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THE POTENTIAL OF THERMOELECTRIC GENERATOR FOR ENGINE EXHAUST HEAT RECOVERY APPLICATIONS

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ABSTRACT: In this study, a thermoelectric generation (TEG) unit was designed and constructed to evaluate the technical potential of exhaust heat recovery system for automobile applications. The TEG system was made up of a commercial thermoelectric module of TEC1 12706 model, an aluminum duct, an aluminum fin heat sink, an electric heater, a cooling fan, AC and DC power supply, an external resistive load and data collection devices. The heater was used as an exhaust heat source simulator to supply heat energy to the hot side of the TEG module. The cooling fan was used for simulating airflow and maintaining uniform heat rejection from the heat sink to the ambient. The experimental investigation had been conducted to characterize the TEG's performance. The tests were undertaken based on the measurements of temperature at both hot and cold sides of the TEG module, open circuit voltage, and output voltage and current under various external resistive loads. The test results showed that the highest temperature difference was 40.1 ^{o}C. This revealed a peak output power of 178.2 mW, a load voltage of 1156.3 mV, a load current of 220 mA and a conversion efficiency of 0.204%. The thermoelectric generation from waste heat energy of a simulated automobile exhaust is technically feasible, though the output power and the conversion efficiency of the TEG unit seem low. In general, it is found that the temperature difference between the hot and cold sides of the thermoelectric module has the most significant impact on the TEG's performance.

Keywords: Thermoelectric generator, Heat recovery, Exhaust heat, Automobile, Feasibility

1. INTRODUCTION

In the automotive sector, more efficiently use of non-renewable fuel energy resources has been a great interest in the present day 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.

Besides the useful mechanical work gained, the waste heat contributes a significant amount of the IACEs energy balance. Up to 45% and 35% of fuel combustion energy is lost from exhaust system for Otto and Diesel engines, respectively. Hence, it is good potential to reuse the exhaust heat which otherwise wasted as an engine water coolant and exhaust gas. If we can generate electrical energy through a temperature difference between waste gases and the environment, which can be restored in the battery of the automobile, both an improvement of efficiency and decrease of fuel consumption would be achieved [1].

The reuse of waste heat by means of the heat recovery from heat rejection of the engine could be initiated via radiator using a water coolant with temperature distribution ranges from 90 ^{o}C to 95 ^{o}C or through exhaust gas system. For instance, a typical BMW diesel engine has exhaust gas temperatures at full load around 600 ^{o}C and 240 ^{o}C at near its exhaust manifold and rear muffler, respectively [2]-[5].

Thermoelectric generator (TEG) is one of the green energy sources for directly converting heat into electrical energy. The TEG system to recover energy lost from dispersed heat is considered useful on an automobile. Through the effect of a temperature difference between the two of the heat source and heat sink, thermal waste energy can be directly converted into electricity from two potential areas, i.e. engine exhaust pipe and radiator [6]-[8].

Thermoelectric technology is presently becoming profitable in the automotive industry because of the increased concerns over vehicle fuel economy and exhaust gas emissions. TEG theoretically offers advantages when compared with conventional electric power generators, i.e. more robust, flexible and reliable since it requires neither moving parts nor working fluids, fewer maintenance requirements, capable of elevated temperature operation, no scale effect, silent operations, position-independent, light in weight and small in size, and environmentally friendly [9]-[13].

Former researches about engine waste heat recovery system progressed proof of concepts of the TEG applications in the automotive field. Kim

et al. [9] investigated a TEG device using engine water coolant of passenger vehicles. They attached 72 bismuth telluride (Bi_2Te_3) thermoelectric modules on the test vehicle. Their experimental results showed that the maximum output power was 75 W, the calculated thermoelectric module efficiency of the TEG was 2.1%, and the overall efficiency of electric power generation from the waste heat of the engine coolant was 0.3% in the driving mode at 80 km/h.

