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Thermoelectric Technology for IC Engine Waste Energy Harvesting: Liquid Cooling Approach

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ABSTRACT

Thermoelectric generators are all solid-state devices that convert heat into electricity. It contains no moving parts and is completely silent. The total heat supplied to the engine in the form of fuel, approximately 30 to 40% is converted into useful mechanical work; whereas the remaining heat is expelled to the environment through exhaust gases and engine cooling systems, resulting in serious environmental pollution. So, it is required to utilize waste heat into useful work. The technologies on waste heat recovery of exhaust gas from internal combustion engines (ICE) are invented as thermo electric generators (TEG) with finned type, Organic Rankine cycle (ORC) and Turbocharger. This paper has presented semi-conductive TEG and GO/Silica composite TEG. Finned and liquid cooling type cooling has been adopted in both of the TEG. The performance of both cooling approaches for semi-conductive TEG has been compared in experimentally for the engine speed in the range 1000-3000 rpm. The result shows that the liquid cooling TEG has 25% higher performance in terms of electric power generation than the finned type TEG. The liquid cooling TEG has exhibited higher performance at engine speed of 5000 rpm and it was developed 524 W which can be used to operate the air-condition system of the vehicle, could contribute to reduce the 7-10% of engine total fuel consumption and improve emission level by 7%.
Keywords:Thermal electric generator; electricity generation; TEG cooling approach, IC engine exhaust temperature.

I. INTRODUCTION

A thermoelectric produces electrical power from heat flow across a temperature gradient. As the heat flows from hot to cold, free charge carriers electrons in the material are also driven to the cold end. The resulting voltage (V) is proportional to the temperature difference (ΔT) via the Seebeck coefficient, α, ($V = \alpha \Delta T$). By connecting an electron conducting (n-type) and hole conducting (p-type) material in series, a net voltage is produced that can be driven through a load. A good thermoelectric material has a Seebeck coefficient between 100 μV/K and 300 μV/K; thus, in order to achieve a few volts at the load, many thermoelectric couples need to be connected in series to make the thermoelectric device [Synder, 2006].

The large amount of energy from the stream of exhaust gases could potentially be used for waste heat recovery to increase the work output of the engine [Stobart, 2007]. Hatazawa et al. (2004), Stabler (2002), Yang (2005), Yu and Chau (2009) stated that the waste heat produced from thermal combustion process generated gasoline could get as high as 30-40% is lost to the environment through exhaust pipe. Sam (2014) reported that the engine energy distribution: shaft power 25-40%; heat rejection- coolant heat rejection 10-35%, exhaust enthalpy loss 20-45%, and engine external surface loss 2-10%.Conklin and Szybist (2010) investigated that the percentage of fuel energy converted into useful work only 10.4% and also found that 27.7% energy lost through exhaust pipe. Dolz et al.(2012) reported that the value of exhaust gases is 18.6% of total combustion energy. Wong et al.(2012) stated that by installing heat exchanger exhaust energy can be saved up to 34%. Rahman et al. (2013, 2015) reported that waste energy of IC engine can be recovered by using waste energy harvesting coolant based (weHS^{c}) and exhaust based (weHS^{ex}) by 15%. Based on the above researches output it could be concluded that the engine waste energy can be turned into useful energy by using thermal electric generator, turbocharging, exhaust re-circulating, heat recovered from coolant and etc.

An accurate estimate of the heat transfer between cylinder gases and cylinder wall of a combustion engine is necessary for a precise calculation of power, efficiency and emissions during engine development [Heywood,1988]. Several models exist for evaluating the heat transfer coefficient, of which the correlations of Woschni [1967] and Annand [1971] are the most widely used. Gu et al. (2009) found that the engine cycle (Rankine Cycle) efficiency of several working fluids is very sensitive of evaporative pressure but insensitive to expander inlet temperature. Boretti (2012) stated that in a given temperature gradient for optimizing the work output, the working fluid's evaporation enthalpy should be as high possible. Different types of waste energy from exhaust can be captured using different energy harvesting materials [Rizal et al, 2012]. The most promising technologies in development include heat that can be captured and transformed into electrical power using thermoelectric and piezoelectric materials. Thermoelectric materials can capture some of this heat, and produce electricity. Thermocouple was first used by Bendersky [1953], to measure gun bore temperatures. Stobart et al.(2010) explored the possibility of thermoelectric generator (TEG) in vehicles in which they found that the 1.3 kW output of thermoelectric device could potentially replace the alternator of small vehicle. By improving thermocouples, it would be possible to convert 3 to 5% of the waste heat into electricity which would be efficient enough to recharge a vehicle's 12V battery. Therefore, the load on the engine is reduced thereby improving fuel efficiency by as much as 10%. However, a 10% efficient thermal electric generator can require at least 500°C [Ahn et al., (2007) and Snyder (2006)]. An increase of 20% of fuel efficiency can be easily achieved by converting about 10% of the engine waste heat into electricity [Yang (2005),Saidur (2010)]. TEG could be coupled with various other devices to maximize its potentiality. Yu and Chau (2009) has proposed and implemented an automotive thermoelectric waste heat recovery system by adopting a Cuk converter and a maximum power point tracker (MPPT) controller as tools for power conditioning and transfer.

