ZULFAQAR Journal of Defence Science, Engineering & Technology
e-ISSN: 2773-5281
Vol. 5, Issue 2 (2022)
DOI: https://doi.org/10.58247/jdset-2022-0502-11
Journal homepage: https://zulfaqarjdset.upnm.edu.my

ENERGY HARVESTING FROM EXHAUST WASTE HEAT USING THERMOELECTRIC GENERATOR (TEG) MODULES

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ARTICLE INFO

ARTICLE HISTORY
Received: 01-07-2022
Revised: 30-09-2022
Accepted: 15-10-2022
Published: 31-12-2022

KEYWORDS
Thermoelectric generator
Waste heat
Seebeck effect
Energy harvesting

ABSTRACT

Gas and electricity have been utilized greatly as the amount of usage in residential, industrial, and transportation has increases which would lead to the production of waste energy in the form of waste heat from the numerous electrical, machinery and electronic appliances. In this study, harvesting energy from the waste heat of motorcycle exhaust using thermoelectric generator (TEG) modules was aimed for a better output. TEG was used to convert heat energy to electrical energy whenever there was the presence of temperature difference between the hot and cold side of the TEG. It was found that, the higher the number of TEG used has achieved even higher output voltage and current due to the arrangement of series array of TEG modules producing up to 5.802W during the engine ramp.

1.0 INTRODUCTION

In recent years, discussion on waste energy recovery has emerged and discoursed among researchers as development of technologies especially in industrial and automotive grow rapidly. Due to the consumption and operation of the technologies, an abundance of waste energy is produced. With numerous advanced research, waste energy can be transformed into renewable energy which is very highly needed in current generation. The usage in power generation, industrial processes, electrical machines, and automotive give out heat as a waste heat [1]. Because of the increasing environmental and economic issues such as, energy security, energy prices, progressively competitive global markets and stringent environmental emission regulations; these are primary driving forces in solving for systematic, maintainable and economically workable technologies for conversion and application of the energy [2]. In the developing era, manufacturing, data processing, heating, cooling, lighting, transportation and food processing are activities that causes energy becoming crucial to the society and environment. Therefore, green technologies such as solar photovoltaic, wind turbine, hydrogenation and biomass are essential are the subject of current interest in finding appropriate solutions to overcome the energy and environmental problems [3].

Waste energy can recuperate by collecting it from various sources of energy used since a large number industrial and transportation processes use a vast amount of energy in the form of heat. Thus, with the heat and temperature variation produced as waste energy from many sources, renewable energy can be harvested in means to recover and conserve the depletion of energy sources. Thermoelectric can be significantly applied in harvesting energy from heat whereas Seebeck effect, Peltier effect, and Thomson effect have been utilized in the devices. In this work, Thermoelectric generator (TEG) is an essential component of the device to transform heat to electricity and vice versa with entirety on the principle of the Seebeck effect. TEG is highly decisive, having motionless parts, and being environmentally friendly,

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when related with conventional electric power generators [4]. Thermoelectric modules are mandatory alternatives to heat engines in the harvesting of waste heat [1] as the development of transformation (power generation) ability of TEGs is a critical factor to make TEGs more interesting for recovering energy from waste heat.

Consumption of energy in human activities as an alternative energy becomes significantly important as sources of energy for harvesting include, but are not limited, to light, thermal gradient, vibration, and radio frequency radiation. Hence, almost 60% of waste heat is produced compared to the energy used in the world. Therefore, TEG is used to harvest waste heat energy to become alternative source of energy. However, the low efficiency in harvesting waste energy using TEG has been the basis of this study where there is the necessity to further investigate the progress in attempt to increase the performance of harvesting waste heat energy using TEG modules. This study is embarked to develop and assess the thermoelectric based energy harvesting using TEG modules whereby the waste heat is harvested from the motorcycle exhaust.

