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PROTOTYPE DEVELOPMENT OF THERMOELECTRIC GENERATOR SYSTEM FOR EXHAUST HEAT RECOVERY OF AN AUTOMOBILE

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ABSTRACT

In this study, a Thermoelectric Generator System (TEG) for exhaust heat recovery was developed and tested in a commercial small passenger automobile. The current phase of development is still in prototype mode, where the TEG was designed and then tested in a Perodua Myvi car in an idle condition. The main components of the designed TEG system consist of heat source recovery, insulator, TEG panel and heat sink. The TEG was placed at the ideal location on the exhaust system based on the optimum temperature condition of the TEG panel which is in the range of 150-250^{0}C and sufficient space for the TEG system. Based from the TEG performance test results, it indicates that for an idle car condition, the maximum power output of 36.4 W can be obtained. A MATLAB Simulink simulation was performed to predict the extent of TEG performance in the Perodua Myvi car with driving condition under a variable load of an urban daily drive schedule (UDDS) cycle. The simulation results shows that the TEG system can produce an average of 258 W of power output and the total amount of energy recovered is 7, 586 kJ/cycle. In comparison with the estimated amount of waste heat dissipated in exhaust gas, only 4.7 percent of energy is recovered. However, the amount of power produced is sufficient to provide auxiliary power requirement for some of the electrical systems in the vehicle.

Keywords: thermoelectric generator, exhaust system, electrical system, heat recovery, power output, prototype design.

INTRODUCTION

The raising concerns over fuel consumption and engine efficiency have shifted the interest of the automotive industry towards producing fuel efficient car. This gives birth to concepts and technologies such as hybrids and electric cars. However since most of the fuel energy is lost in the form of waste heat in the exhaust, thermoelectric generator can be utilized to recover those waste heat energy and converts it into supplementary electrical energy to the car system.

In this study, a Thermoelectric Generator System (TEG) for exhaust heat recovery was developed and tested in a commercial small passenger automobile. The current phase of development is still in prototype mode, where the TEG was designed and then tested in a Perodua Myvi car in an idle condition. The main components of the designed TEG system consist of heat source recovery, insulator, TEG panel and heat sink. Developed to be integrated in an actual Perodua Myvi, the study focuses mainly on the extracting heat from exhaust system of the car. These two critical components of the system compliments each other as the rate of energy conversion directly related to the amount of heat recovered from the exhaust.

LITERATURE REVIEW

Conventional internal combustion engine loses much of the fuel energy in the form of released heat, parasitic resistance and mechanical force. John W. Fairbanks (2012) of the U.S. Department of Energy commented that as low as 22% of the energy is used to actually move a car. With the introduction of thermoelectric generator, those energy lost in the form of exhaust heat can be recovered and this has seen a drastic plan in recent years to further research and develop such technology in the automotive industry.

Thermoelectric generator (TEG)

Thermoelectric device converts heat energy into electricity. Explaining that, G. Jeffrey Sneider (2008) in his article illustrates the concept of electric current production through a series of heat flow that drives the free electron, e$^-$ and holes, h$^+$ in a series connection. Higher temperature gradient increases the rate of heat flow thus producing greater current in the form of electron flow. Figure-1 shows a schematic representation of a TEG module.

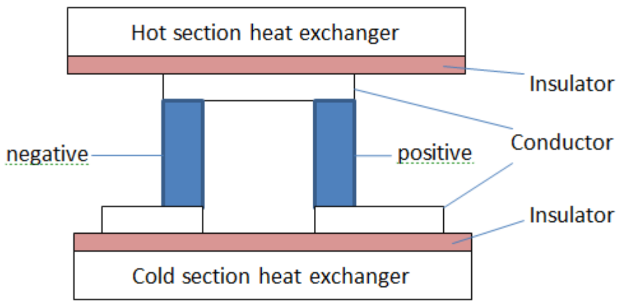

Figure-1. Schematic diagram of TEG module.

The efficiency of TEG works upon Carnot cycle in which it is given as;

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

In which ZT is the Figure Merit of the module and is given

as; $ZT = \frac{\sigma\alpha^2}{(K_e+K_L)}T$ (2)

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Based on the equation above, higher ZT is desired which depends on opposite nature of heat conductivity and electrical resistance of the particular materials. The 3rd International Conference of Thermoelectric goes Automotive (2012) had presented a methodological concept development of TEG which includes procedural design of simulation, construction, FE analysis and Dyno test bench.