Yang (2005) had investigated the potential applications of thermoelectric (TE) waste heat recovery in the automotive industry. He reported that TE waste heat recovery technology could potentially offer significant fuel economy improvements where a significant savings in national fuel consumption can be achieved by applying it across the board to conventional and/or hybrid vehicles. Jihad Haidar and Jamil Ghojel (2001) had investigated the applicability of the usage of thermoelectric generator (TEG) in order to recover the medium-temperature heat waste from low-power stationary diesel engine. They used heat transfer modeling to locate the optimum mounting position of the waste heat recovery system (WHRS) on the exhaust pipe. They designed a compact device incorporating six modules with the exhaust pipe acting as the heat source. At the end, they found out that WHRS developed can be applied to any type of engine provided that the required hot-side temperature was available but its mass should be considered in the application of a transportation vehicle.

II. MATERIALS AND METHODOLOGY

Energy is supplied to the engine in the form of chemical energy of the fuel and producing useful power and losses as heat through exhaust and coolant. First Law of thermodynamics states that energy is conserved. Therefore, the energy balance equation for the engine can be represented as,

$$\dot{m}_f h_f + \dot{m}_a h_a = P_{brake} + \dot{Q}_c + \dot{Q}_{exh} + (\dot{m}_a + \dot{m}_f)h_e + \dot{Q}_{rad} \quad (1)$$

with $\dot{Q}_C = \dot{m}_c c_{pc} \Delta T$ and $\dot{Q}_{exh} = \dot{m}_{exh} c_{exh} \Delta T$

where, $\dot{m}_a$ and $\dot{m}_f$ is the rate of flow of air and fuel to the engine as initial energy, $\dot{Q}_c$ and $\dot{Q}_{exh}$ is the heat transfer rate of the engine to the coolant and exhaust respectively, h_e is the enthalpy of unburned gas mixture.

$$p_{brake} = \dot{m}_f h_f + \dot{m}_a h_a - \dot{Q}_c - \dot{Q}_{exh} - (\dot{m}_a + \dot{m}_f)h_e - \dot{Q}_{rad} - \dot{Q}_{fric} \quad (2)$$

Equation (2) indicates that the P_{brake} will be increased if % of $\dot{Q}_c$ and $\dot{Q}_{exh}$ can be recovered and can be reduced the unburned gas mixture of $(\dot{m}_a + \dot{m}_f)h_e$. Recover of waste heat energy can increase the brake power, improve the fuel consumption and reduce the CO_2 emission.

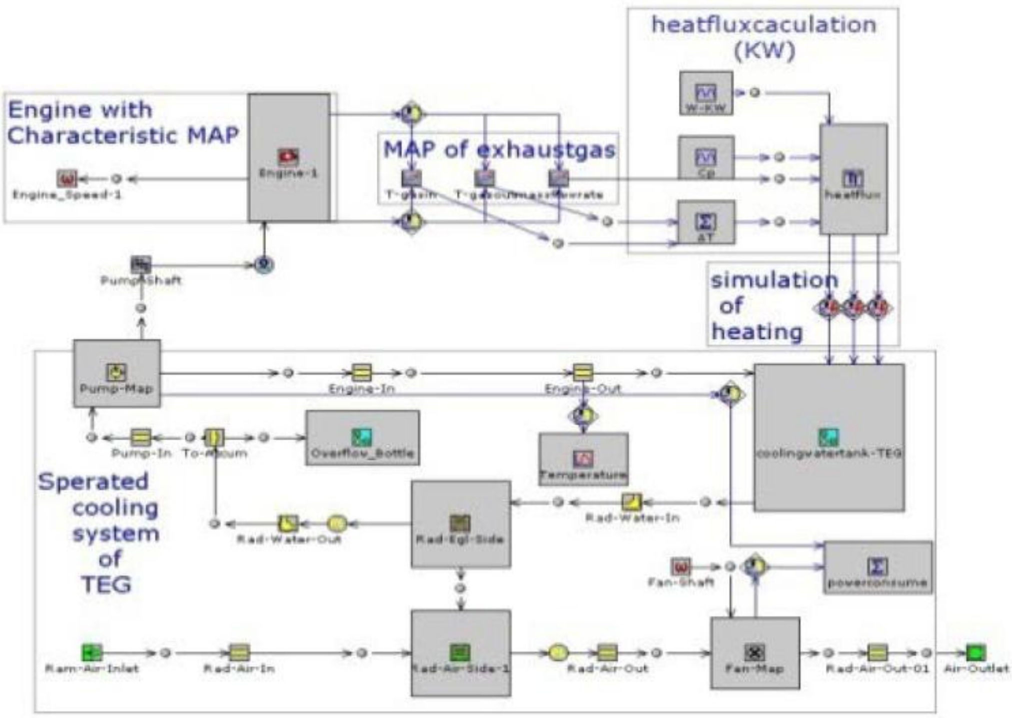


Figure 1: GT-suite model for exhaust heat.

