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Effect of Different Condition on Voltage Generation and Thermal Gradient from Road Pavement Using Thermoelectric Generator

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ABSTRACT

Thermal energy harvesting is an interesting topic to be studied due to its advantage of being easily to be acquired, whether from natural sources or from waste heat. Road pavement is one of the example of waste heat sources which can be easily harvested because asphalt road is paved everywhere to facilitate land transportation. The thermal energy from a road can be collected by using a thermoelectric generator (TEG). TEG operates based on the Seebeck effect; when there are temperature differences between two dissimilar electrical conductors, potential differences will be generated. Harvesting thermal energy from the road using TEG does not only provide a clean, renewable source of energy but also can save cost. The government does not have to build electricity poles along the road to power up road lamps and traffic light, which can cost a fortune, especially in rural areas. This research aims to investigate factors that can affect thermoelectric generator energy harvesting from asphalt road, which includes, TEG configuration, TEG cooling technique, and thermal conductivity. Pavement samples were built with aluminium and copper plates installed to collect thermal energy and were tested with different conditions. The final result shows that thermoelectrics with 4x1 configuration provides the highest voltage output with 142.7 mV. The TEG cooling technique using a water tank generates the highest output voltage with 281 mV. Copper plate, which has higher thermal conductivity than aluminium generates more output voltage with 36.9 mV of voltage differences between them.

Keywords: Thermoelectric; thermal gradient; road pavement

INTRODUCTION

Humankind has always depended on electrical energy, whether for daily life usage or industrial purpose. However, the way we generate electricity is not efficient, and some methods can harm the environment, such as fossil fuel and coal burning. So, new ways to create electrical power that can prevent pollution to the environment must be considered. Photovoltaic, wind turbine, biomass, and hydrogenation are regarded as green technologies that play vital roles in generating electrical energy and at the same time, help to sustain the environment (Zheng et al. 2014).

Freely available heat can be divided into two types; nature heat and waste heat. These sources of heat can be captured and converted into mechanical and electrical energy, which this method is called thermal energy harvesting (Kishore & Priya 2018). Human or animal body heat and other energy sources from nature such as solar, mechanical movement, light from the sun, or artificial and electromagnetic energy are sources of ambient energy that can produce thermal energy (Bhatnagar & Owende 2015).

Thermal energy harvesting can be realized by using thermoelectricity. Thermoelectricity operates based on the Seebeck effect; when there is a temperature difference between two different conductors or semiconductors, potential different will be produced (Akhtar & Rehmani 2015; Mustafa et al. 2017). Thermoelectric generator or TEG is a device that converts thermal energy into electrical potential with a simple design and no moving parts (Ali & Yilbas 2016).

TEG is a device which comprises of p-type and n-type semiconductors. P-type has excess holes and extra n-type electrons. When thermal energy moves from hot area to cold part of TEG, electrons and holes will also move. This phenomenon creates electrical power (Siddique et al. 2017)

Road pavement is one of the sources of waste heat. During day time, sunlight reaches the surface of the earth. Sunlight does bring not only light energy but also thermal energy. Road pavement absorbs the thermal energy and making its surface becomes hot. This thermal energy stored in the pavement can be harvested into electrical energy using thermoelectric technology.

Several papers have investigated the technique or method of thermal energy harvesting from the asphalt road. Wu and Yu have done computational simulations that analyzed a system that can harvest thermal energy from road pavement using TEG. The system was able to provide a power output of 0.02 W and energy output more than 1000 J over a day to be used for the pavement monitoring system (Wu & Yu 2013). According to Zhou et al., during summer, 2821 kWh of heat energy was stored over 69 days from a system that collects heat energy from road pavement at the same can decrease the pavement temperature. The heat stored during summer was then used for winter to defrost the road pavement (Zhou et al. 2015). An experiment done by Jaiswal et al. found that 5 V of voltage was able to produce from three TEGs connected electrically in series with copper plates and an insulated copper board implanted in the asphalt pavement (Jaiswal et al. 2016). Datta, in his research, presents a TEG prototype that harvests heat energy from airport runway pavement, which can produce an average of 12 mW of electricity for over 8 hours (Datta, 2017). Jiang et al. reported a prototype named RTEGS (Road thermoelectric generator system) able to generate a maximum of 0.4 V voltage from a temperature gradient of 15 ^{0}C during winter (Jiang et al. 2017).

