surface thermal contact between the TEG ceramic covers and
aluminium surface thus reducing thermal resistivity. The two sides of the TEG were attached to an electric heater as a heat source inside the ducting and the other facing side to the aluminium fin heat sink. A DC fan was equipped to simulate ambient air flows to cool the aluminium fin heat sink.

Figure 3. Schematic arrangement of the TEG experimental system

The electric heater was set up at 110 volt power supply, while the cooling fan was varied with 3 different step supply voltage (i.e. 3V, 6V and 7.5V). Two K-type thermocouples were mounted in both thermoelectric sides to measure temperature difference between the hot side and cold side of the TEG. The data acquisition system employed a digital thermometer thermocouple. Two digital multimeters were used to measure open circuit voltage, loaded output voltage, load current and load resistances. The TEG module was loaded by using 10 different resistors resistance.

3.2. Procedure

The procedures applied to evaluate technical performance of the TEG module are as follows: first, the TEG was tested to characterise open circuit voltage ($V_{oc}$) and temperature difference ($\Delta T = T_{hot} - T_{cold}$) between the hot side and cold side in respect to the time. The electric heater was kept powered constantly at 110 volt supply voltage, while the cooling fan was varied at 3 V, 6.5 V and 7 V and the corresponding $V_{oc}$ and the thermoelectric $\Delta T$ readings were recorded; second, the temperature difference of the varied cooling fan supply voltage, i.e. at 31.9 °C, 37 °C and 42°C was set to be constant heat flow for different resistive load by controlling the cooling fan and heater using dependent analog control (by switching on/off of the power supply). The resistive load at each 1 ohm, 1.2 ohm, 2.2 ohm, 3.8 ohm, 5.8 ohm, 7.8 ohm, 10 ohm, 15 ohm, 25 ohm and 33 ohm were connected to the thermoelectric output. The data of loaded output voltage and load current were taken for respective load resistance and $\Delta T$ setting. The loaded power output then can be calculated accordingly using Eq. 1.

4. RESULT AND DISCUSSION
Figure 4 shows variation of the open circuit voltage ($V_{oc}$) and temperature difference ($\Delta T$) with respect to the time. As can be seen from the figure, the cooling fan was switched off at approximately 15-20 minutes after $V_{oc}$ and $\Delta T$ stable. The highest hot side temperature achieved during the test was at 101°C. The higher cooling fan supply voltage delivers the higher $V_{oc}$ and $\Delta T$. The average $\Delta T$ is 31.9 °C, 37 °C and 42 °C for the fan supply voltage of 3 V, 6.5 V and 7 V, respectively. The peak value of $V_{oc}$ is around 1,300 mV at $\Delta T = 42°C$.

Figure 4. (a) Open circuit voltage versus time (b) temperature difference versus time

Figure 5 shows variation of the loaded output power and output current with the applied load resistance. As can be seen from Figure 5 (a), the loaded output power increases sharply achieving maximum value as high as 75 mW at $\Delta T = 42°C$ and then decreases gradually with the load resistance increases. The graph seems to form parabolic curve since the loaded output power is obtained from the square loaded output voltage divided by the load resistance. Meanwhile, Figure 5 (b) indicates that the load current decreases in almost logarithmic curve as the load resistance increases which following theoretical Ohm’s law between resistance and current. The maximum load current is approximately of 190 mA at load resistance of 1.2 ohm and $\Delta T = 42 °C$.

Figure 6 presents the relationship between loaded power output with the loaded output voltage and the load current for each of $\Delta T$. The loaded power output of the TEG module depends on the loaded output voltage (controlled by the load resistance), and this relationship changes for various $\Delta T$. As can be seen from the figure, the highest $\Delta T$ delivered the highest loaded power output. For each curve, the highest loaded power output happens at the point at which the TEG module resistance matches with the load resistance. The maximum output power is about 72.4 mW for 658 mV of loaded output voltage and 110 mA of load current at the highest $\Delta T = 42°C$.
A single Peltier thermoelectric module (TEC 12706) has been tested to function as a TEG device. The test results revealed a promising application of the Peltier thermoelectric module for the engine exhaust heat recovery, though the loaded output power produced and loaded output voltage are still far lower than the commercially thermoelectric module originally purposed for the TEG application. The option to choose a high temperature thermoelectric module is the next improvement of this research.

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