The flow of the exhaust at beginning of the exhaust manifold has high sonic velocity and kinetic energy. The kinetic energy of the exhaust is converted to additional enthalpy with an increase in temperature. The maximum temperature of the exhaust can be computed by applying the energy conservation law,

$$T_{\max} = T_{ex} + \Delta T = T_{cy}\left(\frac{P_{ex}}{P_{cy}}\right)^{\left(k-1/k\right)} + \frac{V^2}{2gc_p} \quad (3)$$

where, V is the velocity of the exhaust in m/s which could be 694 m/s and c_p is the specific heat at constant pressure.

The simulation study on the effect of engine speed (rpm) to the heat transfer in cylinder wall and the volumetric efficiency has been conducted by using GT-suite software model as shown in Figure 1. At higher engine speeds, there is less time per cycle. Combustion occurs over about the same engine rotation at all speeds, so the time of intake and combustion is less at higher speeds. The less time for intake and ignition and less time for heat transfer per cycle, causes the engine runs hotter as shown in Figures 2-3.Therefore, the wall of the cylinder becomes hotter which might affect the fuel lost. Reitz (2012) reported that up to 30% of fuel energy is lost to the wall heat transfer. Therefore, the exhaust temperature will be high and it could be in the range of 300 – 900^{0}C. By using a thermoelectric generator waste heat energy of exhaust can be harvested.

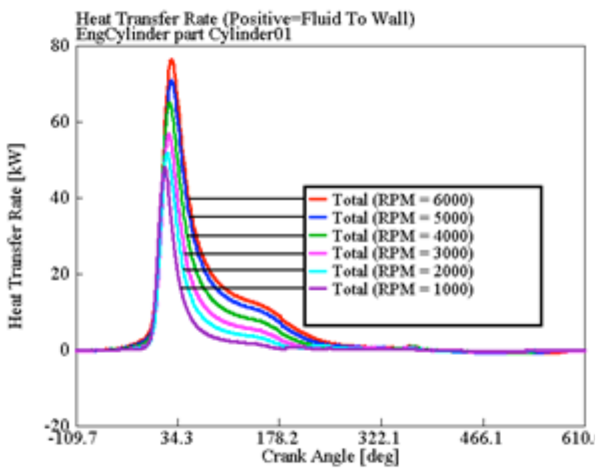


Figure 2:Heat transfer at different crank angle

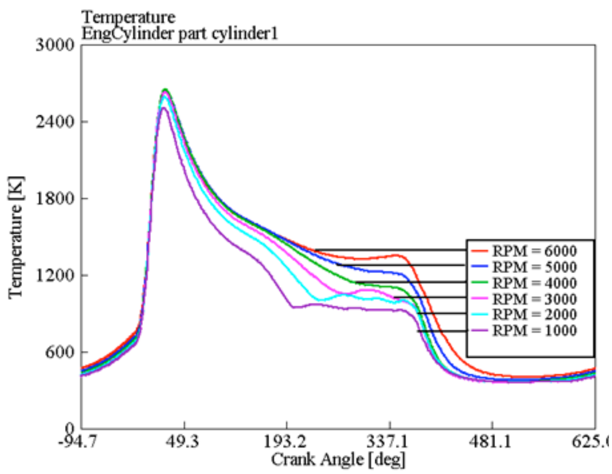


Figure 3: Temperature of the exhaust at different crank angle.

Megha Tak and Mohit Setia (2012) investigated the feasibility and potential of thermoelectric conversion. They reported that the technical feasibility of conversion of heat energy radiated from automobile engines produce power, using thermoelectric generators applying about 35 Ah chrage can be produced. The resulting voltage (V_v) is proportional to the temperature difference (ΔT) via the Seebeck coefficient, α, ($V_v = \alpha\Delta T$). A good thermoelectric material has a Seebeck coefficient between 100 μV/K and 300 μV/K; thus, in order to achieve a few volts at the load, many thermoelectric couples need to be connected in series to make the thermoelectric device. A thermoelectric generator converts heat (Q) into electrical power (P) with efficiency η.

$$P = \eta_{TEG} Q \qquad (4)$$

The amount of heat, Q, that can be directed though the thermoelectric materials frequently depends on the size of the heat exchangers used to harvest the heat on the hot side and reject it on the cold side. The efficiency of a thermoelectric converter depends heavily on the temperature difference, $\Delta T = T_h - T_c$ across the device. This is because the thermoelectric generator, like all heat engines, cannot have efficiency greater than that of a Carnot cycle ($\Delta T / T_h$). The efficiency of a thermoelectric generator is typically defined as,

$$\eta = \frac{\Delta T}{T_h} \bullet \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c / T_h} \qquad (5)$$