An ideal thermoelectric performance can be influenced by several aspects, such as material type and system operation (Twaha et al. 2016). One of the most crucial elements when designing a TEG power generation system is TEG's configuration. According to Yusop et al. when a TEM (thermoelectric module) is connected electrically in series, and the thermal connection is in parallel, the open-circuit voltage of TEM will increases (Yusop et al. 2014). An experiment is done by Kuchroo et al. uses solar radiations to warm the hot side of 12 TEGs positioned at the center of a mirrored parabolic reflector dish. The system was installed with cold water as a heatsink for cooling the cold side of TEGs and generate 7.24 volts and 136.68 mA current, which are used to drive an Arduino Uno (Kuchroo et al. 2016).

Cooling the TEG's cold side can boost the temperature gradient between the cold surface and the hot surface of TEG, subsequently producing higher power generation. As stated by Mahdiraji, the greater the temperature gradient between the TEG's cold side and hot side, the electrical power generated will also increase (Wincent & Mahdiraji 2018). Several cooling techniques for the thermoelectric cold side have discussed and categorized (Sajid et al. 2017) as air-cooled and water-cooled, which the primary objective is to increase the power output of TEG.

Good thermal conductivity between the heat source and TEG can increase the power output as the thermal energy can transfer efficiently. Wu and Yu present a thermoelectric power generator system that uses heat from an asphalt concrete sample, which able to power up LED periodically. Aluminium plate and rod were covered with a thermal insulator to produce a good thermal gradient between the cold and hot sides of TEG (Wu & Yu 2012).

This research paper focusses on the study of parameters or elements that can affect the thermoelectric generator's behavior, which are; configuration of TEGs, cooling techniques, and thermal conductivity. The result will be based on the thermal gradient and voltage output comparison for each test. The efficiency of some experiment is also calculated and compared. All the experiments are conducted using the same set of experimental setup to provide the same environment in aim to produce a reliable result.

METHODOLOGY

A road pavement prototype was developed using a cold premix asphalt and planted into a plywood box with a dimension of 30 cm x 30 cm x 10cm (length x width x height). Metal plates were installed with 2 cm depth inside the pavement prototype. 10 cm of the metal plates are left exposed, and the other end of the metal plates was glued to the hot side of TEGs using thermal adhesive.

A basic test configuration was used as an experimental setup to record data, as depicted in Figure 1. Two 100 W bulbs were installed inside a test box to mimic the sun in producing thermal energy, at the same time can give steady temperatures to the pavement sample for every test. 4 TEGs used were the TEC1-12706 model. Temperature data was taken using Picolog TC-08 Temperature Data Logger, while Multimeter was used to measure voltage output. The hot temperature was taken from the metal plate, while the cold temperature was measured from the cold side of TEG. A laptop was used as an interface for the Picolog TC-08 software. Each test was run for 120 minutes, where the data was stored using the devices mentioned before every 15 minutes. Figure 2 illustrates the process of the test using the basic test configuration.

TEG's performance and behavior were observed based on three types of test; TEGs configurations, cooling methods, and type of metals (thermal conductivity).

TEGs CONFIGURATION

According to Siddique et al. typically, a large number of thermoelectric elements were connected electrically in series and thermally in parallel to increase the output power of the TEG (Siddique et al. 2017). So, for this part, the pavement sample was tested using 4 TEGs with three different configurations, 4x1, 2x2, and 1x4, as illustrated in Figure 3.

