Experimental study on waste heat recovery system of an internal combustion engine using thermoelectric technology

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Abstract. Internal combustion engines do not effectively convert energy from the chemical reaction into useful energy, notably mechanical energy. In fact, majority of the energy are converted into heat energy, and dissipated into environment which does not fully contribute to the performance of internal combustion engine. This results in lower overall efficiency of the engine. The heat released into the environment can be converted into useful electrical energy by using thermoelectric generator (TEG). TEG consists of cold side and hot side and works based on the principle of Seebeck effect. The hot side of TEG is exposed to hot surfaces of the exhaust, and the cold side is cooled with fan cooled heat sink. The function of heat sink is to increase the temperature differences across the TEG. The conversion of waste heat into electricity by TEG in an automobile can be a good case study to replace the alternator for battery charging and increase the overall efficiency of the Internal Combustion (IC) engine. In this study, eight pieces of TEG with dimensions of 40 mm x 40 mm each were attached to a square heat exchanger. This heat exchanger was connected to the exhaust pipe of the engine. The temperature recorded in the exhaust was more than 150 °C. Thermocouples were embedded on the hot side and cold side of the thermoelectric generators to evaluate the temperature differences across the TEGs. The output of the TEGs were obtained at idle and half-throttled engine conditions. An electronic load was applied to obtain the voltage, current and the power output from the TEGs system. The TEGs were tested individually, all connected in series and parallel connections. The maximum output voltage was recorded for the series connections at 5.8 V with an average hot side temperature of 48 °C across TEGs. Maximum power output obtained when all the TEGs connected in series was at 2.3 W.

Keywords: Thermoelectric Generator (TEG), Heatsink, Exhaust Heat Utilization System, Voltage

1. Introduction

Vehicle emissions became a main concern in the recent past. As the population grows, the number of vehicles also increases to meet the mobility demand. In 2012, worldwide production of vehicles reached 84.1 million units, as reported by Organisation of Motor Vehicle Manufacturer (OICA) [1]. As the number of vehicles goes up, so does the rate of emission to the environment. Climate change is the effect of greenhouse gases produced by human activities. Carbon dioxide (CO₂) gases are released during the combustion of fossil fuel and deforestation [2].
Before a new vehicle is released to the market, the vehicle must undergo a series of emission regulation tests [3]. Different countries have different regulations, but usually these regulations become more stringent with time. For the vehicle manufacturer to meet the regulations, they are required to reduce their vehicle fuel consumption. A typical fuel energy in an automobile is converted accordingly: 40% of the energy is converted into exhaust heat energy, 30% of energy is transferred to coolant, 5% is converted to radiation and friction losses and 25% are used for vehicle mobility and accessories [4].

Based on the information, many technologies were developed to utilize the waste exhaust thermal energy and convert it into useful energy. The technologies that are considered to convert this heat energy are organic Rankine cycles (ORC) engine, thermally driven absorption chiller (AbC), electrically driven mechanical heat pumps (MHP), thermally driven absorption heat pump (AHP), absorption heat transformers (AHT) [5], and heat exchanger with thermoelectric generator that can directly convert heat energy from exhaust system.

From the options listed above, thermoelectric generator technology is favorable as thermoelectric generator has no moving parts, compact in construction, and robust [6]. Thermoelectric generator works by the principle of Seebeck effect, which is based on temperature differences and produces electrical energy. Generating electricity from TEG heat exchanger from automobile waste heat provides a great advantage as this electricity can be used to power up any auxiliary devices and battery charging. This can help to improve the overall efficiency of the overall performance of IC engine. Moreover, the simple design TEG heat exchanger with air cooling used in this study due to its simplicity and wide range of usage will enable the widespread application of waste heat recovery for power generation from exhaust heat.

In this project, a system integrating thermoelectric generator was attached to the exhaust system of the internal combustion engine, after the exhaust manifold. When the internal engine reached idle state, the temperature of the exhaust stabilizes and thermoelectric generators convert the available thermal energy, proportional to the temperature difference across the thermoelectric generators. The cold side of the thermoelectric generators were cooled by using fan.

2. Methodology

2.1 Fabrication of System

The exhaust waste heat utilization system consists of rectangular tube, cylindrical tube, heat sink, thermoelectric generator (TEG), and cooling fan. The first step in the fabrication is to cut the rectangular tube and cylindrical tubes based on the measurement decided. Then, the rectangular tube and cylindrical tubes was fused together with Tungsten Inert Gas (TIG) welding. Rectangular tube and cylindrical tubes before, during and after the welding process is shown below.
Figure 2: The system after TEG and thermocouple are attached

For the heat sink to able to attach to the system, a total of eight holes were drilled into the rectangular tube, and also a total 16 holes have to be drilled on the heat sink (eight holes to attach the heat sink, another eight holes to attach the fan).

Next step, for the thermocouple to be able to fit under the thermoelectric generator (TEG), a total of eight (8), 2 mm width, 1 mm deep, 25 mm long lines were milled by using milling machine.

