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Experimental investigation of a thermoelectric generator assisted with heat pipe sinks for pickup car exhaust waste heat recovery

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Abstract

In internal combustion engine vehicles (ICEV), about 40% of the heat is discharged into the environment as waste heat. This study proposed to develop an energy recovery device to utilize exhaust heat as electrical energy using a thermoelectric generator (TEG) assisted with a heat pipe sink. Six TEG units were installed on the stainless-steel heat block in an exhaust pipe where each TEG unit varied with one-stage TEG and two-stage TEG modules. The results showed that the maximum power generated and TEG efficiency of 1.4 W and 1.14% were obtained under 180°C of exhaust pipe temperature, with a two-stage TEG with a heat pipe sink under forced convection. The use of a heat pipe sink and under-forced convection improves the TEG system's performance by increasing the temperature difference between both sides of the TEG module, which impacts the electric power generated. This research provides some practical guidance for increasing the power and efficiency of TEGs by improving heat transfer performance through heat pipes.

Keywords: Thermoelectric generator; heat pipe sink; ICEV; exhaust waste heat; efficiency

1. Introduction

Cars are an essential means of transportation, which are quite convenient for passenger vehicles and goods transportation. The increasing use of cars, especially internal combustion engine vehicles (ICEV), has led to the problems in terms of the increasing fossil fuel combustion [1]. Data about energy utilization reveal that transportation is a sector with the largest energy consumption, predominantly from fossil fuels [2]. Fossil fuels such as gasoline and diesel are finite energy resources, and continue to deplete as consumption increases [3,4]. Conserving energy and exploring alternative energy sources for transportation, therefore, is deemed essential. Commercial ICEVs, especially pickup cars, are widely used to transport goods. To save energy, they are often used with non-active air conditioning systems, which may impact driver comfort [5]. Improving efficiency in transportation, particularly in internal combustion engine vehicles (ICEVs), therefore, is deemed crucial for mitigating the environmental impact of fossil energy.

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In ICEVs, only about one-third of energy is used to drive the vehicle, and the energy source for accessories [6,7]. While, the rest is lost and released in the form of heat and friction [6-8] in which 40% of the heat is discharged into the atmosphere as exhaust gases through an exhaust [9]. The temperature of exhaust pipe is still relatively high, and this heat will be discharged into the atmosphere; this, if not utilized, can lead to global warming. Commonly, in a car at 2000 rpm, the exhaust pipe temperature can reach about 100 - 500°C, making the reutilization of motor vehicle waste heat into useful energy is very urgent [10]. The ability to convert exhaust heat into electrical energy can enhance vehicle efficiency by reducing fuel consumption while generating the equal power [11,12].

The waste heat from the exhaust gases of these ICEVs opens opportunities for electrical energy to be utilized through energy recovery systems. Technologies that can convert heat energy into electrical energy include the Organic Rankine cycle (ORC) [13-15] and thermoelectric generator (TEG) [12,16-18]. The ORC system employs an organic fluid that has a lower boiling point compared to water as its working fluid. The primary components of the ORC system include the organic working fluid, heat source, pump, evaporator (heat exchanger), expander or turbine, generator, and condenser.

Exhaust heat is utilized as a heat source to vaporize the organic working fluid. This process generates high-pressure steam, which is then expanded through the expander or turbine to produce mechanical work, subsequently driving the generator to generate electricity [19,20]. TEGs, meanwhile, operate based on the Seebeck effect [21], stating that when two different metals are joined, heating one end while keeping the other end cool produces a voltage. The temperature difference between the two ends is directly proportional to the voltage generated. A TEG generates power through the temperature gradient maintained along the p-type and n-type semiconductors. TEGs are composed of thermoelectric materials with a strong thermoelectric effect, enabling them to generate significant voltages from temperature differences. Typically, these materials are semiconductors such as bismuth telluride or silicon germanium. The thermoelectric materials are positioned between two conductors, such as copper or aluminum, which serve as the hot and cold junctions of the device. In essence, the Seebeck effect is a way to directly convert heat energy into electrical energy using the intrinsic properties of the materials involved [22].

Compared to ORC, applying TEG in car exhaust components is simpler, where TEG converts heat energy into electrical energy directly using both the Seebeck effect and fewer and simpler components [1,23]. Compared to ORC, TEG has more advantages regarding its small size, lack of moving components, silent operation, and minimum maintenance costs, all of which have made TEG a favorable choice for specific applications over ORC systems [6].