The first number shows the number of thermal sources or metal plates, and the second number is the numbers of TEG in parallel thermal connection, as depicted in Table 1. For 4x1, four sources of heat were given to the TEGs, while 2x2 have two heat sources, and 1x4 have one source only. All the TEGs were electrically connected in series with each other. The cold side of the TEGs was not connected to any cooling devices. Copper plates were used for this part.

COOLING METHOD

Three types of cooling methods are chosen to be tested; no cooling, heatsink, and water tank. No cooling method is the cooling of TEG's cold side without using any cooling device or known as ambient cooling. Figure 4 (a) shows heatsink cooling using two aluminium type heatsinks with each has a dimension of 10 cm x 4.5 cm x 1 cm (length x width x height). The water tank used has a size of 35 cm x 15 cm x 16 cm (length x width x height) with 30 cm x 14

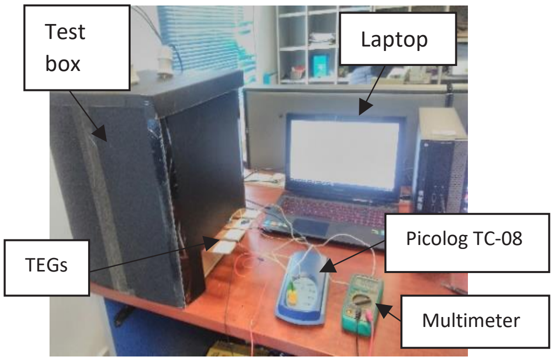


FIGURE 1. Basic test configuration

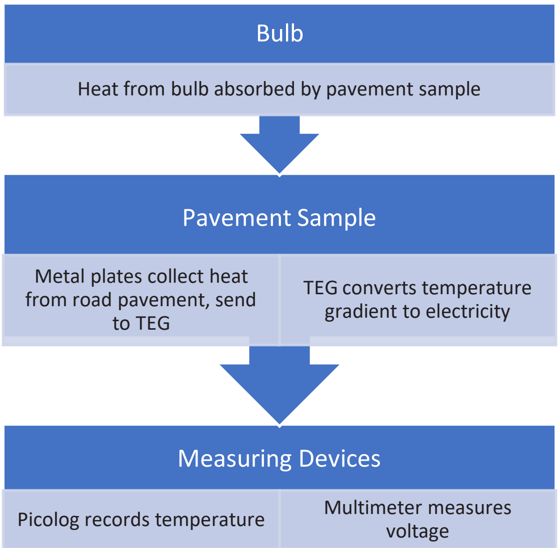


FIGURE 2. Process of the test using the basic test configuration

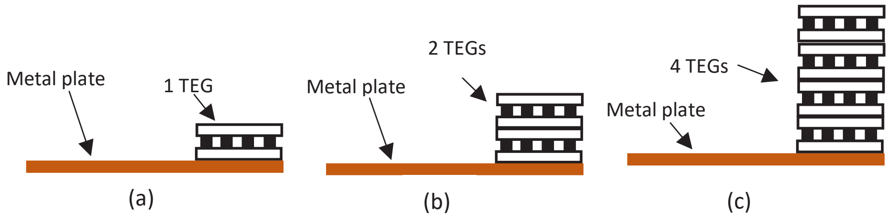


FIGURE 3. TEGs configuration; (a) 4x1 configuration, (b) 2x2 configuration, (c) 1x4 configuration.

cm x 2 cm (length x width x height) heatsink on two sides of the water tank as depicted in Figure 4 (b). The 1x4 TEGs configuration and copper plates were maintained for each test of this part.

METAL TYPE

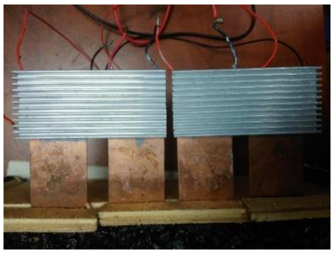
In this part, two types of metal plates are tested; aluminium and copper, as shown in Figure 5. Both metal have the same dimension 30 cm x 4 cm x 0.1 cm (length x width x thickness). This experiment aims to observe whether thermal conductivity can affect TEG's output voltage. The 1x4 TEGs's configuration and ambient cooling were maintained for each test.