2.0 EXPERIMENTAL

This study focuses on the harvesting of waste heat from the motorcycle exhaust. The methodology is divided into two main sections; circuit simulation and hardware of the waste heat energy harvesting system is consisting of array of waste heat source, TEG modules and step-up DC-DC buck converter circuit as indicated in Figure 1. For simulation process, by using Proteus Professional 7.7 software the simulation process is conducted to design the circuit and to get the preliminary results based on the TEG modules with certain specification and physical. While in terms of hardware, there are some components that are being used in this work which is bismuth telluride-based TEG modules that are connected in series array and followed by a step-up DC-to-DC converter to enhance output power.

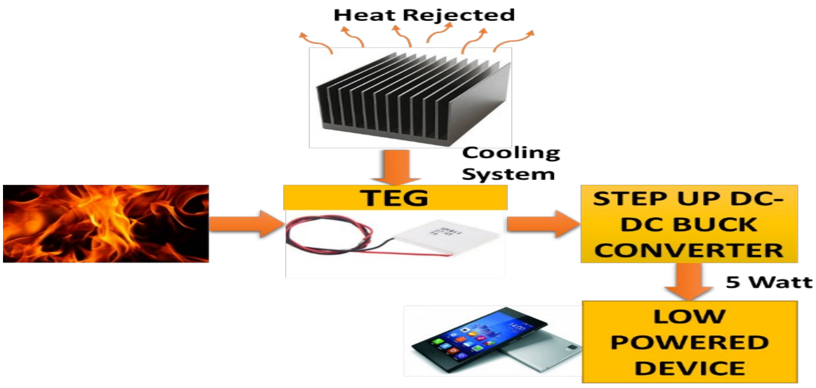

Figure 1. TEG-based energy harvesting

2.1 Heat Source

The waste heat produced by the motorcycle exhaust during the motorcycle engine running was chosen as a heat source for the TEG to be converted into useful energy. TEG modules were positioned at the hottest temperature to get the higher temperature difference. Once the temperature of the motorcycle Kawasaki Z800 800cc exhaust was measured, it was possible to determine the most suitable area to place the TEG modules. The heat produced was able to create a higher temperature difference as the higher the temperature difference, the better output can be obtained from the TEG. TEG would perform better if it is facing the hottest temperatures side. Figure 3 reveals the potential heat source from the motorcycle exhaust employed for this study.

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Figure 2. Heat source

2.2 TEG Module

The main component to convert heat energy to electrical energy in this study is the TEG module. TEG module of different materials with the same temperature difference could produce different output. In this experiment, TEG consists of bismuth telluride (Bi_2Te_3) module that can hold out at maximum temperature of 200°C with the dimension of 40 mm length 40 mm wide and 3.4 mm height has been utilized.

Bismuth telluride-based TEG is used because of its wide availability in the market, and it performs much better at lower temperatures [5] since the waste heat is in the range of low temperature and suitable for the scope of this study (< 450 Kelvin). Bismuth telluride also has a good value of figure of merit; Z value which is determined by Seebeck coefficient (α), electrical resistivity (ρ), and thermal conductivity (κ). The larger the value of Z, the better properties of the thermoelectric material [6]. Hence, the voltage output that can be produced by TEG depends on the size and the thickness of the module. To enhance the performance of TEG, the number of TEG is increased, and it is connected in series array. This is because such arrangement system could produce excellent conversion efficiency for waste heat recovery using TEG module.

2.3 Heat Sink

In this study, the type of materials and the geometry of heat sinks as a cooling system become the main role to increase the performance of the TEG system. Elliptical shaped heat sink corresponds to least thermal resistance and the graphite heat sink possessed the lowest thermal resistance while the aluminium and copper have the highest [7]. Based on those materials, aluminium heat sink was chosen in this study because of its utmost property in thermal resistance. The comparison of maximum temperature and minimum temperature with the four different types of geometry of the heat sink which are parallel plate fin heat sink (H1), parallel plate fin heat sink with difference length and thickness of fin (H2), staggered pin fin (H3), elliptical pin fin (H4) and three different types of materials are shown in Table 1. From Table 1, aluminium indicates the best performance in temperature difference.