The electrical energy generated in the thermoelectric generator is related to the temperature difference between the hot and cold sides of the TEG module. The greater the temperature difference (ΔT), the greater the power generated [5,24,25]. A number of heat dissipation methods have been applied to increase heat dissipation in TEG. Asaduzzaman et al. [26] used a thermoelectric generator to convert heat energy from vehicle exhaust gas into electrical energy with two types of triangular-shaped TEG systems using copper (a) and steel (b) mounted on the exhaust end of a gasoline car. In this test, the exhaust gas temperature was kept at 300◦C, the number of thermoelectric modules was six arranged in series, and on the cold side of the TEG module, water was kept constant at 25◦C. The maximum power from using TEG-copper is 2.96 W at an exhaust temperature of 297◦C and a 126◦C temperature difference between hot and cold sides. The use of TEG-steel type obtained a maximum power of 2.0 W for exhaust temperature conditions of 305◦C and temperature difference at 107◦C. The use of copper can provide a higher temperature difference and indirectly increase the power obtained. Ramkumar and Ramakrishnan [27] also attempted to reduce the temperature of the TEG cold side to raise the temperature difference between the hot and cold sides. On the cold side of TEG SP1848-27145, a heat reflective coating (Thermacool 0.3M) of 120 μm was added to lower the cold side temperature and compared with conventional heatsinks. The results showed that the use of Thermacool 0.3M coated could reduce the cold side temperature of TEG lower than conventional heatsinks and increase power and efficiency by 0.18W and 3.8%, respectively. Liu et al. [28] conducted a research utilizing the heat of exhaust gases in the exhaust as an electric power generator. The thermoelectric generator consists of 60 TEG modules, Bi2Te3-based, arranged into six rows with five modules on each, installed on the upper and lower surfaces of the exhaust pipe, and using water cooling. The test results showed the total power reaching 183.24W under a temperature difference of 235ºC and an engine revolution rate of 3200 rpm. The utilization of waste exhaust heat to generate electrical energy for cooling energy sources was also carried out by Kim et al. [1]. A total of 24 thermoelectric generator modules, TGM-199-1.4-0.8, were placed on the heat block attached to the exhaust pipe. A water-cooling block was installed on the cold side to increase the temperature difference between the TEG's hot and cold sides. The results then showed that the TEG system generated 90.715 W of power at an average temperature difference of 90.37°C. Furthermore, Abderezzak and Randi [29] experimentally investigated the utilization of exhaust heat from car radiators to generate electricity using a thermoelectric generator. It also performed a mathematical modelling to predict the performance of thermoelectric generators under different conditions. Tests were conducted using a single TEG on a Renault Kangoo 1.5 DCI passenger car radiator. A double water heat exchanger was placed on the TEG module's cold side. This then obtained the maximum power of 1.8 W and an efficiency of 3.85% at a radiator temperature of 95°C. Thermoelectric generators become a good solution to recover waste gas from car exhausts into electrical energy and have been widely developed, but application of them has not been widespread in view of their low energy efficiency [30,31].

The use of heat pipes as a heat exchanger in this TEG has several advantages, including high thermal conductivity, no moving components, and no maintenance required. Heat transfer between both sides of the thermoelectric module can be further enhanced using heat pipes [32]. Heat pipes are the passive heat exchanger devices with very high thermal conductivity that is capable of transferring a large amounts of heat with very small temperature differences [33,34]. Astrain et al. [35] conducted a number of experiments to investigate the effects of radiative treatment of heat pipes on the cold side in thermoelectric generators on TEG efficiency and electrical energy production equipped with heat pipes on the cold side in thermoelectric generators. A thermoelectric module was placed between the heat source and the electric heater, and the cold side was equipped with three heat pipes assembled in a metal block. The results showed that heat pipes and radiative coating heat exchangers was able to reduce thermal resistance, increase the electrical energy generated by production by 8.3% at wind velocities of 1 m/s, and reach up to 54.8% under free convection conditions. The maximum power obtained from 1 thermoelectric module paired with a radiative-coated heat exchanger at a wind speed of 1 m/s was 0.52 W. While, at natural convection conditions, it is 0.48 W. Liang et al. [36] compared the performance of single and two-stage TEGs utilizing car exhaust heat. The results showed that two-stage TEGs could provide higher performance compared to single-stage TEGs. Furthermore, the application of a heat pipe coupled to a thermoelectric as a heat recovery device for exhaust heat was carried out by Cao, Luan, and Wang [10]. Heat pipes were inserted into the exhaust at a certain depth and angle to improve the performance of thermoelectric generation (TEG). The results showed that the use of 36 TEG modules was able to produce a voltage of 81.09 V, an electrical power of 13.08 W, and a pressure drop of 1657 Pa, with a TEG efficiency of 2.58%.

The literature review indicates that thermoelectric generators (TEGs) can effectively convert waste heat into electrical energy and have been extensively developed. However, low energy efficiency becomes one of the main limitations of TEG implementation. Efforts to increase power output and TEG efficiency continue by increasing the temperature difference between the two sides of the TEG module. The higher the temperature difference, the higher the power output; thus, using an effective heat exchanger for heat release on the cold side of the TEG module becomes significant. A greater temperature difference leads to higher power output, making using an effective heat exchanger for heat dissipation on the cold side of the TEG module crucial. While the addition of cooling water on the cold side of the TEG module has been commonly applied, this method introduces more complex components and requires extra pump power to circulate the water. As an alternative, heat pipes are often employed as the passive heat exchangers. However, previous research primarily utilized heat pipes in the exhaust pipe channel, which affected the pressure drop of the exhaust gas flow and complicated their application. This study, therefore, aimed to develop an energy recovery device converting exhaust heat into electrical energy using a TEG coupled with a heat pipe sink. This system was designed for simple installation on the exhaust pipe without necessitating changes to the existing exhaust structure. In this study, a stainless-steel heat block support was also developed to facilitate the placement of the TEG system on the exhaust pipe. A total of six TEG units were installed on either side of the stainless-steel heat block support, with each TEG unit including single-stage and two-stage TEG modules arranged in thermal parallel.