Efficiency can be defined as the ratio between the output and input. A system with higher efficiency produces less waste and the best possible usage of available resources. The performance of the thermoelectric generator can be analyzed by its efficiency. Shareef et al. provides a method to find the ideal efficiency of a TEG system(Adnan, 2016). Firstly, the energy conversion maximum efficiency of TEG, Z is calculated using;

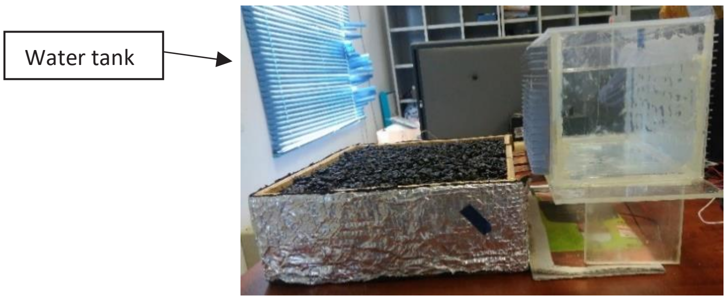
$$Z = \left[\frac{S_H - S_C}{\sqrt{P_H K_H} + \sqrt{P_C K_C}} \right]^2 \quad (1)$$

TABLE 1. Configurations and the setting

Type of configuration	Number of Metal Plates	Number of TEG in Parallel for Each Metal Plate
4x1	4	1
2x2	2	2
1x4	1	4



(a)



(b)

FIGURE 4: Cooling method; (a) Heatsink cooling, (b) Water tank cooling.

(a) (b)

FIGURE 5. Different metal; (a) Copper, (b) Aluminium.

Where;

P_H = Electrical Conductivity for cold material, μ Ωm
P_C = Electrical Conductivity for hot material, μ Ωm
K_C = Thermal Conductivity for cold material, W/mK
K_H = Thermal Conductivity for hot material, W/mK
S_C = Seebeck Coefficient for cold material, μv/K
S_H = Seebeck Coefficient for hot material, μv/K

Next, the Z value is applied to the conversion unit formula, M;

$$M = \left[1 + \frac{Z}{2}\left(T_H + T_C\right)\right]^{\frac{1}{2}} \qquad (2)$$

Where;

T_C = Temperature of the cold side of TEC (K)
T_H = Temperature of the hot side of TEC (K)

Then, finally the ideal efficiency η_{ideal} of TEG system can be calculated using;

$$\eta_{ideal} = \frac{T_H - T_C}{T_C}\left[\frac{M-1}{M + \frac{T_C}{T_H}}\right] \qquad (3)$$

While the optimum Efficiency, η_{opt} is given by;

$$\eta_{opt} = \eta_{ideal} *100 \quad (4)$$

The specification of TEC1-12706 can be referred to in Table 2.

RESULTS AND DISCUSSION

All of the experiments were performed in a lab with room temperature (22 ^{0}C) to maintain the environment. The results are shown below.

TEGs CONFIGURATIONS

Figure 6 shows the temperature gradient for all three TEG configurations; 4x1, 2x2, and 1x4 configurations. All of the arrangements show an increase in the temperature differences until 90 minutes for 1x4 and 2x2, while 4x1 dropped after it reaches 105 minutes. This drop in temperature gradient is due to the cold side of TEG cannot maintain its temperature as heat is not released fast enough to the environment by which affected by the laboratory room temperature profile. Even though the temperature difference for 1x4 TEG's configuration is the highest, but the heat is shared for four TEGs, which are connected thermally in parallel. For example, at 90 minutes, the temperature difference for the 1x4 configuration is 4.45 ^{0}C, and the average temperature difference would be 1.11 ^{0}C. As for 2x2 configuration (two TEGs in parallel thermal connection), the temperature difference is 2.50 ^{0}C with an average temperature of 1.25 ^{0}C. The highest average temperature difference is 4x1 configuration, with 1.37 ^{0}C.