Conventional car exhaust system study

The exhaust system is comprised mainly of pipes in several different shapes, each designated to connect to one another and shaped to conform to a specific part of the underside of the car. The pipes however are usually bent to wrap around or accommodate other nearby components under the car. Each pipe is responsible to move the exhaust gas towards the back, but many of the sections are specialized in function such as the resonator and muffler.

I.P. Kandylas and A. M. Stamelos (2009) has published their findings on the design of engine exhaust system based on heat transfer computation in which the main challenges in accurately estimating the parameters are due to complex geometry of the exhaust pipeline as well as the special flow condition. In the published paper as well they have tabulated exhaust pipe transient heat transfer model in which the model characterize the heat transfer mode in the form of rate expression and equation according to particular cases.

M. Kober, C. Hafele, and H. Friedrich (2012) has developed a methodical concept development of TEG in which they focused on finding the best TEG architecture for vehicle application. On the conference itself, they presented an analysis on the exhaust system of BMW 535i in the form of experimental testing of temperature along different parts of the exhaust system under different load.

METHODOLOGY

The study are designed in such a way that it comprises of two phases over the period of 24 weeks. The first phase mainly concentrates on studies data collection through experimental setup and simulations in which those data are utilized in the second phase of the project. This phase focuses on design process of the prototype up to the installation and performance testing.

Phase I

This phase involves evaluation of TEG panel performance characteristics by using lab-scale experimental set-up. Voltage, current and Power relationship with the temperature difference is investigated. Then, the exhaust system of a commercial passenger car is looked into, where temperature data are measured. This is to determine the best location in a car for a TEG system and to identify the physical and space limitation that an exhaust system can have on the TEG design.

Phase II

This phase involves designing, fabrication and evaluation of the TEG system. Performance test of TEG system was conducted on commercial passenger car under idle condition, while a MATLAB Simulink simulation was used to predict the TEG system performance for a driving condition.

PRE-EXPERIMENTAL STUDY ON THERMOELECTRIC GENERATOR

A simple experiment is conducted to investigate the extent of power produced by the TEG panel in a laboratory-scale environment. Values of Maximum power produced in relation to the temperature difference between the hot and cold source are observed, as shown in Table-1.

Table-1. Experimental results on TEG.

T_H [^{0}C]	T_C [^{0}C]	ΔT [^{0}C]	V [V]	I [A]	P [W]
80	40	40	14.0	0.15	2.1
105	55	50	15.0	0.32	3.0
150	65	85	15.5	0.80	12.4
200	80	120	15.5	1.00	15.5
250	110	140	15.5	1.25	19.4

Based on the experimental result, it can be deduced that as the temperature difference increases, the current and therefore, the power increases. It can be noted that the increase in voltage and current is rapid. Maximum power of 20 W was obtained by the set-up when the difference of temperature is 110°C.

TEMPERATURE DISTRIBUTION ON PERODUA MYVI EXHAUST SYSTEM

Perodua Myvi was selected as the commercial car to be tested with the TEG system. Temperature distribution across the exhaust pipeline of the Perodua Myvi under an idle condition was recorded using thermocouple and data logger system. Components that are involved with the temperature measurement are the components of exhaust manifold, catalytic converter, extension pipe, sensor pipe, resonator and muffler. The temperature along the exhaust pipeline drop drastically as the gas travels further down the system. The ideal location to place the TEG would be those with temperature range of 150-250^{0}C. Any less than that would cause the TEG to lose its functionality while higher temperature could pose

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risk of damage. Based on the result of the studies, the most ideal location was on the resonator entry pipe. The location also provide ample space to install the TEG of the exhaust system.

THE STRUCTURE OF TEG SYSTEM

Conceptual design enables the overall system of the TEG to be properly established and connected. The design suggested that it should comprise of three main sub-systems which are the heat source, energy converter and heat sink. Without any of these sub-systems, the design would not achieve its objectives.

Parametric design on the other defines the necessary parts of the system and its dimensions in developing the design. It has to take consideration of various aspects including materials selection, fabrication feasibility and structural conformity. Figure-2 illustrates the optimized developed design of TEG.