2. Materials and Methods

2.1. Experimental setup

The waste heat energy emitted by ICEVs is typically released into the environment through the exhaust pipe system in the form of exhaust gases. In fact, it is essential to note that this waste energy still holds significant potential for conversion into other usable forms of energy. The exhaust pipe system in ICEVs is composed of several parts, including a header, catalytic converter, pipe, and muffler. It is designed to make the combustion gas removal process smooth and efficient while minimizing pollution. In this study, the TEG system was placed in the pipe section, with a straight construction between the catalytic converter and the muffler. A heat block support, as seen in Fig. 1, was developed to facilitate the TEG system placement on the exhaust pipe. This support structure featured one side designed to conform to the curvature of the outer surfaces of the exhaust pipe. In contrast, the other side was flat to accommodate the shape of the TEG module. The heat block support was made of a stainless-steel plate with a length of 300 mm and a diameter of 50 mm, according to the pipe length and diameter installed in the car. In addition to function as a TEG module holder, this heat block also transfers heat from the exhaust pipe section to the hot side of the TEG module. On the opposite side or the cold side, a heat exchanger was installed to accelerate the release of heat on the cold side of the TEG module purposely to obtain the maximum temperature difference.

In the application, car users did not expect any changes in the existing exhaust system, so in this study, a TEG system consisting of 1 heat block and 3 TEG units was designed in one unit, then enabling it to be attached to the exhaust pipe on two opposite sides easily, as shown in Fig. 2. With two-sided installation on the exhaust pipe, there were two heat blocks and 6 TEG units; therefore, this TEG system easily attached to the exhaust pipe. Each TEG unit comprised one-stage and two-stage TEG modules and a conventional heatsink or heat pipe sink. When each TEG unit used a one-stage module, the total number of TEG modules used was 6, and when each unit used two-stage TEG modules, the total number of TEG modules used was 12.

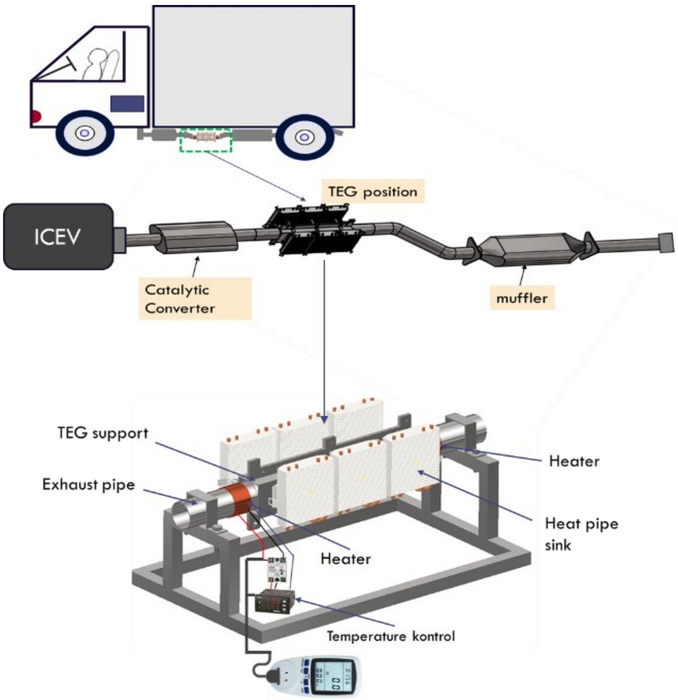


Fig. 1. Prototype test model

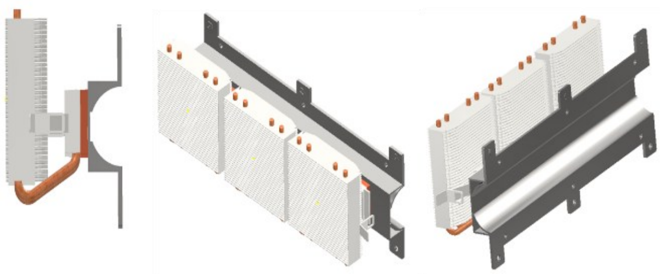


Fig. 2. TEG system assembly

The use of a heat pipe sink on the cold side of the thermoelectric generator (TEG) aimed to improve heat dissipation. This enhanced heat dissipation lowered the temperature on the TEG's cold side, increasing the temperature difference between the two sides. To evaluate the impact of the heat pipe sink on the temperature difference and power output, this test was then compared with a TEG system employing a conventional heatsink.

As shown in Fig. 3(a), the waste heat energy recovery system used in this study was varied in several configurations.

i. One-stage TEG module and conventional heatsink
ii. One-stage TEG module and heat pipe sink
iii. Two-stage TEG modules and heat pipe sink
iv. Two-stage TEG modules, heat pipe sink, and 2 m/s air velocity

In the testing of waste heat energy recovery systems, the configuration of one-stage TEG module and conventional heatsink included (i) one-stage TEG module and heat pipe sink, (ii) two-stage TEG modules and heat pipe sink and (iii) conditioned on natural convection. During testing, the three configurations of the waste heat energy recovery system were left without air velocity. While configuring two-stage TEG modules, a heat pipe sink, and a 2 m/s air velocity, testing was carried out by adding a fan in front of the heat pipe sink to simulate forced convection conditions. The speed adjustment was conducted by adjusting the DC voltage flowing to the axial fan through a potentiometer. Subsequently, the speed was calibrated using a Lutron AM-4204 hot wire anemometer, which had an accuracy of ± 0.1 m/s.