Figure 7 shows the graph of open-circuit voltages for the different TEG's configurations. As presented in the graph, at 120 minutes, configuration 4x1 voltage is the highest with 142.7 mV and increases faster compared to 2x2 configuration (128.1 mV), and the smallest is by 1x4 configuration with 127.1 mV. These results complement the graph in Figure 6, which indicates the 4x1 configuration generated the best voltage. So, this follows the principle of TEG, the higher the temperature difference, the higher the voltage output.

The efficiency for each metal plate for different configurations can be calculated using the formula in Equation (3). Firstly, the efficiency by which a material is capable of generating power, Z, is calculated based on the information in Table 2 and yield a value of 2119 K^{-1}. The efficiency of each TEG's configuration is tabulated in Table 3.

The 1x4 configuration produces the highest optimal efficiency, with 0.99 %, followed by the 2x2 configuration with 0.69 %. The 4x1 configuration produces the lowest efficiency with 0.32 %. For 4x1 configuration, each TEG receives its own heat source, but the excess heat will be wasted to the environment. For 1x4 configuration, the four

TABLE 2. Specification of TEC1-12706.

Parameter	Description
PH	12.6 μΩm
PC	12.6 μΩm
KC	1.3 W/mK
KH	1.8 W/mK
SC	185 μv/K
SH	-228 μv/K

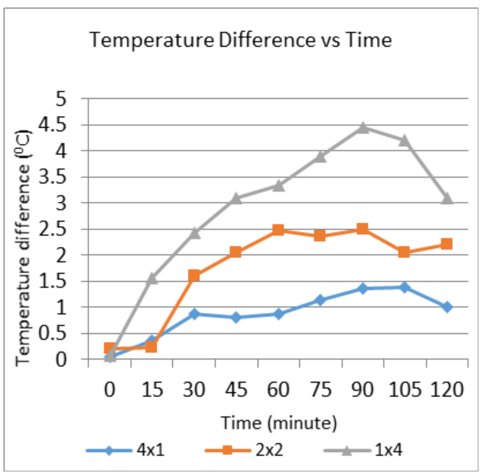


FIGURE 6. Temperature differences vs time graph for different TEGs configurations

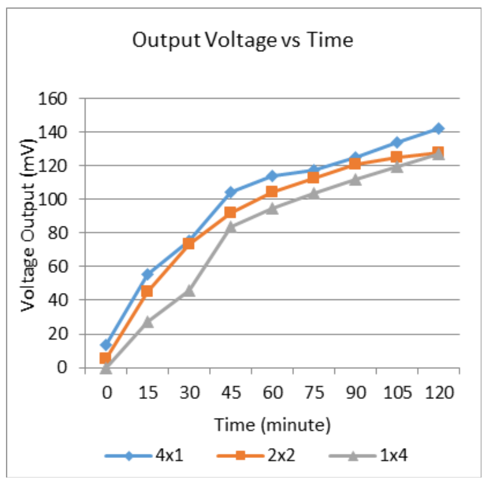


FIGURE 7. Output voltage vs. time graph for different TEGs configurations

TEGs depend only on one heat source, and the heat of the first TEG is transferred to the next TEG, until the fourth TEG. Same case with 2x2 configuration, where the four TEGs depend on two heat sources. For 1x4 and 2x2 configurations, the heat will be reduced from the first TEG until the last TEG, which receives the least heat, that is why they produce higher efficiency compared to 4x1 configuration. This shows that by connecting TEGs in parallel thermal connection can increase efficiency.

COOLING METHOD

The data for no cooling is the same as the 4x1 TEGs configuration, where no cooling was used for the experiment. Figure 8 shows the graph of the temperature gradient for all cooling methods used.