with $zT = \dfrac{\alpha^2 T}{\rho k}$

where, the first term is the Carnot efficiency and ZT is the merit for the device. Seebeck coefficient (α), electrical resistivity (ρ), and thermal conductivity (κ) are temperature (T) dependent material properties. Increasing the temperature gradient of TEG's module can increase the efficiency of thermoelectric generator. The basic physical phenomena is associated with the operation of thermoelectric generators (TEG), the Seebeck effect. Under steady state condition, the equation that governs the heat flow at the hot side, Q_H is:

$$Q_N = K_{TEG}\Delta T + S_{TEG}\left(T_H I\right) - 0.5 I^2 R_{TEG} \tag{6}$$

where, K_{TEG} is the total thermal conductance of thermoelectric module, S_{TEG} is the total Seebeck coefficient of thermoelectric module, R_{TEG} is the total resistance of thermoelectric module, T_H is the temperature at hot side, ΔT is the temperature difference between hot and cold side and I is maximum current. The efficiency of thermoelectric generator can be determined,

$$\eta_{TEG} = \frac{S_{TEG}}{Q_H}\left(T_H - T_C\right) \tag{7}$$

where, η_{TEG} is the efficiency of thermoelectric generator.

2.2 DEVELOPMENT OF TEG

Many thermoelectric couples of n-type and p-type thermoelectric semiconductors are connected electrically in series and thermally in parallel to make a thermoelectric generator as shown in Figure 4. The flow of heat drives the free electrons (e^-) and holes (h^+) producing electrical power from heat.

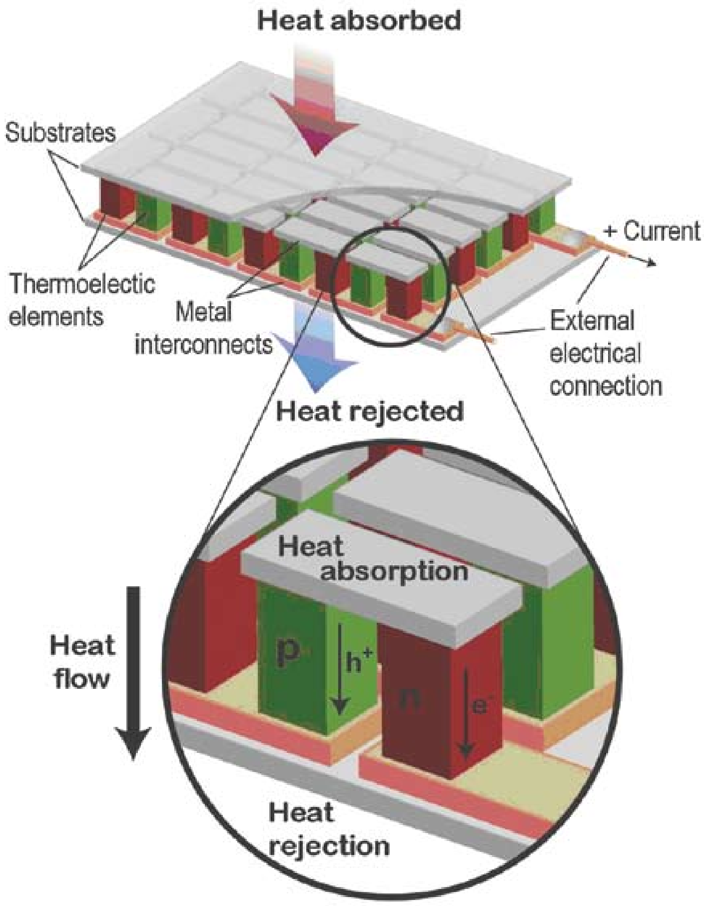


Figure 4: Thermoelectric generator model [Snyder, 2006]

The main focus of the thermoelectric generator is to generate electricity based on temperature gradient. The direct conversion of heat energy into electrical energy can be accomplished through the *Seebeck* effect. Covering the exhaust pipe with the thermocouples modules develops the TEG. The P/N thermocouple consists of a single pellet of P-type and N-type thermoelectric material each that are connected electrically in series. Heat carries the majority carriers from one junction to the other producing electrical power.

TEG module and exhaust gas pipe has been modeled by [2] as shown in Figure 5 by using a TEG module TEC1-12708 with connecting 126 units of semiconductors (p-type and n-type) in series. The module specification: maximum voltage 15.4V, maximum current of 8A, temperature difference ≤66^{0}C and maximum allowable heat of 73.92W.