The TEG test bench built by Liu *et al*. [15] roughly generated a maximum power of 944 W and system efficiency of 1.85%. The TEG system employed four identical TEGs, which contain 240 thermoelectric modules and a water-cooled system. Low-temperature thermoelectric modules of up to 360 ºC of hot side temperature were used in the TEG.

Chung *et al*. [16] constructed a prototype of the thermoelectric waste heat recovery system. The main feature of their study was to use a high-temperature condition up to 200 ºC to ensure the reliability of the thermoelectric generation system, especially for the case of diesel vehicles which discharge exhaust gas of as high as around 200-300 ºC at the outlet of the catalyst filter.

Through experiments on an automotive diesel engine, Zhang *et al*. [17] found that the TEG system generated 1002.6 W of electricity and 2.1 % heat to electrical efficiency using exhaust waste heat at an average temperature difference of 339 ºC between the TEG hot and cold surfaces at a 550 ºC exhaust temperature. The complete TEG system in their work included 400 thermoelectric modules with a high-efficiency nanostructure material.

The use of thermoelectric cooler (TEC) modules for automobile exhaust heat recovery was reported by Cao *et al*. [18]. They built a prototype of heat pipe assisted TEG that comprises 36 pieces of thermoelectric modules of TEP1-142T300 and a water-cooled heat sink. In their system, exhaust gas was simulated by hot air. The TEG system generated maximum open circuit voltage of 81.09 V. The corresponding power output and conversion efficiencies were 13.08 W and 2.58 %, respectively.

Orr *et al*. [19] developed a bench type model of the TEG system for exhaust heat recovery applications in typical passenger cars. The system was intended to be a proof of concept of power production by the TEC using heat pipes and hot engine exhaust gases. Eight pieces of the TEC modules were used. The heat pipes with water as a working fluid were also used to cool the TEC modules. The experimental results showed that the system produced 6.03 W of electrical power with a heat to electricity conversion efficiency of 1.43%.

Maneewan and Chindaruksa [20] constructed a TEG system for recovery of waste heat from biomass dryer. Twelve thermoelectric modules of TEC1-12708 were used in this system. Their experimental results showed that the power output was about 22.4 W (14 V, 1.6 A) with an air flow of 9.62 m^3/s achieving 4.08% conversion efficiency.

The purpose of this work is to evaluate the technical feasibility of the thermoelectric generation from waste heat energy of a simulated automobile exhaust. A Peltier thermoelectric module of TEC1 12706 model, which originally designed for cooling purposes was used and experimentally tested to function as a TEG device through the reverse process. In addition, its merit of low cost and wide availability compared to the basic TEG becomes the other considerations. Furthermore, it is expected that the thermoelectric module could be applied to automobile Diesel engines, particularly on the rear muffler of the engine exhaust pipe system.

2. WORKING PRINCIPLE OF THE TEG

Fig.1 shows a schematic diagram of an operating principle of the TEG. The basic operating principle of the TEG is based on its thermoelectric effects, i.e. Seebeck effect, Peltier effect, and Thomson effect. It also accompanies with Joulean and Fourier effects. The Seebeck effect 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. The Peltier effect states that heat can be absorbed or liberated at the junction of two dissimilar conductors when a current is passed. The Thomson effect states that heat can be liberated or absorbed in a single homogeneous conductor when an electric current flows in the presence of temperature gradient [21].