Table 1. The comparison of maximum temperature and minimum temperature with the four different types of geometry of heat sink and three different types of materials [7]

Materials	Temperature of heat sink models (°C)				
	Temperature	H1	H2	H3	H4
Aluminium	T_{max}	60	60	60	60
	T_{min}	25.52	25.51	25.13	25.12
Copper	T_{max}	60	60	60	60
	T_{min}	26.62	26.61	25.56	25.53
Graphite	T_{max}	60	60	60	60
	T_{min}	32.71	32.39	30.39	30.32

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2.4 Step-Up DC To DC Converter

Step-up DC-to-DC buck converter was used to boost the output voltage of TEG from 3V into 40V DC voltages. The TEG modules are connected to the Step-up DC-to-DC buck converter and the circuit of the respective converter is shown in Figure 3.

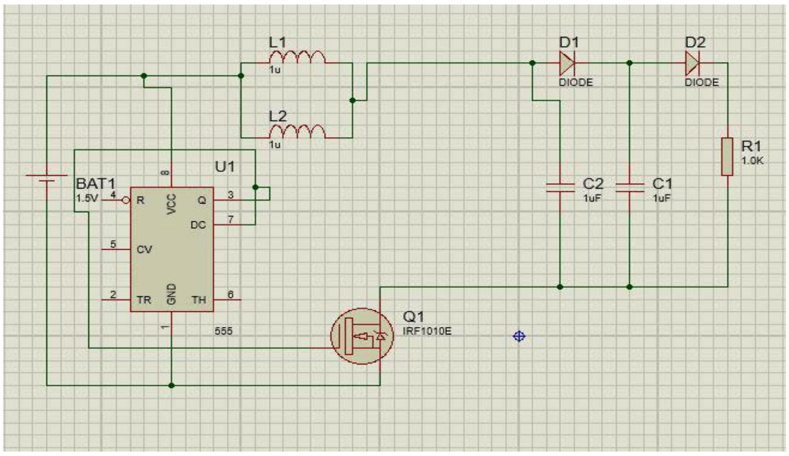

Figure 3. Step-up DC to DC buck converter

3.0 RESULTS AND DISCUSSIONS

For this study, several experiments have been carried out from the usage of waste heat in generating voltage and current by using TEG modules. The results of the experiment were properly taken during engine start, ramp and stop conditions. All the experiments were conducted by using motorcycle type Kawasaki Z800 800cc with TEG modules attached on the exhaust pipe of the motorcycle as shown in Figure 4.