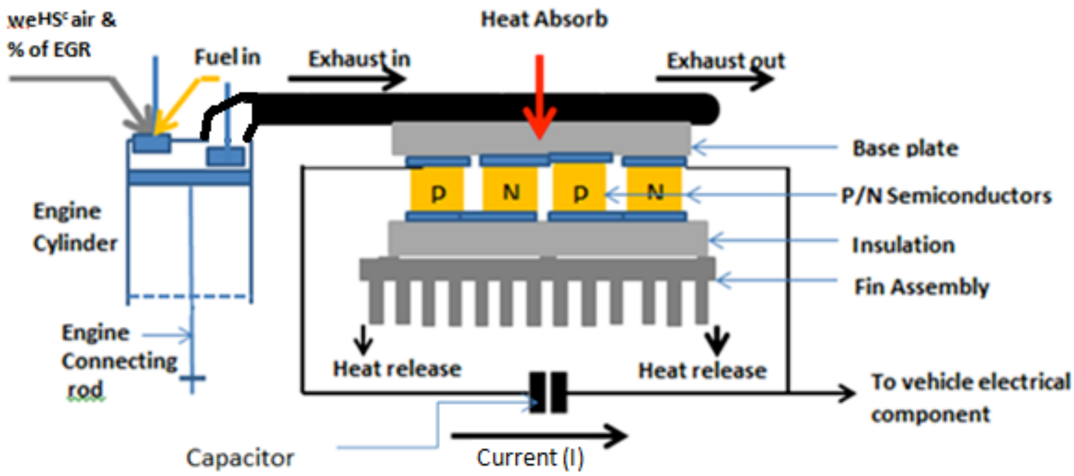
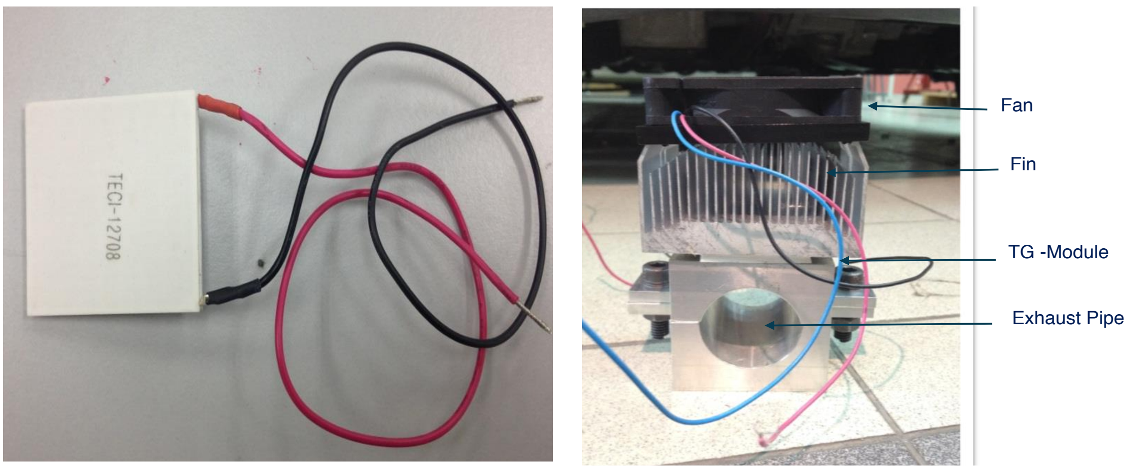


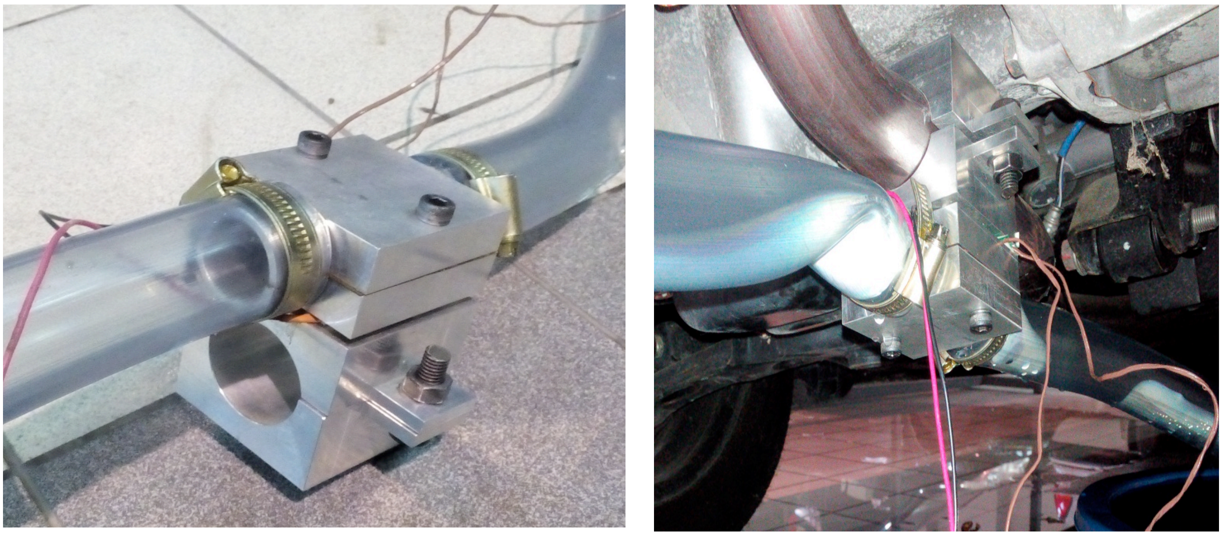
Figure 5: Model of TEG [Rahman et al.,2015]

In this study the performance of TEG on electric power generation from exhaust has been investigated by developing two types of TEG cooling model: fine-type air cooling as shown in Figure 6 and liquid-type cooling as shown in Figure 7. In fin type air cooling, a draft fan has been used to draw additional fresh air to the fin for increasing temperature gradient ($\Delta T = T_h - T_c$) with decreasing T_c. In liquid cooling TEG, the liquid (H_2O) flow has maintained continuously to keep-down T_c. The performance of liquid cooling TEG performs better than the air cooling at higher engine RPM as the heat rejection ($Q = hA\Delta T$) of liquid is greater than the air due to the values of heat transfer coefficient (h). The heat transfer coefficient is considered: h=100 W/m^2K for air and h=1000 W/m^2K for H_2O.