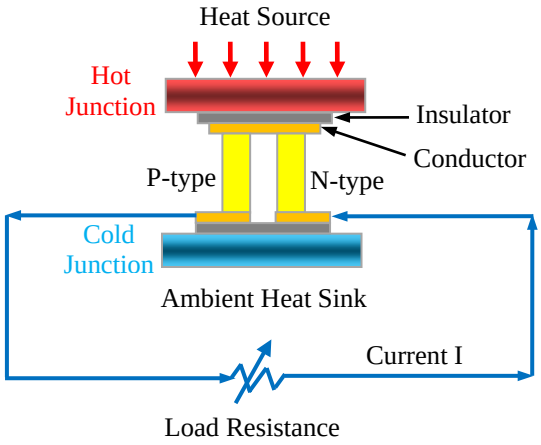


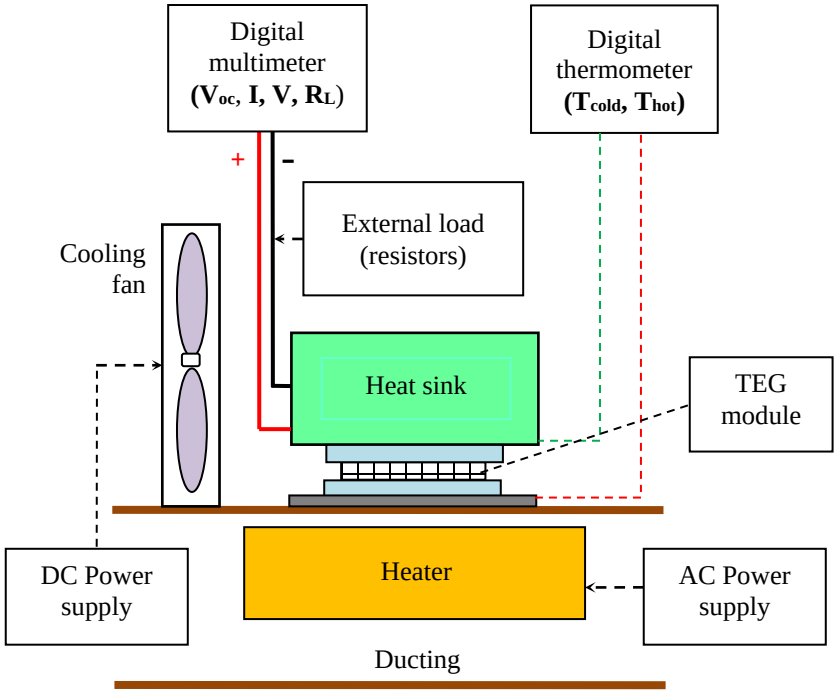
Fig.1 Schematic diagram of an operating principle of the TEG [6]

Typically, the structure of the TEG module consists of a thermoelectric element (which

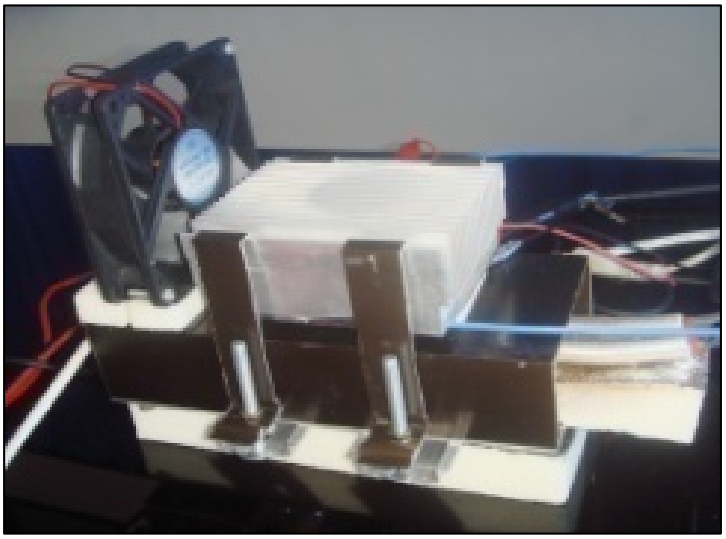
composed of ceramic substrates, electrical insulators, electrical conductors and N-type/ P-type semiconductor block), a heat source and a heat sink. By applying different temperature on both sides in which one side was heated (as a heat source) while the other side was kept at a lower temperature (as a heat sink), electric current is induced because of the thermoelectric effect [6].