The total TEG systems installed in the exhaust pipe was six units, each of which was varied using one-stage TEG modules and two-stage TEG modules. Thus, the total number of TEGs used was six modules when using one-stage TEG modules and 12 modules when using two-stage TEG modules. Two-stage TEG module configurations were arranged in parallel thermal and electrical series, as seen in Fig. 3(b).

The conventional heatsink was made of aluminum 6063, extruded with a thermal conductivity of about 201 W/m·K, and had the dimensions of 120 mm x 100 mm x 20 mm (length x width x height). At the same time, the heat pipe sink heat exchanger consisted of four U-shaped heat pipes in each device, mounted to TEG and equipped with fins. The heat pipe was constructed from copper material, utilized water as its working fluid, and maintained a filling ratio of 50%. Table 1 and Table 2 present the detailed specifications of the conventional heatsink and heat pipe sink, respectively. The TEG module used was SP1848-27145 SA Bismuth Telluride-based with the dimensions of 40 mm x 40 mm and 3.6 thickness with a maximum power capacity enabling TEG of 3.2 W to generate at a temperature difference on the hot side and cold side of 100°C. Thermal paste was applied to the cold side of the TEG module and the heat sink surface to enhance heat transfer efficiency from the exhaust pipe and heat block to the TEG module and from the TEG module to the heat sink.

Fig. 4 illustrates the construction of the TEG test rig system. An exhaust pipe with a diameter of 50 mm and a length of 500 mm made of stainless steel was used as a substitute for the exhaust according to the original size to provide heat to the exhaust based upon the conditions in the vehicle, two heaters of 600 W each were placed at both ends of the pipe.

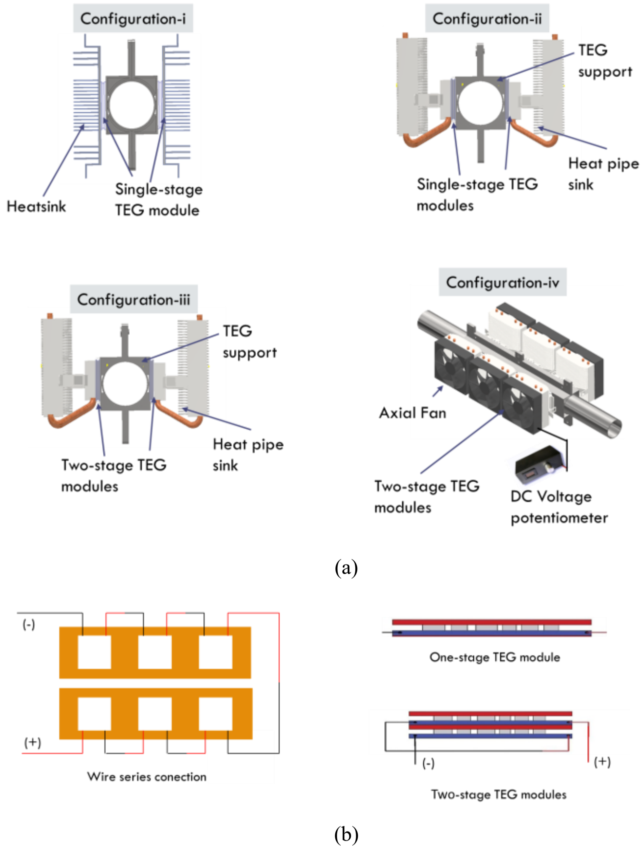


Fig. 3. TEG configuration (a); TEG modules arrangement (b)

Table 1. Conventional heatsink specification

Parameters	Value
Total Dimension (w x h x d)	120 mm x 100 mm x 20 mm
Material	Aluminum
Fin	Aluminum, 21 fins total, thickness: 0.4 mm, fin spacing: 2.5 mm
The total number of heatsink	6 units

Table 2. Heat pipes sink specification

Parameters	Value
Assy dimension (w x h x d)	110 mm x 90 mm x 56 mm
Model	U-shaped heat pipe
Pipe material	Copper
Outside diameter	6 mm
Length tube	210 mm
Wick	Sintered copper
Working fluid	water
Filling ratio	50%
Number of heat pipes in each unit	4 heat pipe/unit coupled with Stainless steel heatsink
Dimension heat pipe sinks total	120 mm x 100 mm x 22 mm
Fin	Stainless steel, continuous fins, 36 fins per unit heat pipe sinks, thickness: 0.3 mm, fin spacing: 2 mm
The total number of heat pipe sink	6 units

In this study, the exhaust wall temperature varied at 100 – 180ºC according to the vehicle exhaust temperature conditions using a temperature controller. Tests were conducted under natural and forced convection conditions at an ambient temperature. Both sides of the heat block and TEG system were mounted on the exhaust pipe using a clamp connection. A fan with a velocity of 2 m/s was then added to the heat pipe sink to simulate both the heat transfer effect by forced convection and the air velocity hitting the fins of the heat pipe sink, obtained freely when the vehicle was running.