(a) (b)

Figure 6: Thermoelectric generator (a) module TECI-12708 (b) air cooling TEG generator.



(a) (b)

Figure 7: Thermoelectric generator (a) liquid cooling TEG unit (b) Mounting of liquid cooling TEG unit with exhaust pipe

3. RESULT AND DISCUSSION

This thermoelectric generator is tested at Perodua Myvi. The installation part is attached at the closest exhaust manifold of internal combustion engine to gain the highest temperature to generate high voltage gain and prevent heat loss to the surroundings. Three mounting points of TEG model have been considered to investigate its performance as shown in Figure 8.

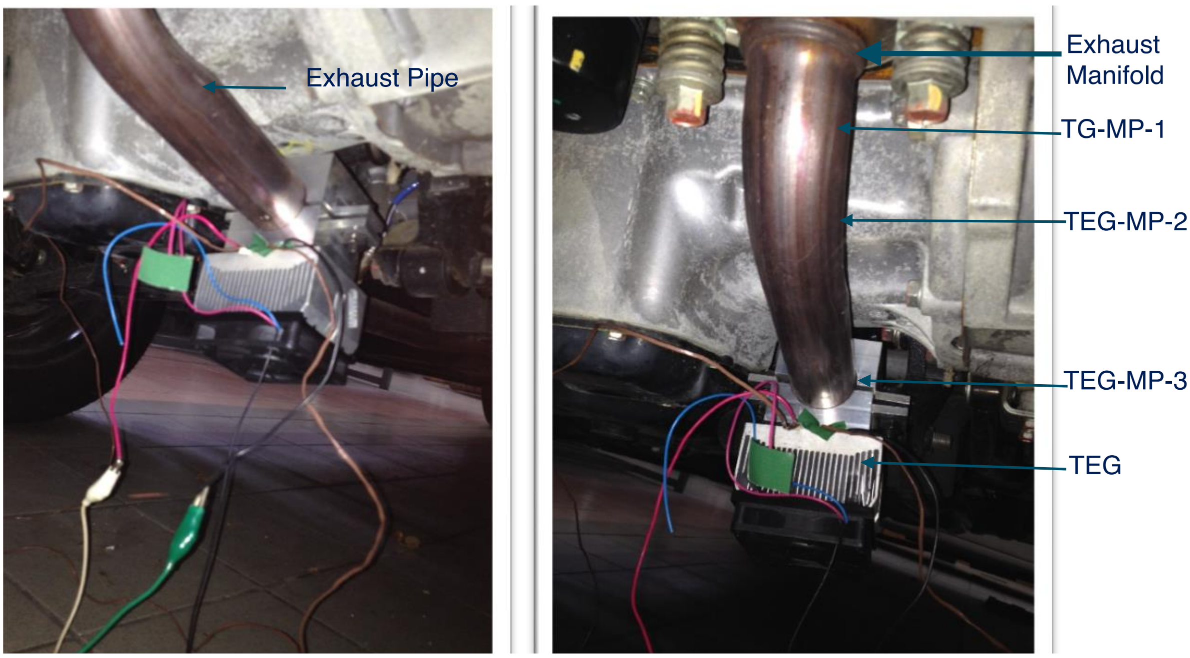
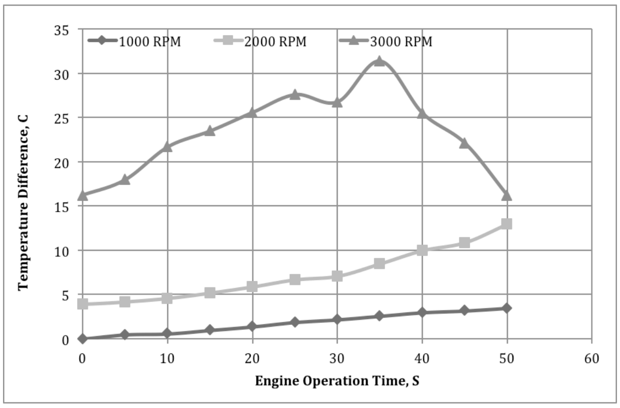
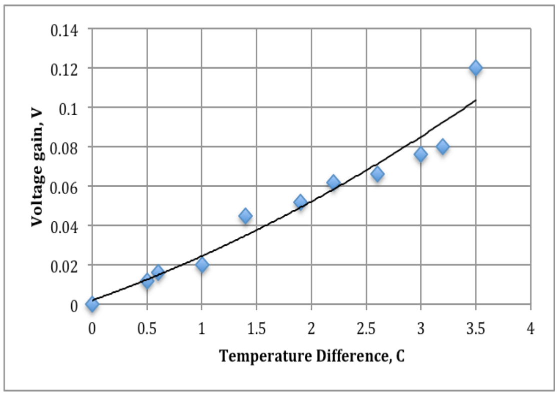