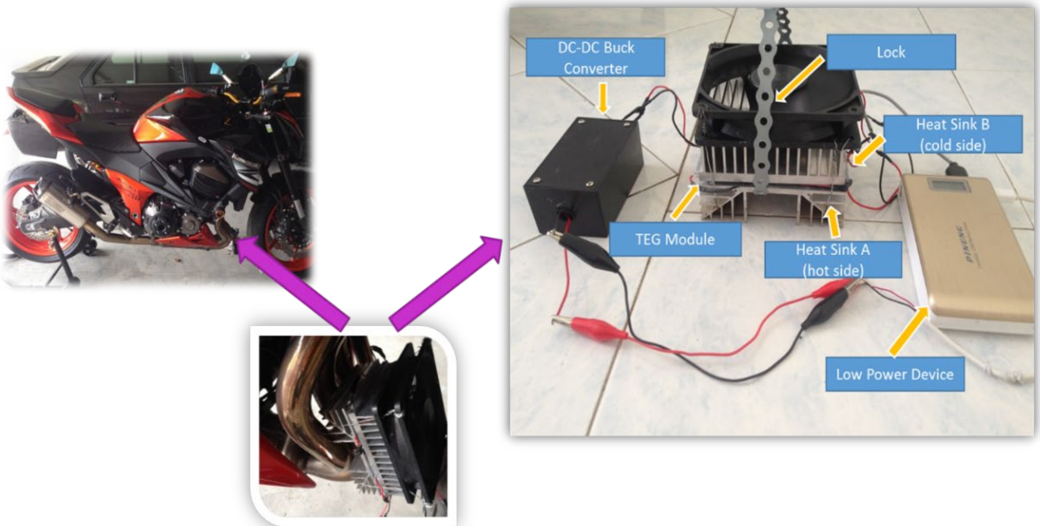

Figure 4. Input part attached to exhaust system

3.1 During Engine Start

Before starting the engine, the equipment and instrument were set up as shown in Figure 5 to measure the temperature on the hot side and the cold side of TEG, voltage output, and current that produced by TEG. The temperature values of hot and cold side of heat sink, the voltage and current were measured every minute throughout the duration of 15 minutes.

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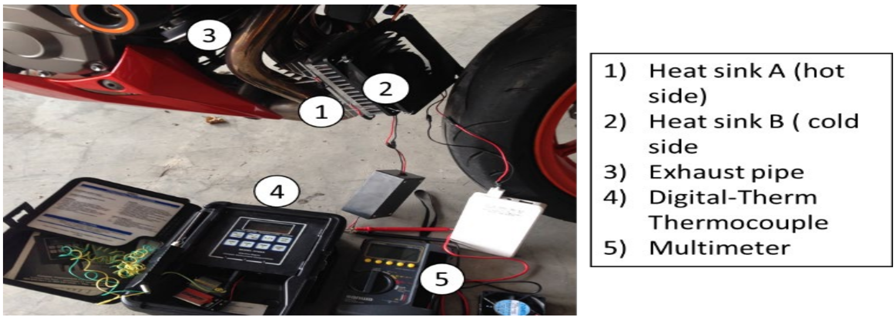

Figure 5. Setup of experiment

An experiment was also conducted to monitor the output voltage that produced from TEG versus time when the engine started until minute 15th. Based on the graph in Figure 6, it shows that the voltage increases when the time increases as the motorcycle exhaust also increases in temperature when there was combustion in the engine system. Therefore, the hot side of TEG that attached to the exhaust indicates an increase in temperature along with the increase in temperature difference between both parts.

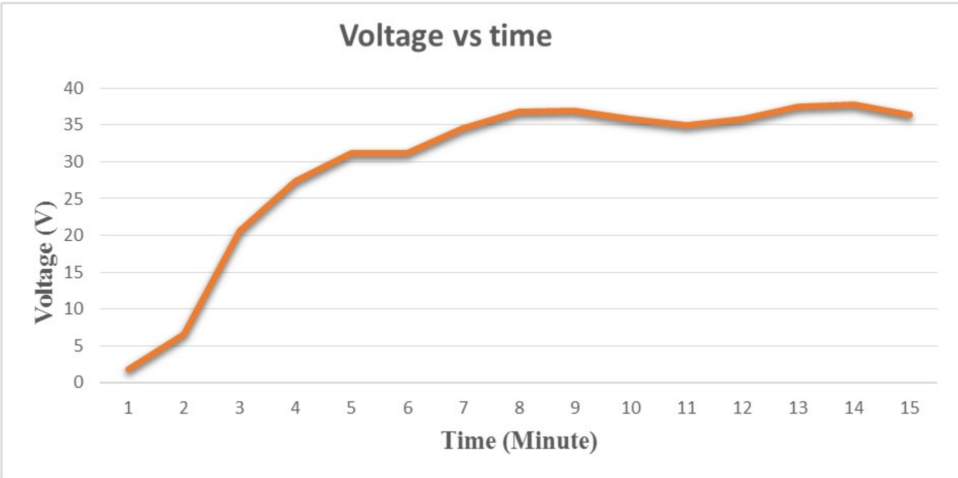

Figure 6. Voltage vs time

Through series of experiments, it has been observed that the maximum voltage produced is 37.80V at 51.6°C temperature difference between hot side and cold side of TEG modules. The current that has been generated was at maximum during minute 15th which is 0.075A. By using basic formula of power (P=IV), the maximum power that was produced by TEG during this experiment is 2.729W.