2.2. Experimental procedure and measurement

Testing was carried out for 30 minutes for each variation after steady conditions. The exhaust pipe temperature, TEG module hot side temperature, TEG module cold side temperature, heatsink temperature, and ambient temperature were measured using K-type thermocouples connected to an ADAM 6018+ data acquisition. Meanwhile, Arduino-based data acquisition was used to measure the output current and voltage.

Temperature measurements were taken by placing several K-type thermocouples at eight different measurement points. Two measurements were made on the hot side of the thermoelectric generator (TEG) at the positions of $T_{T,h1}$ and $T_{T,h2}$, while on the cold side, measurements were made at the positions of $T_{T,c1}$ and $T_{T,c2}$. Subsequently, the temperature measurement was also carried out on the exhaust pipe (T_{pipe}), at two positions on the outer end of the heatsink or condenser heat pipe ($T_{hp,c1}$ and $T_{hp,c2}$), and the ambient temperature (T_{amb}). Since the position of the conventional heatsink base temperature and heat pipe evaporator temperature was the same as the hot side of the TEG, the temperatures of the two points were taken at the same point ($T_{hp,e1}=T_{T,h1}$ and $T_{hp,e2}=T_{T,h2}$). The eight thermocouples were then connected to the Adam 6018+ data acquisition system, displaying and recording the data to the computer. Fig. 4 shows the placement of the thermocouple and the data acquisition system.

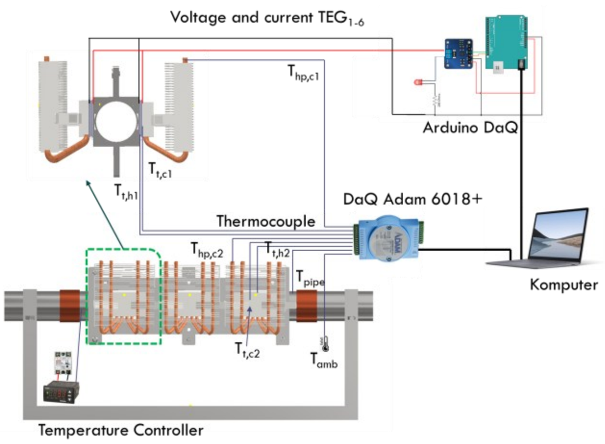


Fig. 4. Experiment setup

2.3. Thermoelectric Generators Performance

The temperature of the heat source from the exhaust affected the hot side temperature (T_h), and the air temperature affected the cold side temperature (T_c). The performance of the TEG system can be expressed by the power generated (P_{el}) [24], while the TEG system efficiency (η_{TEG}) can be determined as the ratio of the net energy obtained to the amount of heat extracted from the source represented as Eq. (1) and Eq. (2) [37,38].

$$P_{el} = V.\, I \tag{1}$$

$$\eta_{TEG} = \frac{P_{el}}{\dot{Q}_{TEG}} \tag{2}$$

V is the output voltage (V), I is the current load (A), and $\dot{Q}_{TEG}$ is represents the heat supplied to the hot side of the thermoelectric generator from the automobile exhaust. More details on symbols, units, and term definitions are summarized in the Nomenclature, as shown in Table 3.

Table 3. Nomenclatures

Symbol	Unit	Term definition
ICEV	[-]	Internal combustion vehicles
TEG	[-]	Thermoelectric generator
ORC	[-]	Organic Rankine cycle
T	[ºC]	Temperature
ΔT	[ºC]	Temperature difference
T_h	[ºC]	The hot side temperature of the TEG module
T_c	[ºC]	The cold side temperature of the TEG module
η_{TEG}		TEG efficiency
P_{el}	[W]	Electric power generated
$\dot{Q}_{cool}$	[W]	The heat released in the cold side of the module
$\dot{Q}_{TEG}$	[W]	The heat supplied from the car exhaust
V	[v]	Voltage
I	[A]	Current
P_h	[W]	The heat load on the evaporator side of the heat pipe
R_{TH}	[oC/W]	Thermal resistance
$T_{hp,e}$	[T]	Hot side temperature of the heat pipe sink (evaporator side)
$T_{hp,e}$	[T]	Hot side temperature of the heat pipe sink (condenser side)
S	[V/K]	Seebeck coefficient (S)

2.4. Heat pipe performance

The heat pipe comprises a closed tube with a wick on the inner surface and filled with working fluid under vacuum conditions. The working principle of the heat pipe is based on the phase change process (liquid to vapor) and capillary flow circulation driven by the working fluid. Heat is absorbed on the evaporator side, so the working fluid inside evaporates and flows through the adiabatic side. Then, heat is released on the condenser side so that the vapor will change phase and return to the evaporator side. This process will work if there is heat on the evaporator side [39,40]. The addition of fins increases the heat transfer area of the heat pipe.