Heat Source Cover Channels and contains the flowing exhaust gas

Heat Source Recovery Captures heat as the exhaust gas flows through the upper surface fins

TEG Panel Allow flow of heat to produce electricity

Insulator Isolates and insulates two side of TEG to encourage flow of heat across the Peltier chips

Heat Sink Removes the heat to the surrounding t create a temperature different across the TEG layers

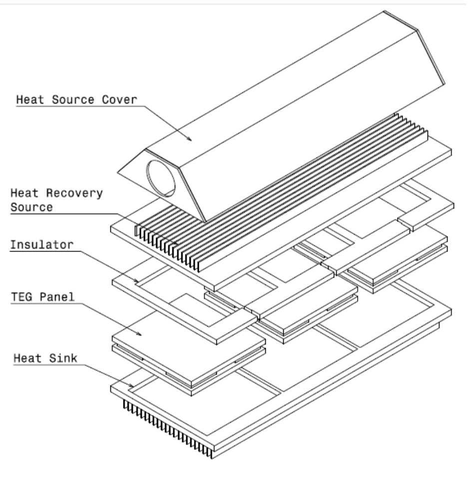

Figure-2. Optimized design of TEG.

ASSEMBLY OF TEG AND INSTALLATION OF TP EXHAUST PIPE

The TEG is fabricated according to the defined parameters involving various methods and machinery including conventional milling and metal shear machine. Each of the parts are inspected and properly assembled.

Table-2. Specifications of developed TEG.

Thermoelectric Generator (TEG)	
Height	**75.5mm**
Length	295.0mm
Width	105.5mm
Weight	5.75kg
Material	Top part mild steel and bottom aluminium plate with ceramic as insulator
Pipe assembly	Inlet and outlet hole of diameter 40mm at both ends
Power Output	Electrical cables of three DC output to controller at right side

The fabricated TEG is installed on the exhaust pipeline ahead of the resonator as per previous experimental study. To fit the assembly, the pipeline is removed and cut according to the specified location where the TEG is welded on both ends. The exhaust pipeline is then installed back with additional support via exhaust hanger to compensate the additional weight of the TEG.

Figure-3. Assembly of TEG on exhaust pipe.

TEG MODEL PERFORMANCE TEST

The installed TEG is tested under idle engine condition in which the major focuses are the temperatures profiles across the layers and the power output produced. Table-3 below summarizes the result of the experimental testing.

Table-3. TEG performance result.

TEG performance testing			
Steady-State Cold Temperature, T_C	42.0 ^{0}C	Max. Voltage, V	14.2 V
Steady-State Hot Temperature, T_H	135.0 ^{0}C	Max. Current, I	2.6 A
Temperature Gradient, ΔT	93.0 ^{0}C	Max. Power, P	36.4 W

Using thermocouples to record real time data, the hot and cold temperature of the TEG increases gradually over time until it reach a steady state temperature. The temperature profiles are shown in Figure-3.

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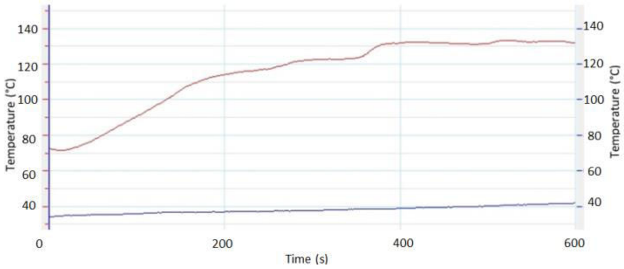

Figure-4. Temperature vs time.

The voltage (red line) and current (yellow line) increases gradually until it reach maximum values as shown in Figure-4. The maximum power produced is 36.4Watts as shown as blue area of the graph.

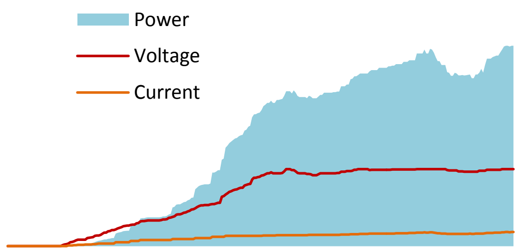

Figure-5. Power output of the TEG.

As shown by the result, the designed TEG model is proven of its functionality upon installation on an actual exhaust system of a car and has shown a steady operation after 400s.