2.2 Experiment Setup

After the system was fabricated, the system was then taken to Automotive Lab, Level 3, Faculty of Mechanical Engineering, UiTM Shah Alam. The internal combustion engine used for the experiment is diesel generator as shown in figure 3 below. The specification for the engine is listed in the table 1 below.
Table 1: Specification of the Engine

| Brand     | Engine System                                    | Revolution per minute (rpm) | Output | Start         | Fuel tank capacity | Cooling system                        |
|-----------|--------------------------------------------------|-----------------------------|--------|---------------|-------------------|----------------------------------------|
| Yanmar    | Direct Injection, 1 Cylinder, 4 Stroke Natural Aspirated | 3600 rpm                   | 100 W  | Push Button   | 400 ml (educational purposes) | Forced air cooling by flywheel fan |

The system was connected to the diesel generator exhaust outlet. The experiment was conducted for 30 minutes, and the reading of the open circuit voltage from thermoelectric generators (TEGs) were taken every five (5) minutes. The hot side and cold side temperature of each thermoelectric generator was also taken, along with temperature in ($T_{in}$) and temperature out ($T_{out}$) of the hot exhaust gas through the setup. The temperatures were recorded using data logger. DC cooling fans were powered up by using DC power supply, set at 12 V.

3. Result and Discussion

3.1 Temperature In, $T_{in}$ and Temperature Out, $T_{out}$
In Figure 5, the temperature increases steadily as the time increases. This shows that the engine used is in good condition. Average temperature for $T_{in}$ was 94°C. For the rest of the time (5 minutes to 30 minutes),
the temperature increased steadily. Average temperature for $T_{\text{out}}$ is 76°C. The difference between the $T_{\text{in}}$ and $T_{\text{out}}$ shows that the heat energy has been utilized and converted into electrical energy by the TEGs attached to the heat exchanger. From Figure 5, it is evident that the difference between $T_{\text{in}}$ and $T_{\text{out}}$ is around 19 °C.

3.2 Temperature over Voltage on Given Time

Eight TEGs (40 mm x 40 mm) were used to carry out the experiment. Two TEGs were attached on all 4 sides of rectangular channel by applying thermal paste on bottom and top surfaces (hot and cold side of TEG). Then, TEGs were clamped with heatsink and four, 12 V DC fans were attached to the heatsink. Voltage of each TEGs were taken by using voltmeter every five (5) minutes, and the temperature of hot side of TEGs were taken using thermocouple connected to a data logger.

As shown in Figure 6 and Figure 7 both voltage and temperature of the TEGs increased steadily with time. This is coherent with the Seebeck effect that temperature differences across TEG is directly proportional to electrical output. The readings for the temperature and open circuit voltage reached steady state approximately after 20 minutes.

Both the figures below show that the open circuit voltage generated is directly proportional to the temperature difference across the TEGs. Due to the location of the TEGs on the rectangular tube, all eight TEGs did not produce similar values of open circuit voltage. This is due to the uneven application of thermal paste. The heat dispersion in the rectangular channel is also not uniform and this is also a factor that contributes to uneven reading for the open circuit voltage of TEGs. The variation in hot side of TEG temperature is around 5 °C and the maximum variation of TEGs for open circuit voltage is 0.10 V.

All TEGs were then connected in series. An electronic load was used to measure the maximum output power and also maximum voltage generated. The maximum output power for all the TEGs were recorded at 2.4 W and the maximum voltage generated was at 5.8 V. This shows that the potential of converting waste heat into electrical energy through the system developed in this study needs further enhancement in terms of number of TEGs and efficient heat transfer rate through the TEGs. In order to charge a battery in IC engine, a minimum of 13 V open circuit voltage is needed. This can be simply accomplished by using more TEG.

The TEG heat exchanger can be constructed with more TEGs with higher output in terms of output voltage. An output voltage of more than 13 V will be suitable for battery charging in an automobile and power output from TEGs can be used for powering auxiliary equipment in an automobile such as sensors and electrical devices.
Figure 6: $T_{hot}$ versus Time for all TEGs

Figure 7: Open Circuit Voltage versus Time for all TEGs
4. Conclusion
Exhaust waste heat recovery can help to increase the efficiency of internal combustion engine. The experimental results obtained in this study show that TEG based heat exchanger was able to convert waste heat from exhaust and generate electrical power output. The maximum output voltage was recorded for the series connections at 5.8 V with an average hot side temperature across TEG of 48 °C across the TEGs. Maximum power output obtained when all the TEGs connected in series was at 2.3 W. As the number of vehicle increase every year, exhaust waste heat is considered as the future hybrid technology available on vehicles.

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References
[1] OICA, “World vehicle production reached 84.1 million in 2012,” vol. 33, no. 0, p. 1, 2013.
[2] T. J. Wallington, C. K. Lambert, and W. C. Ruona, “Diesel vehicles and sustainable mobility in the U.S.,” Energy Policy, vol. 54, pp. 47–53, 2013.
[3] B. Orr, A. Akbarzadeh, M. Mochizuki, and R. Singh, “A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes,” Appl. Therm. Eng., vol. 101, pp. 490–495, 2016.
[4] D. Monga, G. Baradia, S. Nangia, R. Mishra, Y. Chawla, and T. Chadha, “Energy Harvesting System Using Thermoelectric Generators and Heat Pipes: A Review,” vol. 5, no. 2, pp. 258-263, 2017.
[5] G. Oluleye, N. Jiang, R. Smith, and M. Jobson, “A novel screening framework for waste heat utilization technologies,” Energy, vol. 125, pp. 367–381, 2017.
[6] T. Y. Kim, A. A. Negash, and G. Cho, “Waste heat recovery of a diesel engine using a thermoelectric generator equipped with customized thermoelectric modules,” Energy Convers. Manag., vol. 124, pp. 280–286, 2016.
[7] M. Sajid, I. Hassan, and A. Rahman, “An overview of cooling of thermoelectric devices,” Renew. Sustain. Energy Rev., vol. 78, no. April, pp. 15–22, 2017.