The heat transfer performance of heat pipe sinks and conventional heat sinks can be indicated by thermal resistance; the lower the thermal resistance, the better the ability of a heat exchanger to transfer heat [41]. The heat pipe sink's total thermal resistance (R_{TH}) is determined by the hot side temperature of the heat pipe sink ($T_{hp,e}$), the condenser side of the heat pipe sink ($T_{hp,c}$), and the heat load on the evaporator side (P_h) as in Eq. (3) [42].

$$R_{TH} = \frac{T_{hp,e} - T_{hp,c}}{P_h} \quad (3)$$

The primary function of the heat sink and heat pipe sink in the TEG system is to reduce the temperature on the cold side of the TEG module as low as possible. To determine the performance of the heat sink and heat pipe sink in releasing heat, separate tests were conducted by varying the heat load of the hot side of the heat sink and heat pipe sink in the range of 50 – 200 W, as shown in Fig. 5.

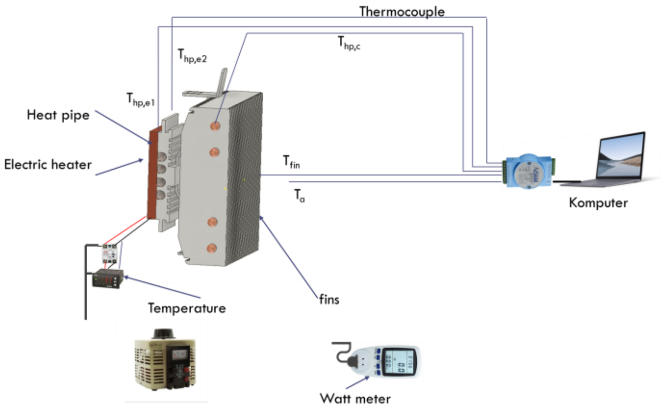


Fig. 5. Thermal resistance testing schematic

3. Results and Discussion

3.1. Profile temperature

The profile temperature of the TEG system under the exhaust pipe temperature at 100 - 180°C is shown in Fig. 6. The heat from the exhaust pipe section was transferred to the TEG module's holder and the hot side. There was a temperature difference in the exhaust pipe and the TEG module due to heat loss while passing through the TEG holder. Then, on the cold side of the TEG, the temperature became lower dependent upon the heat release process by the heat exchanger; the more the heat released, the higher the temperature difference between the hot and cold sides of the TEG module.

The use of a conventional heatsink on the cold side of the TEG module produced a low-temperature difference, approximately from 7.3 to 22.5°C in the measurement range of 100 - 180ºC, as shown in Fig. 6(a). As the exhaust pipe temperature increased, the temperature difference between the TEG module's hot and cold side of the TEG module increased. In the condition of exhaust pipe temperature at 180ºC, the temperature difference on both sides of the TEG module was found at 22.5°C when using a single-stage module and heatsink, and 92.8°C when using a single-stage TEG module and heat pipe sink, as shown in Fig. 6(b). The use of the same number of single-stage TEG modules increased the temperature difference of the TEG modules when using heat pipes. This condition indicated that using heat pipes can significantly affect heat dissipation on the cold side of the TEG module. Meanwhile, the use of two-stage TEG modules arranged in parallel increased heat dissipation compared to a one-stage TEG module. Still, the exhaust pipe temperature condition at 180ºC with the two-stage TEG module and heat pipe resulted in a temperature difference of 99.5ºC, as shown in Fig(c). When both heat pipes were used, the use of two-stage TEG modules increased more heat dissipation compared to single-stage TEG modules. Two-stage TEG modules was able to provide a greater temperature difference than single-stage TEG modules as the heat absorbed on the cold side of the TEG module was cooled again by the second TEG module, thus making the second TEG's cold side temperature lower. As the difference in temperature on both sides of the TEG modules increases, the power generated is higher [43]. Adding air velocity further improved heat dissipation on the module's cold side, making the temperature difference even more significant. This can be seen when using two-stage TEG modules and heat pipes, and with a 2 m/s air velocity produced a temperature difference of 132.8ºC, as shown in Fig. 6(d).

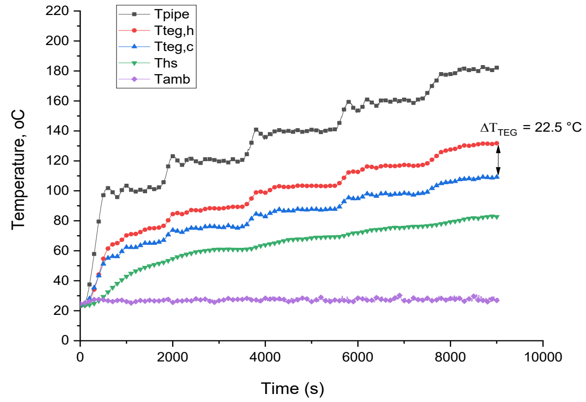
3. 2. Power generated

Fig. 7 shows the effect of exhaust pipe temperature on short circuit voltage and current output. Fig. 8 compares the open circuit voltage and maximum power output of the TEG generated. Electrical power was obtained by multiplying the short circuit voltage (V) and current (I) generated from the TEG system. In the TEG system with one TEG module and a conventional heatsink, the lowest open circuit voltage was 2.5 V, the highest one was 9.1 V, and the maximum power generated was 0.3 W.