3.2 During Engine Ramp

An experiment was conducted when the engine of motorcycle is under "ramp" which means increasing in combustion of the engine by the opening of throttle valve. It results in the temperature of exhaust from motorcycle to increase due to time because amount of combustion occurred in the engine system significantly greater. Therefore, the hot side temperature of TEG that attached to exhaust will increase as well as the temperature difference between both sides of TEG. Similarly, the value of temperature on the hot and the cold side of heat sink, the voltage and the current produced were measured and recorded every minute for 15 minutes. The results recorded are shown in Figure 7, Figure 8, Figure 9, and Figure 10. Based on those graphs, the maximum voltage produced is 40.10V at temperature difference between hot side and cold side of TEG is 60.50 ºC. The current that has been generated is at the maximum during minute 10th, which is 148.0 mA, whereas by using basic formula of power (P=IV), the maximum power produced by TEG during this experiment is 5.802W.

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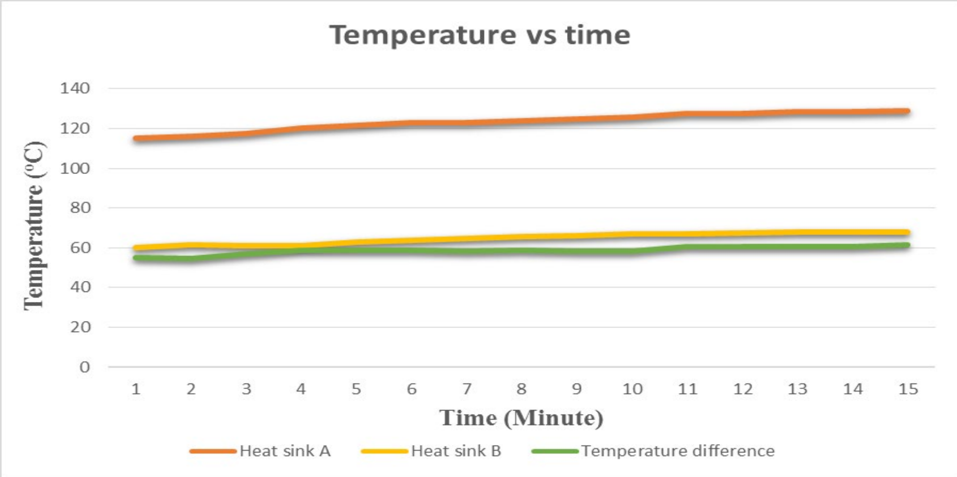