3. METHODOLOGY

3.1 Experimental Setup



(a)



(b)

Fig.2 (a) Schematic of system setup (b) photograph of the experimental system

An arrangement of the experimental system is shown in Fig.2. The system was made up of a thermoelectric module, a duct, a heat sink, a heater, a cooling fan, AC and DC power supply, an external resistive load and data collection devices.

A commercial Peltier cooler module of TEC1

12706 model was used as a generator through thermoelectric conversion. The thermoelectric module has 127 couples of bismuth telluride semiconductor and alumina ceramic cover with a physical size of 40 mm x 40 mm x 3.8 mm. An aluminum duct with the size of 40 mm x 60 mm x 1.2 mm was utilized to represent the engine exhaust pipe. The duct was attached directly to the bottom surface of the thermoelectric module as a hot side while an aluminum fin heat sink was mounted on the top of it as a cold side of the thermoelectric module to maintain constant temperatures. A thermal paste was used to maintain surface thermal contact between the module cover and both the ducting surface and the heat sink thus reducing thermal resistivity.

A 220 VAC/350 W heater made from copper was used as an exhaust heat source simulator to supply heat energy to the hot side of the thermoelectric module and located inside the duct at about 1 cm gap to the top surface. A cooling fan of 12 VDC/0.15 A was used for simulating airflow and maintaining uniform heat rejection from the heat sink to the ambient. For temperature monitoring, two K-type thermocouple sensors were attached on both sides of the module in which one on the bottom of the heat sink surface and the other on the top surface of the duct plate. The data collection system employed a digital thermometer (Krisbow KW06-283) and two digital multimeters, i.e. Krisbow KW06-272 and Refco X-475. Table 1 shows range and accuracy of the measuring instruments associated with the experiments.

Table 1 Range and accuracy of the measuring instruments

Instrument	Range	Accuracy
Temperature sensor: (K-type thermocouple)	0-1300°C	±0.75%
Temperature reading: (Krisbow KW06-283)	-50-1300°C	±0.5%±1°C
Multimeter reading: (Krisbow KW06-272)		
~ Ammeter (DC A)	0-200m	10±(1.5%±3d)
~ Voltmeter (DC V)	0-1000	±(0.5%±2d)
~ Ohmmeter (Ω)	0-40M	±(1.0%±2d)
Multimeter reading: (Refco X-475)		
~ Ammeter (DC A)	0.1μ-10	±(1.0%±2d)
~ Voltmeter (DC V)	0.1m-1000	±(0.5%±2d)
~ Ohmmeter (Ω)	0.1-40M	±(1.0%±5d)

3.2 Test Procedure

The procedures applied to evaluate technical performance of the TEG module were as follows:

a. The TEG was tested to characterize open circuit voltage (V_{oc}) and temperature difference ($\Delta T = T_{hot}-T_{cold}$) between the hot side and cold sides with respect to the time. The electric heater was kept powered constantly at 110 VAC, while the cooling fan was powered at 3 VDC, 6.5 VDC, and 7 VDC. The corresponding V_{oc} and temperature difference (ΔT) readings were then recorded every 1 minute.

b. The ΔT of the varied cooling fan supply voltage, i.e. at 31.9 °C, 37 °C, and 40.1 °C was set at constant heat flow for different value of resistive load by controlling the cooling fan and heater using analog control (i.e. by switching the power supply on or off). The 10 set of external resistive load, i.e. 1 Ω, 1.2 Ω, 2.2 Ω, 3.8 Ω, 5.8 Ω, 7.8 Ω, 10 Ω, 15 Ω, 25 Ω and 33 Ω were consecutively connected to the thermoelectric output. The data of load voltage and load current were taken for respective load resistance and ΔT setting in a 1-minute interval. The output power can be calculated accordingly using Eq. 1.