In the graph, all the cooling technique's temperature differences increase exponentially until 30 minutes due to the metal plates started to absorb heat energy from the road pavement sample. All the temperature differences in the graph increase slightly after that and starting to maintain because it is in steady-state. At 120 minutes, the temperature gradient produced by the water tank is the highest with 8.58 ^{0}C compared to heatsink cooling (1.49 ^{0}C) and then followed by no cooling (1.01 ^{0}C). This shows that water tank cooling can decrease the overall temperature significantly. Even though the heatsink cooling produces a low-temperature difference, it is still higher than the ambient cooling method.

Figure 9 above shows the graph of open-circuit voltage for all cooling methods. The highest voltages can be observed at 120 minutes, where the water tank cooling produces the best voltage out of all three techniques with 281.0 mV, followed by heatsink with 172.1 mV and ambient cooling provides the least with 127.1 mV. The graph in Figure 9 complements the output voltage graph shown in Figure 8, the higher the temperature gradient, the greater the voltage generated by TEG. Table 4 indicates the efficiency of different types of cooling methods.

The efficiency of ambient cooling is the lowest compared to other cooling methods, with 0.32 %. Heatsink cooling produces higher efficiency than ambient cooling with 0.47 %, while water tank cooling yields the highest efficiency with 2.83 %. The water tank cooling significantly improves the cooling of TEGs and produces nearly nine times higher efficiency than the ambient cooling method and about six times higher than heatsink cooling.

TABLE 3. Efficiency for each configuration

Setting	Conversion Unit, M	Ideal Efficiency, ηideal	Optimal Efficiency ηopt, (%)
4x1	820.93	0.0032	0.32
2x2	816.88	0.0069	0.69
1x4	813.57	0.0099	0.99

TABLE 4.: Efficiency of each type of cooling.

Setting	Conversion Unit, M	Ideal Efficiency, ηideal	Optimal Efficiency ηopt, (%)
Ambient	820.93	0.0032	0.32
Heatsink	815.67	0.0047	0.47
Water tank	806.79	0.0283	2.83