Figure 7. Temperature vs time

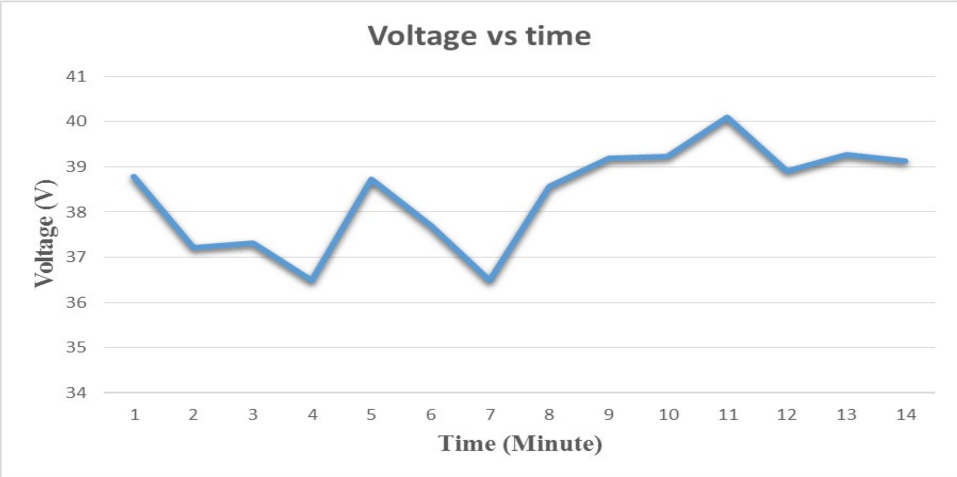

Figure 8. Voltage vs time

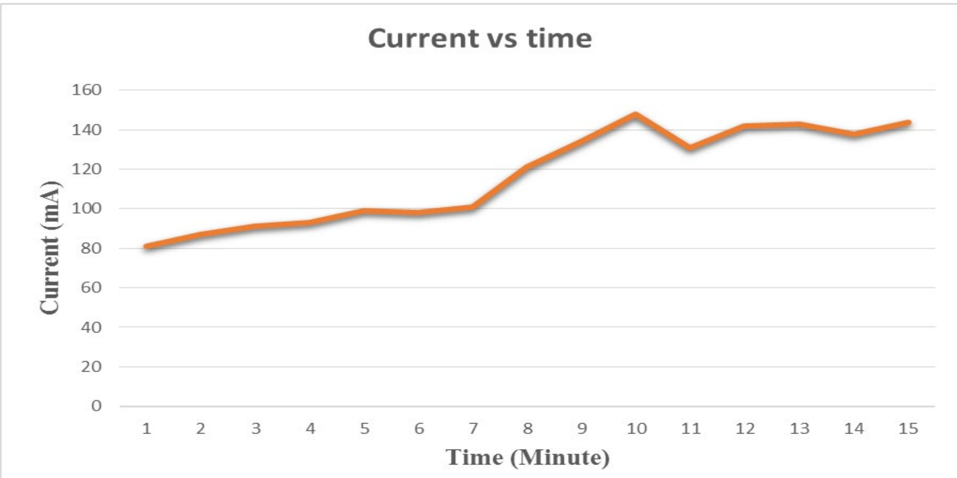

Figure 9. Current vs time

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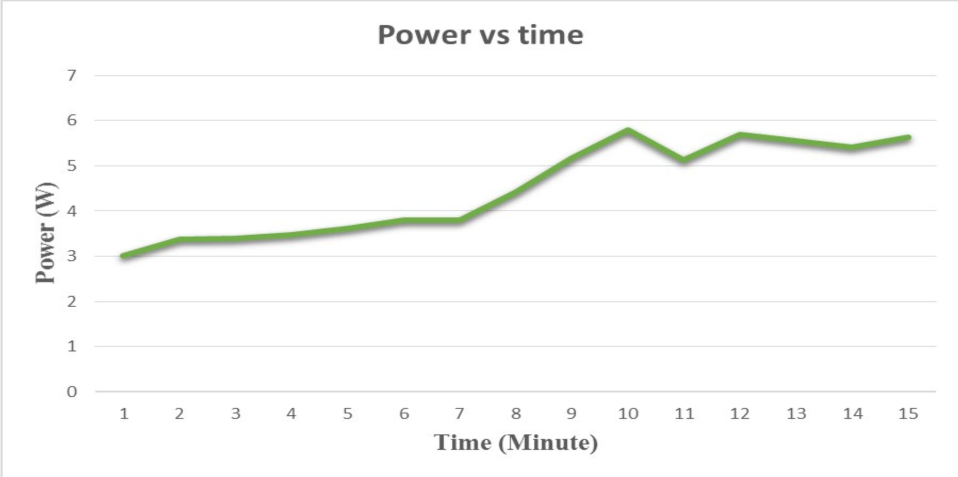

Figure 10. Power vs time

3.3 During Engine Stop

For the last experiment, data was also recorded when the engine of motorcycle was in stop condition. Therefore, no combustion occurs within the engine system. Figure 11 and Figure 12 show the temperature difference and voltage produced by TEG modules versus the time. We observed that the temperature difference decreased when the time of engine approaching stop condition as no combustion occurred in the motorcycle's engine as the heat from the exhaust was released to surrounding area and later reducing the temperature of the exhaust system. Temperature on the hot side and the cold side achieved thermal equivalent due to no heat supplied to the hot side of heat sink, and the voltage produced was also decreasing. Based on all the results recorded in this experiment, the minimum voltage produced is 18.90V at temperature difference of hot side and cold side of TEG is 15.70 ºC. In addition, the current that has been generated is at the minimum during minute 15th that is 4.0 mA. By using basic formula of power (P=IV), the minimum power that is produced by TEG during this experiment is 0.076 W.

