The waste heat recovery for power generation from automotive exhaust using thermoelectric cell (TEC)

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Abstract. The internal combustion process to move the vehicles had indirectly releasing waste heat into the environment which contributed to global warming. Thermal-electric Cell (TEC) is a device that able to convert thermal energy to electrical energy cleanly. The TECs system work when it is sandwiched between the hot and cold side. The objective of this study is to investigate the possibility of tapping a waste heat using thermoelectric cell (TEC) from car exhaust. The experiment had been carried out in stagnation condition in the laboratory using 1500 cc petrol engine DOHC (4G91). Four TECs (SP1848-27145) were connected in series on the top of exhaust muffler. The experiments were run in two type of cooling methods using air flow from standing fan and the flowing cold water. The maximum voltage of 2.42V was produced when temperature difference, DT reached 83°C. The LED bulbs were connected to TEC and light up when the voltage of 1.60V is obtained. The results have proved that the temperature difference between two sides is the dominant effect to determine the TEC performance. The generated power could be utilized to power an auxiliary application in the vehicle itself.

1. Introduction
The ongoing debate on global warming is unanimous in that the change is caused primarily by many factors. The hazard of the global warming is considering as critical problems of the world. There were many issues that contributed to the rising global warming such as combustion of fossil fuel, hazard gasses from industry, the use of chemical for fertilizers, deforestation for agriculture activities and transportation. Road transportation vehicle has been identified as one of the potential to produce renewable energy from waste heat. According to a study by Kim et al.[1], the transportation sector is responsible for 27% of the total greenhouse gas emission. Approximately 40% of the energy used is wasted as heat to the exhaust gases which surely to be rejected to the environment [2]. Thus, recapturing this waste heat and convert into electricity for useful applications is significantly urgent.

Thermoelectric cell (TEC) is seen as the best solution to recover the waste heat from the effect of internal combustion process by converting the thermal energy into electrical energy. TEC make use of what is known as the “Seebeck effect” [3], where the electricity could be produced from two difference conductors that form a thermal gradient. It has an advantage of working without moving part, less space consumption, quiet and environmental friendly. Orr et. al. [4] has used eight cells on bench type, proof of concept model of power production by TEC using heat pipes and hot engine exhaust gases and
managed to produce 6.03 W when charging the battery. In another study, Orr et. al. [5] has tested the performance of the the TEC by attaching the cells to the passenger car exhaust. They managed to achieve 28.18 W when the surface temperature reached 250°C and 4000 rpm. Cao et. al. [6] has made a further study by adding the number of TEC to enhance the performance on TEC-HP combination for power generation from automobile exhaust where they managed to produce up to 81.09 V. The main objective of the study is to investigate the possibility of generating power from waste in road vehicle using TEC in stagnation condition. It could be a beneficial to restore the energy to the engine alternator and contributes to reduce the global warming and pollution issues.

A typical thermoelectric cell module is composed of two ceramic substrates. The two types of thermoelectric materials must be configured within the module such that they are connected in series, and thermally in parallel. The thermoelectric module is a circuit containing thermoelectric materials which are packed between the hot side and the cold side that can produce electricity from heat directly. The temperature difference between two dissimilar materials will produce a direct electrical current to flow in a circuit [2]. Joining to the end of two dissimilar thermoelectric materials to a function that requires the thermoelectric module is n-type (negatively charge) semiconductor and a p-type (positively charge) semiconductor [2]. Hence, it creates a closed circuit to allow the flow of current and generating power. The typical of the thermoelectric module is manufactured using ceramic substrate as shown in Figure 1.

![Figure 1. Structural diagram of thermoelectric module [6].](image)

The voltage generated from a TEC can be calculated from the following formula;

$$V = \alpha \Delta T$$  \hspace{1cm} (1)

$\Delta T = T_h - T_c$ is the temperature difference

$\alpha$ is the Seebeck coefficient which is considered to be material coefficient and constant at all temperature [3].

If the $\alpha$ is positive then it driving an electric current through the wire from hot to cold junction [5]. Increasing the voltage difference ($\Delta V$) increases the temperature difference between two joints ($\Delta T$). The Seebeck coefficients are a nonlinear function of temperature. The relatively low in electrical power generation and has restricted their use to specialised situations where reliability is a major consideration [8].
2. Experimental Set-up and Testing

2.1 Experimental Set-up

The proton petrol engine-testing unit of 1500 cc DOHC (4G91) at Automotive Laboratory, UiTM Pulau Pinang is used for this purpose as shown in Figure 2. Four units of TEC, Bismuth Telluride thermoelectric device (SP1848-27145) that composed of ceramic substrates was used in this project. The four units of TEC were arranged in series on top of the surface of the exhaust muffler as shown in Figure 2. The TEC were sandwiched between the hot surface of the exhaust muffler and a cold air from standing fan, as a heat sink. Another cooling method is using the cold water flowing through the fabricated channel on top of the TEC as shown in Figure 3. The programmed Arduino system is used as the data logger to track the temperature and the Fluke 1750 power recorder to measure the generated power.