Figure 8: Mounting of air cooling TEG unit for experiment

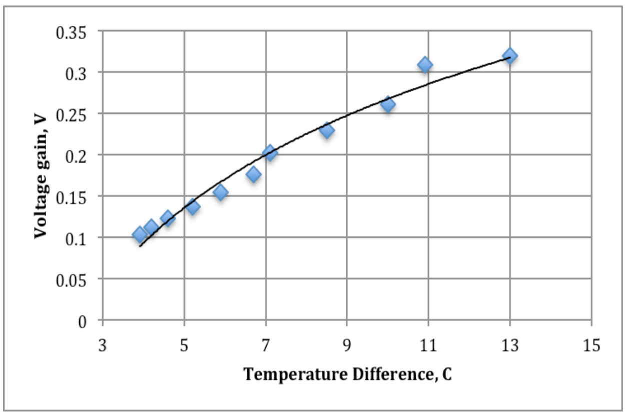
The TEG performance has been conducted with engine RPM range from 2000 to 3000 rpm. Figures 9 and 10 show the voltage development by the TEG increases with increasing the RPM of the engine which is due to the increment of fuel heating value. It could be mentioned that waste exhaust harvesting system by coolant (weHS^c) heated intake air in the range of 60^0 – 70^0C which allows the fuel atomization and vaporization up to 90% and fuel ignite almost completely in the combustion chamber. Figure 9(a) shows at engine 3000 RPM, the temperature difference (ΔT) decreases over time which affects the TEG performance for over time which is due to the lower heat transfer co-efficient of air. The TEG performance for the engine rpm of 5000 is recorded very less. Figure 10(a) shows that the temperature differences of TEG has been increased for the engine rpm in the range of 1000-3000 rpm over time and increases the TEG performance. This is becuase of higher heat transfer values of liquid. The test result also shows the TEG temperature differences has been incresed until the engine rpm of 7000. This rpm is normally not considered for the engine of passenger car. The maximum engine rpm is considered for the engine for passenger car about 5000 rpm.