3.3 Performance Evaluation

The indicators to evaluate technical performance of the TEG module include output power, load current, load voltage and open circuit voltage as given by Eqs. (1)-(3) below:

$$P_o = \frac{V_o^2}{R_L} \quad (1)$$

$$I = \frac{P_o}{V_o} \quad (2)$$

$$V_o = \frac{V_{oc}}{2} \quad (3)$$

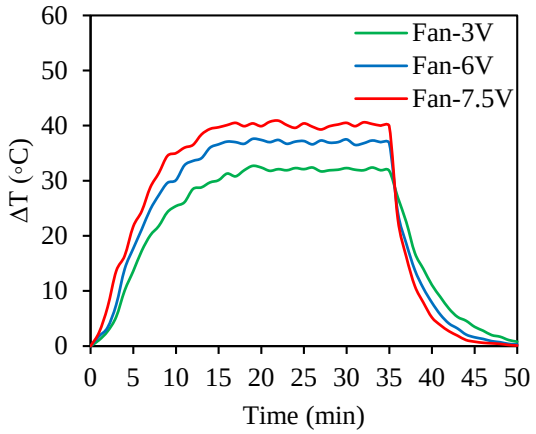
where P_o is output power in watt, V_o is load output voltage in volt, R_L is load resistance in ohm, I is load current in ampere and V_{oc} is open circuit voltage in volt.

4. RESULTS AND DISCUSSION

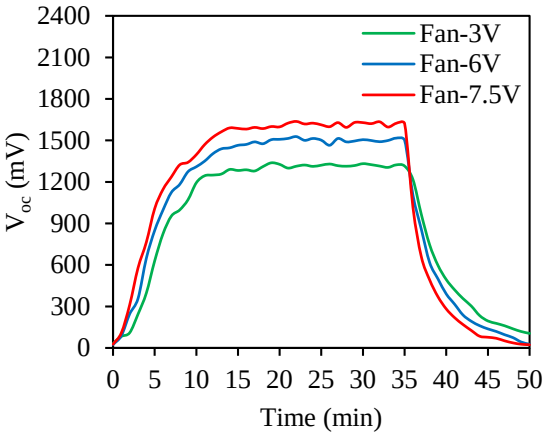
The temporal variation of temperature difference (ΔT) and open circuit voltage (V_{oc}) between the hot and cold sides of the TEG module at various fan supply voltage is depicted in Fig. 3.

As it can be seen in the Fig.3, the ΔT and V_{oc} for the three values of the fan supply voltage are almost stable within 15-20 minutes. The average temperature differences are 31.9 °C, 37 °C and 40.1 °C (Fig.3a), while the average open circuit voltages are 1310 mV, 1500 mV and 1610 mV (Fig. 3b) for the fan supply voltage of 3 VDC, 6.5 VDC, and 7 VDC, respectively. The higher the cooling fan supply voltage the higher both the ΔT and V_{oc}. By increasing the fan supply voltage, it

means that the fan rotation speeds up as well as the TEG heat transfer rate, hence the heat rejection from the heat sink to the ambient increases. The open circuit voltage at the output of the thermoelectric module increases linearly with the temperature difference. Furthermore, the set point of temperature difference could be fixed by controlling on/off of the cooling fan speed at a certain value of the fan supply voltage. In addition, the maximum temperature achieved at the hot side of the thermoelectric module during the test was around 111 ºC.



(a)



(b)

Fig.3 (a) Temporal profiles of temperature difference (ΔT) (b) open circuit voltage of the TEG module at various fan supply voltage

The characteristic of load voltage versus load current of the TEG as a function of temperature difference between the hot and cold sides of the TEG module is shown in Fig. 4. From the figure, it can be noted that the load voltage is linearly proportional to the load current but in almost the same negative slopes. The higher value of the load voltage corresponds to the lower value of the load current. It also indicates that the slope of each line which represents the internal electrical resistance of the TEG is still constant in varying ΔT and load operations as governed by the basic Ohm's law. For instance, the maximum load voltage of about 1217.5 mV is revealed at the load current of 80 mA at the highest ΔT of 40.1 ºC. Both the load voltage and current increases with the temperature differences but the slope of the change of the temperature difference is almost independent of the load current [22].