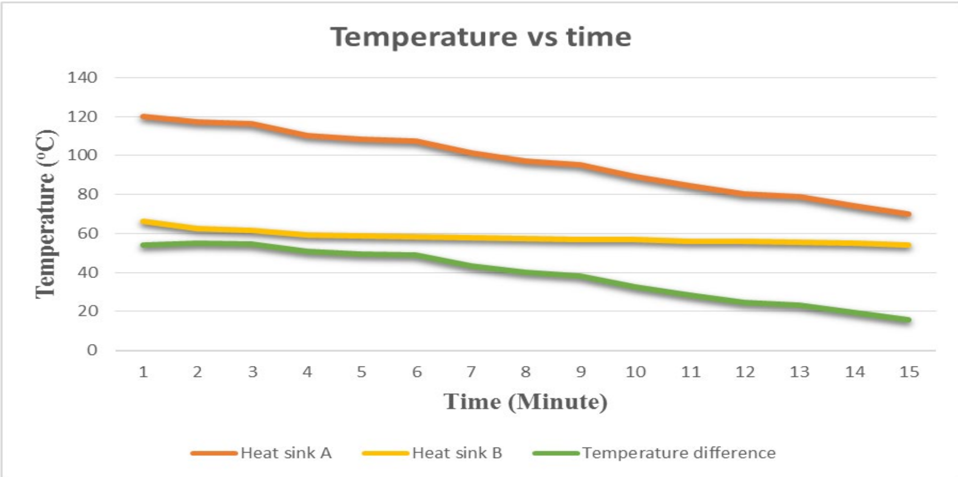

Figure 11. Temperature vs time

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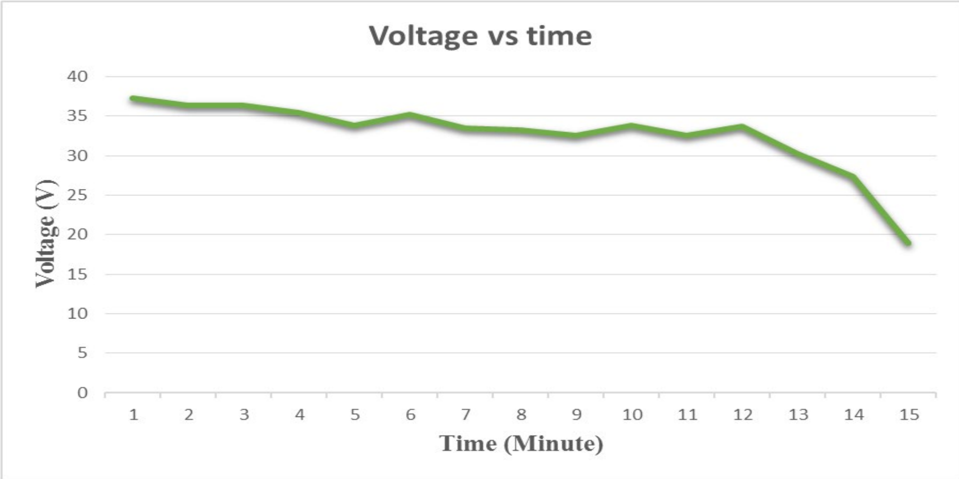

Figure 12. Voltage vs time

3.4 Overall Experimental Result

Based on the data from all the three experiments, Figure 13 indicates the overall collective data taken in those experiments. From this graph, the maximum voltage that can be produced by this system is 40.1 V during minute 27th during the motorcycle is under ramp condition. Moreover, the maximum output current and power produced for this system based on all the experiments are 148.0 mA and 5.802 W, respectively observed during motorcycle was under ramp condition.