Based on the steady state results from Table-3, a thermal model of the exhaust waste heat energy and exhaust temperature outlet from the engine was created and a MATLAB Simulink model was used to simulate the TEG system performance under a variable load of an urban daily drive schedule (UDDS) cycle. A model of engine thermal efficiency map [19] shown in Figure-5 was used to calculate the amount of waste heat carried by the exhaust gas utilizing the following equation:

$$Q_{exhaust} = 0.3\, \dot{m}_{fuel} * LHV_{fuel} - T \cdot \omega \quad (3)$$

Next, the exhaust gas temperature is estimated by the following equation:

$$T_{exhaust} = [Q_{exhaust} / (\dot{m}_{fuel} * Cp_{air})] + T_{ambient} \quad (4)$$

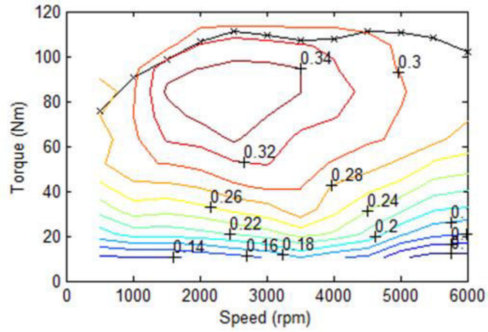

Figure-6. Engine thermal efficiency map [19].

A simulation was performed with 5 units of the TEG systems consisting of 15 TEG chips installed covering a total length of 1.5 meter of the exhaust system. Assumptions on temperature profile along the length were based on actual results as shown in Figure-3. In addition, power outputs as function of the temperature difference were modelled based on experimental results shown Table-1.

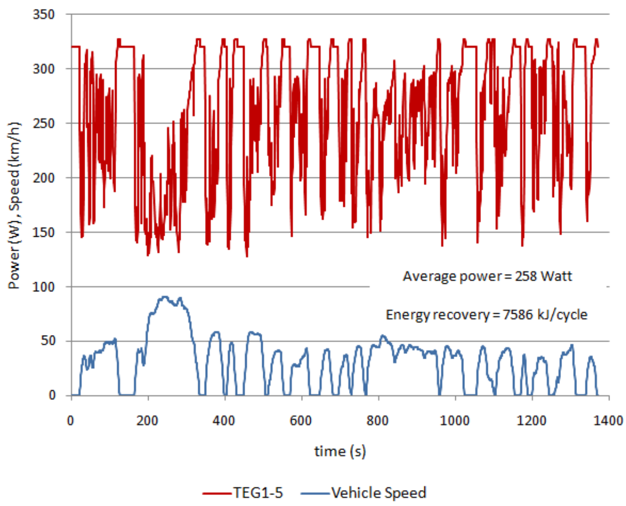

Figure-7. Power output of TEG system (5 units).

The simulation results are displayed in Figure-6. It shows that the TEG system average power output is 258 Watt and the total amount of energy recovered is 7, 586 kJ/cycle. In comparison with the estimated amount of waste heat dissipated in exhaust gas, only 4.7 percent of energy is recovered. However, the amount of power produced is sufficient to provide auxiliary power requirement for some of the electrical systems in the vehicle.

CONCLUSIONS

Development of a TEG on a Perodua Myvi requires various research and studies on mainly two different components of the design which are the exhaust system as well as the thermoelectric devices. Experimental studies and simulation had been conducted on the exhaust system to acquire two crucial data. The first one would be the temperature range along the exhaust pipeline while the later is the feasibility study of TEG installation.

The two critical components above provide necessary information to further building a design for the prototype. The design however should not only comply with the requirements or maximum potential of the device, but also in terms of ease in fabrication and material acquisition. Thus, the design had undergone several changes over the project period and finally be fabricated and installed on an actual exhaust system. Final testing has proven the functionality of the designed TEG with a maximum power output of 36.4 Watts while harnessing heat energy from the exhaust system. Further improvements on the design could possibly increase its performance capacity.

The simulation results indicated that 4.7 percent of the exhaust waste heat energy is recoverable using 5 units of the current TEG design. Further improvements in the internal design of the heat recovery fins and n active cooling system could potentially increase the amount of electrical energy generated, hence increasing the overall thermal efficiency of the vehicle.

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