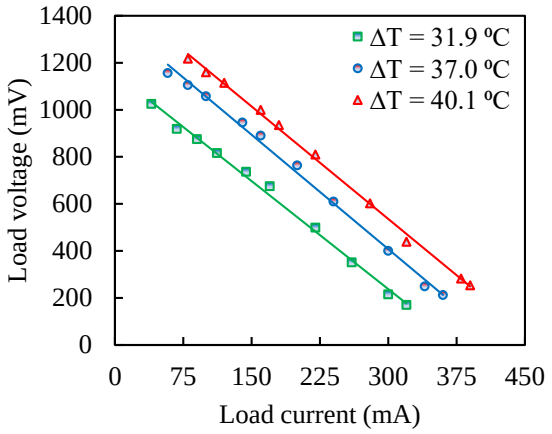


Fig.4 Load voltage versus load current in varying ΔT

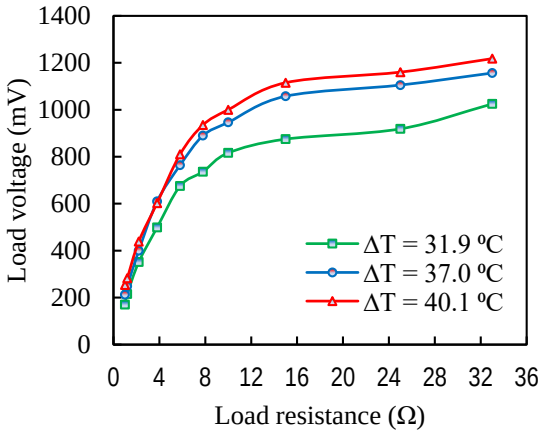


Fig.5 Load voltage versus load resistance in varying ΔT

By varying the load resistance from 1 to 33 Ω, the load voltage of the TEG module versus the load resistance under different ΔT is recorded as depicted in Fig. 5. As can be observed from the Fig. 5, the load voltage increases with increasing the temperature difference at various applied external resistive load. The rise of the temperature difference results in raising the load voltage. As a consequence, the load current will increase for a given load resistance. The load voltage increases drastically with the resistive load value from 1 Ω to 10 Ω and then increases almost smoothly at the

higher resistive load up to 33 Ω. The load voltage of the TEG reaches the maximum at 1156.3 mV with ΔT of 40.1 ºC.

Fig. 6 depicts the relationship between output power and the applied load resistance. It can be seen in Fig. 6 that the output power increases sharply reaching peak value as high as 178.2 mW then decreases gradually as the load resistance increases. Subsequently, the corresponding temperature difference and the load resistance at peak output power are 40.1 ºC and 5.8 Ω, respectively. As the temperature difference increases, the load voltage increases for certain value of the load resistance. As the load voltage is high, the high will be the output power. The output power increases with increasing the temperature difference at different load resistance. The graph seems to form parabolic curve since the output power of the TEG module is obtained by dividing the square of load voltage by the load resistance. The maximum output power of the TEG module is achieved under the load matching condition when the load resistance matches the internal resistance of the module [22], [23].