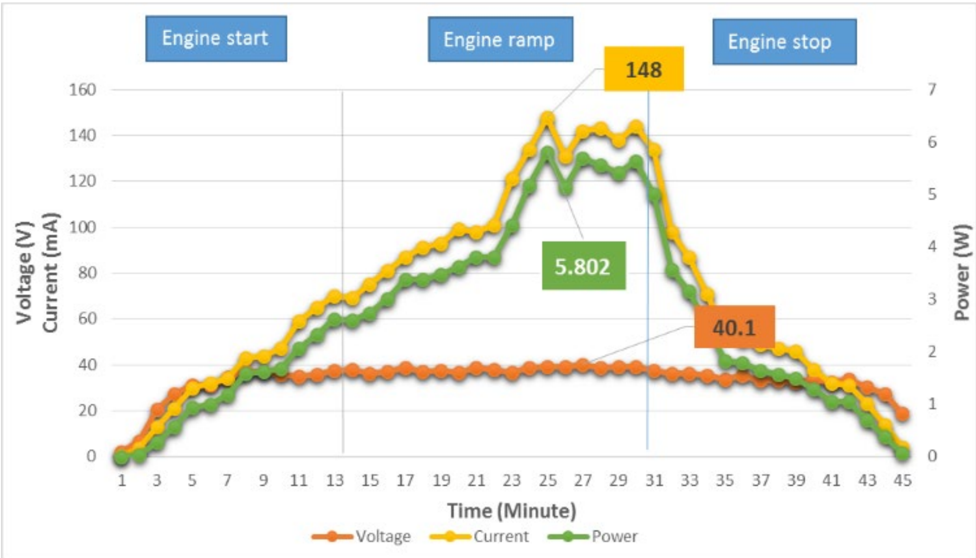

Figure 13. Voltage, current and power vs. time

From our previous study, a single TEG was used to employ the waste heat for thermoelectric based energy harvesting system [8]. The comparison of previous and current studies in term of average, minimum, and maximum power of data taken is shown in Table 2.

Table 2. The comparison results from the previous experiment

	Previous study [8]	Current study
Average power	263.56 mW	2.569 W
Minimum power	2.86 mW	0.897 mW
Maximum power	1242 mW	5.802 W

From this study, the energy harvesting system is significantly enhanced due to the number of TEG, increasing surface area of the heat sink, and improvement of the cooling system to increase the temperature difference. Based on those results in Table 2, the maximum power that can be produced by the previous study is 1.242W while the current study is 5.802W signifying a significant increase by about

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78% that could later possibly allow us to explore more towards its potential application for low power device. In addition, the power increases as the system improved in term of number of TEG and the cooling system.

4.0 CONCLUSION

The prototype of waste heat energy harvesting using thermoelectric generator has been successfully developed to harvest energy from the motorcycle's exhaust. The prototype of this study has undergone several experiments to assess the voltage, current and power versus temperature difference, where it was found that the temperature difference did affect the current and the voltage produced. Besides, we can conclude that the output voltage and the current of TEG are depending on the temperature difference between the hot and cold side; the higher the temperature difference the higher the output voltage and current because every 30 ºC increment of temperature difference will produce approximately 20 mA. Moreover, the output voltage and current are also depending on the number of TEG used; the higher the number of TEG the higher the output voltage and current because series array of TEG modules can produce maximum of 5.802W when attached to motorcycle type Kawasaki Z800 800cc during the engine ramp. Such finding could further promote the potentiality of using this type of alternative source for low power devices.

5.0 ACKNOWLEDGMENT

This work is financially supported by UPNM Short Term Grant (UPNM/2019/GPJP/TK/16). The authors fully acknowledged Ministry of Higher Education (MOHE) and National Defence University of Malaysia (NDUM) for this research feasible. The authors also would like to thank the technical staff in every institution involved for their assistant.

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