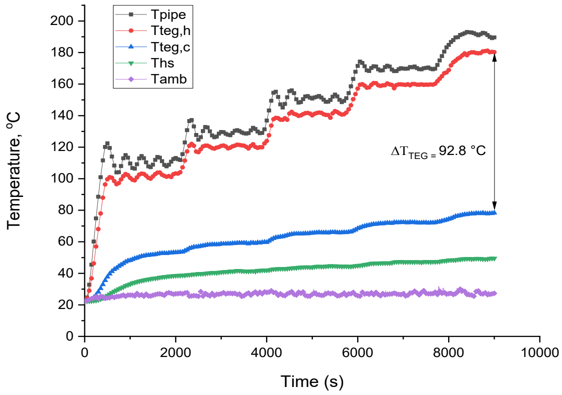
In contrast, in the TEG system with one-stage TEG module and a heat pipe sink, the lowest open circuit voltage was 2.9 V, the highest one was 11.8 V, and the maximum power generated was 0.5 W. In the TEG system with two-stage TEG modules with heat pipe sinks, the lowest open circuit voltage was 3.0 V, and the highest was 12.9 V. The maximum power generated was 1.4 W in the TEG system with two-stage TEG modules, heat pipe sinks, and 2 m/s air velocity. In this condition, the lowest open circuit voltage was 2.9 V, and the highest one was 16.5 V. Adding a fan with an air velocity of 2 m/s in the heat pipe sink increased the open circuit voltage and output power generated by the TEG.

Each TEG module had a Seebeck coefficient (S) specification, allowing current to move with a temperature gradient. The Seebeck effect (S) is the ratio between the Electric voltage change (Δv) to the temperature difference (ΔT) between the two sides of the module, $S = (\Delta v)/(\Delta T)$. The same TEG module has the same Seebeck coefficient (S), so the voltage produced is only proportional to the temperature change. The higher the temperature difference, the higher the voltage and power produced, $\Delta v = S.\Delta T$ [11].

The comparison of exhaust pipe temperature and the temperature difference in the TEG module is shown in Fig. 9(a). The higher the exhaust pipe temperature, the higher of temperature difference between the two sides of the TEG. Using heat pipes, compared to the conventional heatsinks, produced a higher temperature difference and adding fans in the heat pipe further increased the temperature difference at



(a)



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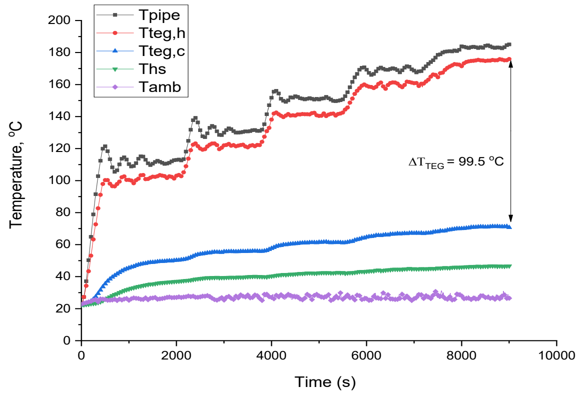

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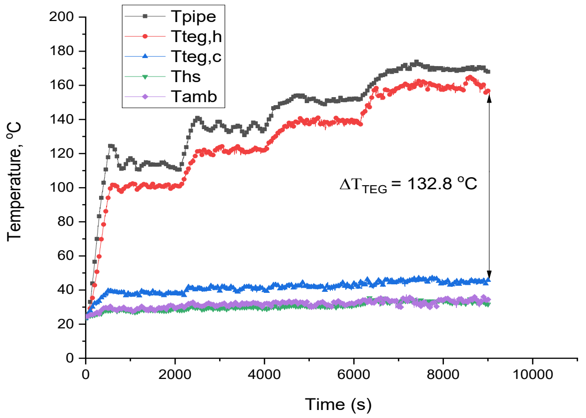
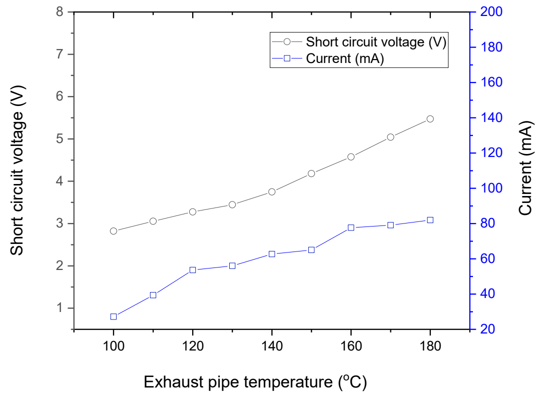


(d)

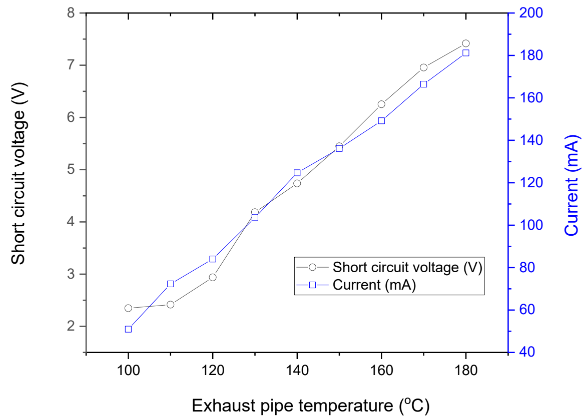
Fig. 6. Profile temperature of TEG system with single-stage module and conventional heatsink (a); single-stage module and heat pipe sink (b); Two-stage module and heat pipe sink (c), two single-stage modules and heat pipe sink and 2 m/s air velocity (d)

the heat pipe sink. Thus, the output power produced increased. As the exhaust temperature increased, the temperature difference between the two sides of the module increased, resulting in increased electric power generated, as shown in Fig. 9.