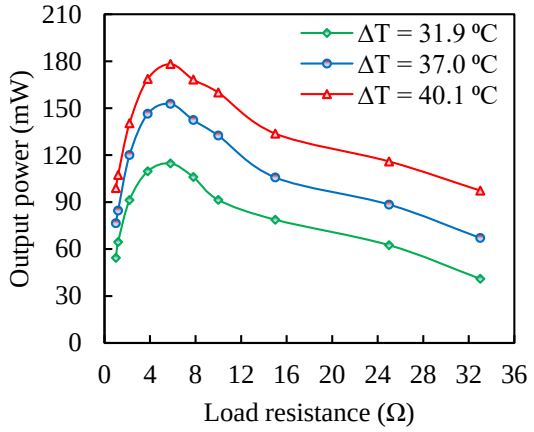


Fig.6 Output power versus load resistance under different ΔT

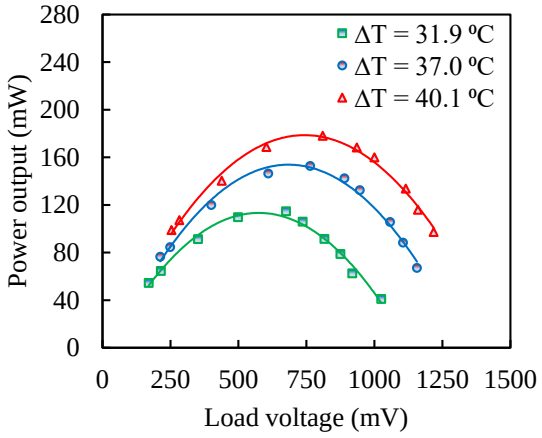


Fig.7 Output power versus load voltage under different ΔT

Figs. 7 and 8 illustrate the variation of the output power with the load voltage and the load current for various ΔT. The output power of the TEG module depends on the load voltage which is controlled by the load resistance, and this relationship changes for various ΔT. The highest ΔT delivered the highest output power. The maximum output power achieved in this experiment is about 178.2 mW. An electrical power of 178.2 mW is generated with a current of 220 mA and a conversion efficiency of 0.204% when ΔT is 40.1 ºC, so there is a temperature difference of up to 40.1 ºC, when the hot side reaches 111 ºC, resulting in performance of 178.2 mW at open circuit voltage of 1610 mV. It is found that the temperature difference has the most significant impact on the TEG's performance.

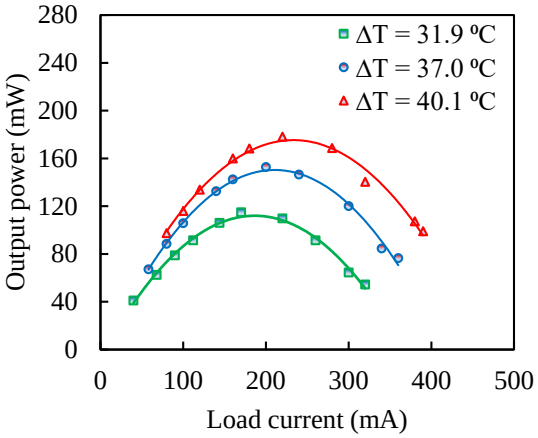


Fig.8 Output power versus load current under different ΔT

5. CONCLUSIONS

A simple TEG unit has been designed and constructed for simulated automobile exhaust heat recovery system. A single Peltier thermoelectric module (TEC1 12706) was used to function as a TEG device. The experimental investigation of the TEG unit had been conducted to evaluate the technical potential of automobile applications. The tests were performed based on the measurements of temperature at both hot and cold sides of the TEG module, open circuit voltage, output voltage and current under the influence of different external loads. The highest temperature difference tested was 40.1 ºC. This revealed a peak output power of 178.2 mW, a load voltage of 1156.3 mV, a load current of 220 mA and a conversion efficiency of 0.204%.

The thermoelectric generation from exhaust heat recovery is technically feasible, though the output power and the conversion efficiency of the TEG unit seem low. By increasing number of the

TEG module connected in series might meet the electrical power demand for a particular application. Furthermore, design and calculation procedures for system's sizing were followed. As the hot side temperature tested was as high as 111 ^{o}C, which was below the exhaust gas temperature of Diesel engines (200-300 ^{o}C), the use of a heat exchanger at upstream of the TEG unit is recommended to reduce the exhaust gas temperature. The maximum allowable operating temperature of the tested thermoelectric module is 138 ^{o}C based on the manufacturer's material data.

6. ACKNOWLEDGMENTS

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