![Figure 2. The experimental setup using Proton petrol engine (left) and the arrangement of TEC on the exhaust muffler (right).](image)

![Figure 3. Schematic diagram of experimental setup for air cooling (left) and cold water cooling (right).](image)
2.2 Experimental work
The experiments had been carrying out in two stages with controlled engine speed at maximum of 2500 rpm. This measure is to avoid the exhaust surface temperature become too hot, which could damage the TEC unit. The first stage is using the cool air from standing fan as a cooling medium as the engine is running. The experiment last approximately in 24 minutes, and the exhaust surface temperature, the top side temperature of TEC and the captured voltage are recorded. In second stage of experiment, a tap water supply is channeled to flow in the hollow steel block on top of TECs to create a cold site as the engine is running. The average flow rate of the water is 0.11 kg/s. The inconsistency of the flow rate is observed as the water supply of the building is shared among other users. The duration of this testing is kept similar to the first stage test, in 24 minutes. All the relevant data of hot surface temperature, cold side temperature and the captured voltages were recorded in the data logger.

3. Results and Discussion
Figure 4 shows the obtained hot surface temperature and cold side temperature when the cooling effect is engaged on top side of the TECs. The hot surface for the first stage shows higher temperature compared to second stage. The maximum temperature reached 132 °C for first stage and 114 °C for the second stage. This is due to the inconsistency of the engine timing, which will influence the engine speed and affects combustion in engine block. In cold side, the water cooling provide lower temperature of average 30 °C, around 7 °C less compared to the air cooling temperature of 37 °C. The incoming water temperature could be kept constant because its properly channelled from the tap water. While for the air, it is exposed to the effect of heat from exhaust hot surface due to the convection phenomenon. The maximum temperature difference of 92 °C for air cooling and 86 °C for water cooling is obtained as shown in Figure 5.

![Figure 4](image1.png)
**Figure 4.** The cold and hot temperature for both cooling method.

![Figure 5](image2.png)
**Figure 5.** The temperature difference from air and water cooling.
The obtained voltage for both condition of using air and cold water as a cooling agent against the temperature difference are shown in Figure 6 for water cooling and Figure 7 for air cooling. The voltage gradually increased to reach the maximum value of 1.6 V at 88 °C temperature difference for the air cooling. While for cold water, a significant effect on producing voltage occurs after passing the temperature difference of 45 °C. It has shown a drastic increment from constantly low voltage of 0.2 V to reach a maximum 2.26 V at 84 °C of temperature difference. At this point, one the TEC unit was burnt that directly affect the sudden drop the voltage value. Never the less, the results have shown a good agreement with the previous study conducted by Orr et. al. [5].

\[ Q = \dot{m} C_p (T_{co} - T_{ci}) \]  \hspace{1cm} (2)

Where, \( \dot{m} \) is the water mass flow rate in kg/s, \( C_p \) is the specific heat for water in KJ/kg °C, \( T_{co} \) is the outgoing water temperature and the \( T_{ci} \) is the incoming water temperature in °C.

The \( Q \) shows the amount of heat extracted by the water. Figure 8 shows the maximum amount of heat that had been extracted is 68 W which was occured at the middle of the duration. Beyond this point, the amount of extracted heat is decreasing. One of the main reason was the temperature difference of the water is decreased due to the effect of the surface temperature. This would directly affect to the temperature of incoming flow to increase further. To improve the situation, the better quality of TEC which could stand high temperature range are to be used. The design of the water channel also need to
be revisited so that the temperature of the water could remain constants.

![Figure 8](image.png)

**Figure 8.** The amount of heat extracted for water cooling method.

3.1 Verification of the results
The purpose of this study is to observe the generating current from the effect of temperature difference on TEC. But, only small amount of power was produced which could not be display of our power unit due to out of range. Hence, three units of small LED light were connected to TEC in the experiment for justification purposes as shown in Figure 9. All the LEDs were light up when the voltage reached approximately between 1.6V. It shows that the TEC start to shows the effect of producing current when the temperature difference reaching 70 °C for water cooling and 80 °C for air cooling. The light is on the whole period of experiment. The LEDs shows brighter light on the experiment with water cooling. This is obviously due to the higher voltage produced that directly contributes for higher current. It has proved that the use of TEC for waste heat recovery would generate power that could be supply directly to the useful applications.

![Figure 9](image.png)

**Figure 9.** The connected LED to TEC.

4. Conclusions
In this study, an exhaust heat recovery system has been proposed. The experimental set-up has been established and tested to analyze the performance of the TEC in two modes of cooling using air flow from standing fan and by attaching the cold water channel block on top of the TEC. The effect temperature difference between the two side affecting the performance of the TEC. The current experiment using four units of the TEC has shown the ability to produce output voltage at 2.42V when
temperature difference was 83°C and lighting up the LED bulbs. From the experiments, it shows that the water cooling provides better performance of TEC, but in the actual condition TEC would exposed to the air for the moving vehicle. By putting more units of TEC, the performance of the systems could be improved. The result has shown the potential of TEC to regenerate power from waste heat from exhaust manifold. The generated power could be channel to the running battery which could potentially increase it life span. The is study also has shown the ability of the system to extract some amount heat for the purpose of power generation and reducing the effect on the global warming.

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