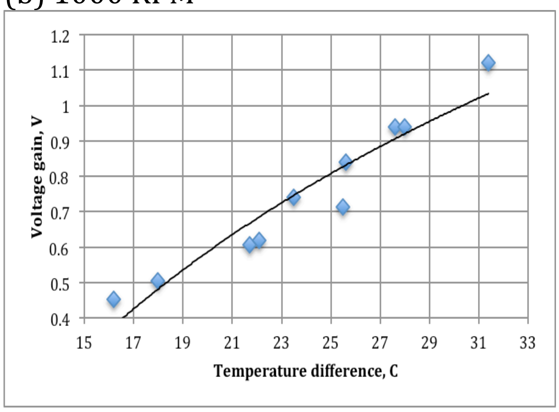
(a) Temperature diffrence



(b) 1000 RPM

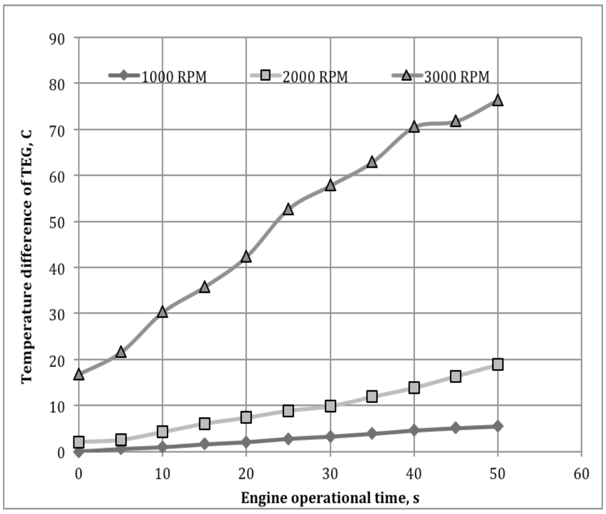


(c) 2000 RPM

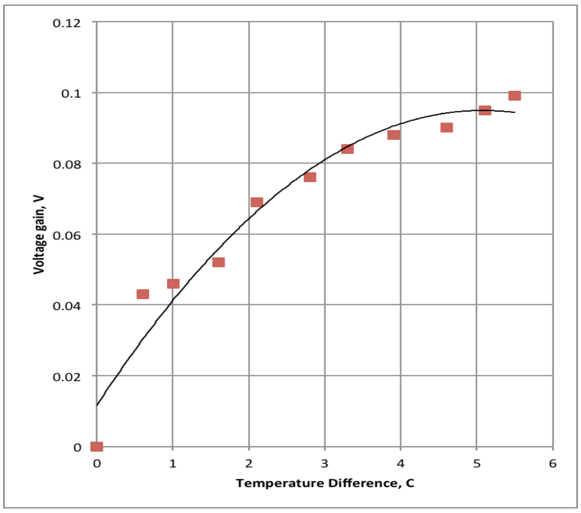


(d) 3000 RPM

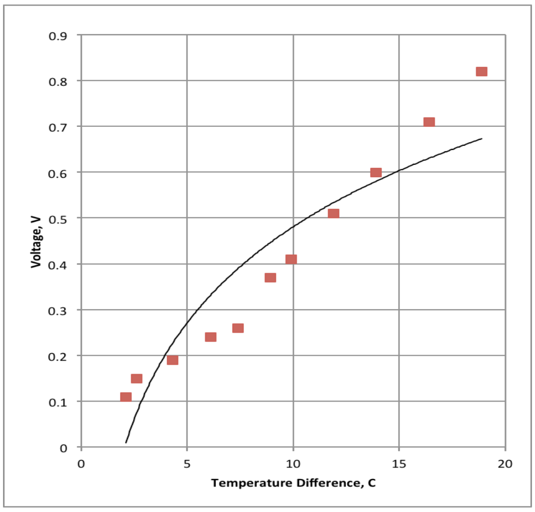
Figure 9: Performance of fine type TEG (a) temperature difference vs engine operation times (b-c) Voltage gain for different engine RPM



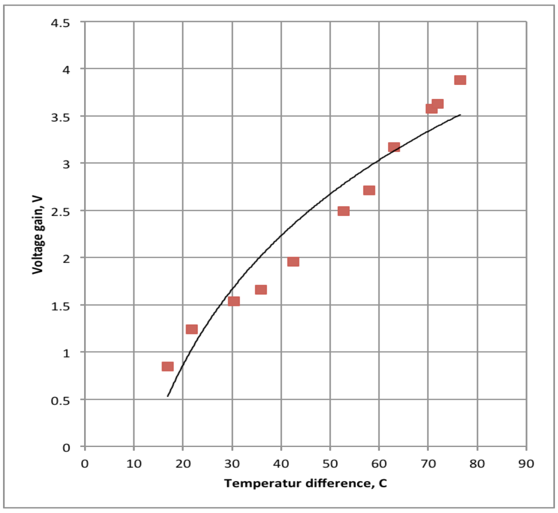
(a) Temperature difference



(b) 1000 rpm



(b) 2000 rpm



(c) 3000 rpm

Figure 10: Performance of fine type TEG (a) temperature difference vs engine operation times (b-c) Voltage gain for different engine RPM

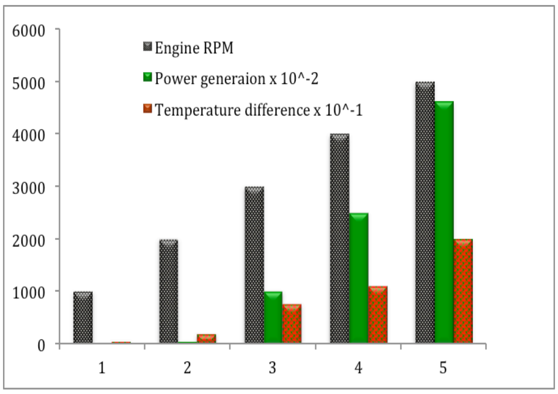


Figure 11: Power generation from

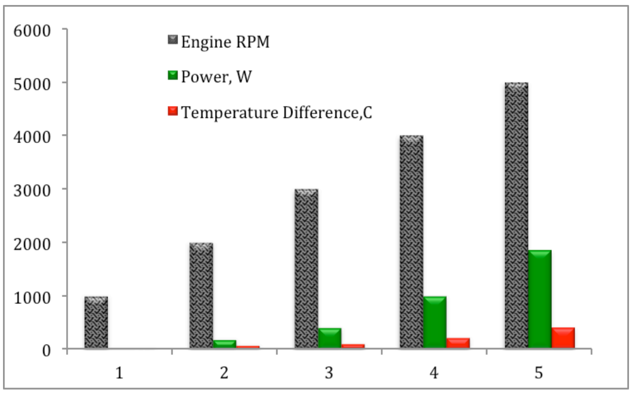


Figure 12: Power generation from engine

engine exhaust by using single TEG module. exhaust by using single TEG module.

Figure (11) and (12) show the liquid cooling TEG performance. Figure (10) shows that the liquid cooling TEG performance increases exponentially with increasing the engine speed. The experiment has been conducted for the maximum engine speed of 5000rpm. The power recovered from the exhaust of engine by using the module mentioned in earlier is about 200W if the exhaust is covered with four modules. Based on the increment of temperature difference, the liquid cooling TEG will able to recover 480W power from the exhaust of engine which is enough to operate the vehicle electrical continuous loads (fuel injection, ignition system and instrumentation system) and prolong load (indicator light, head lamp, wiper motor, CD player and etc).

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