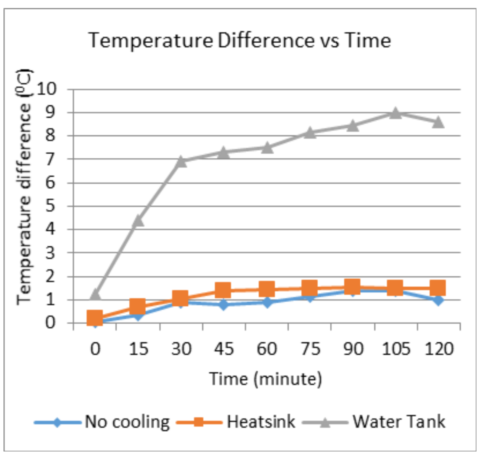


FIGURE 8. Temperature difference vs. time graph for different cooling methods

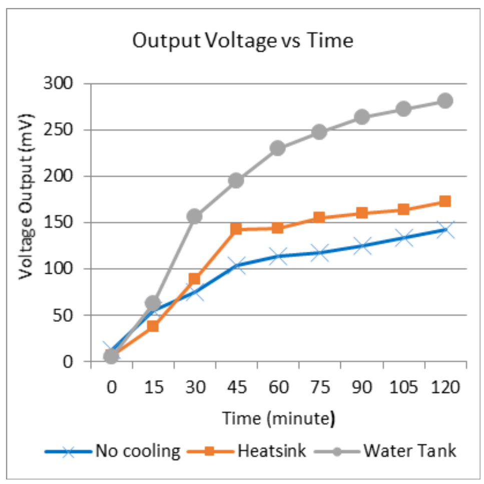


FIGURE 9. Output voltage vs. time graph for different cooling methods

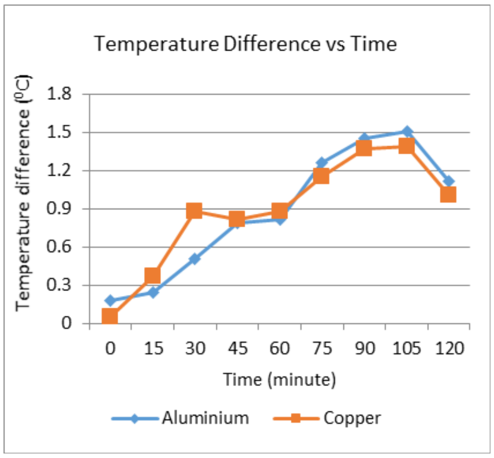


FIGURE 10. Temperature difference vs. time graph for different metals

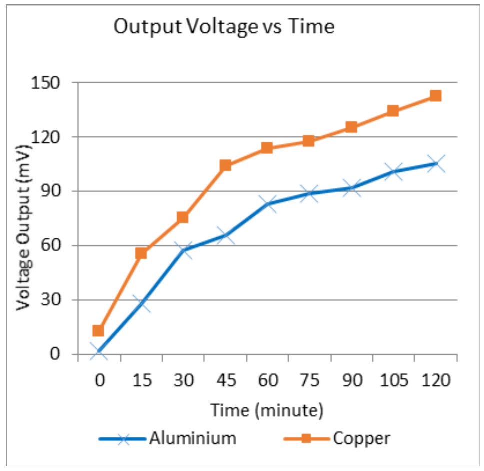


FIGURE 11. Temperature difference vs. time graph for different metals

DIFFERENT METAL

Figure 10 shows the graph of temperature difference for each type of metal plate (copper and aluminium). For the copper plate experiment, the data is the same as the 4x1 TEGs configuration. As shown in the graph, the copper plate temperature difference is slightly higher than the aluminium in the first 60 minutes due to heat is transferred at a higher rate. Consequently, copper plate metal becomes hot faster, while the TEG's cold side is still cool. Generally, the thermal conductivity of copper (401 W m^{-1} K^{-1}) is higher than aluminium, meaning that copper can transfer heat better than aluminum (237 W m^{-1} K^{-1}). After 60 minutes to 120 minutes, the aluminium plate temperature gradient is higher than the copper plate. This is due to the cold side of TEG for copper plate becomes hotter and cannot release heat faster, while for aluminium plate, the heat transfers slower, thus the cold side of TEGs can cope with heat given.

Figure 11 shows the voltage output from TEGs for different metals; aluminum and copper. The maximum voltage output of the copper pavement sample is 142.7 mV, which is higher compared to aluminium (105.8 mV). During the transfer of heat to TEG, heat dissipates to the environment by the metal plate at the exposed area below the TEG, causing low thermal energy receives by the TEG. Aluminium density with 2.7 g cm^{-3} making it better at heat dissipation, which is less dense compared to copper with 8.96 g cm^{-3} density, thus copper can store thermal energy longer than aluminium. In comparing the experiment done by Jiang et al. (Jiang et al. 2017), which uses aluminium to transfer heat, copper plates produced 34.87 % TEG's output improvement compared to using aluminium plate.

CONCLUSION

In summary, several factors that can affect the performance of the road pavement thermal energy harvesting system, which includes TEG's configuration, cooling method, and thermal conductivity, have been studied. From the results obtained, 4x1 TEG's configuration provides the highest voltage, which means that increasing the number of thermal energy sources can increase the TEG's output power. Still, it is not as efficient as the other configuration because some of the heat will be wasted to the environment. The water tank cooling method showed a notable amount of enhancement of TEG's output performance in comparison to ambient cooling and heatsink cooling. Thermal conductivity is a critical aspect to be considered. Higher thermal conductivity can efficiently transfer heat from the source to TEG. This experiment will be a reference to build a complete road pavement thermal energy harvesting system that can generate useful electricity.

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DECLARATION OF COMPETING INTEREST

None.

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