The temperature difference between the two sides of the TEG module increased when using a heat pipe, which aligns with Cao, Luan et al. [10]. It also showed that the increase in electrical power was proportional to the increase in temperature difference on both sides of the TEG. The exhaust temperature influenced the open circuit voltage (V), current (I), and power (P) produced, where the higher temperature of the exhaust pipe wall and the increasing temperature on the hot side of the TEG produced higher voltage, current, and power, as shown in Fig. 7, 8, and 9, respectively.



(a)



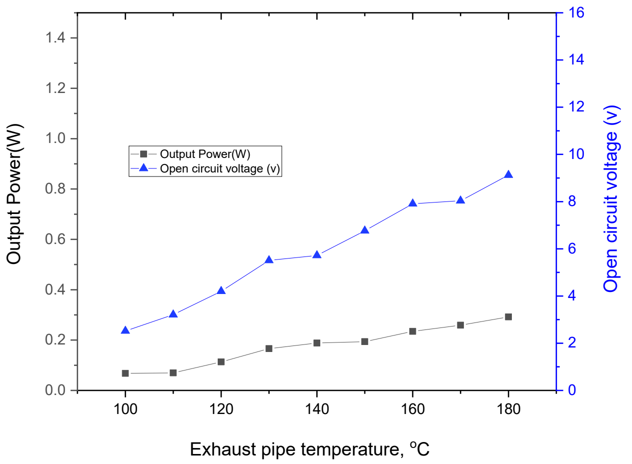
(b)

Fig. 7. Effect of exhaust pipe temperature to short circuit voltage and current output in TEG configuration with 1 module TEG and heatsink (a); with 2 module TEG, heat pipe sink, and 2 m/s air velocity (b)

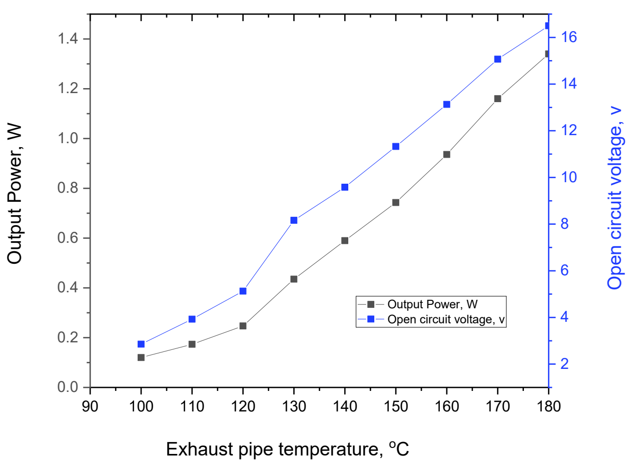
3.3. Heat pipe performance

Heat pipe that works with the principle of phase change transfers latent heat so that the heat release process becomes faster than using ordinary copper pipes [39,40]. Compared to conventional heat sinks, heat pipe sinks more improved heat transfer performance, as proven from the temperature difference between both sides of the module. From the testing, the total thermal resistance on conventional heatsinks was 0.67 – 0.29°C/W, and on heat pipe sinks, 0.40 – 0.14°C/W in the heat load range of 50 – 200 W and temperature on the hot side of 80 – 140°C. The thermal resistance tests showed that the heat pipe sink had a better thermal performance than the conventional heat sink. The increase in thermal resistance showed that the heat pipe significantly impacted the ability to transfer heat, and adding a fan, which caused heat transfer to occur by forced convection, further improved the performance of the heat pipe sink.

The TEG-based energy recovery system consists of three main components, namely the heat exchanger on the hot side (1) which absorbs heat from the exhaust pipe to the TEG module, the TEG Module (2), which generates electricity when there is a temperature difference between the hot side and the cold side of the TEG, and the heat sink or heat pipe sink (3), which functions to release heat on the cold side of the TEG module. TEG generates power through the temperature difference maintained along the p-type and n-type semiconductors through the Seebeck Effect [11]. By using the same type of TEG module during testing, the increased power generated was only determined by the temperature difference between both sides of the TEG. Thus, the use of heat exchangers with lower thermal resistance could increase heat release on the cold side of the TEG module, heat pipes that worked with phase change processes (liquid to vapor) and capillary flow circulation driven by the working fluid, has made heat pipes able to release heat faster and more efficiently. This lowered the temperature on the cold side of the TEG and made the temperature difference between the hot side and the cold side of the TEG bigger.

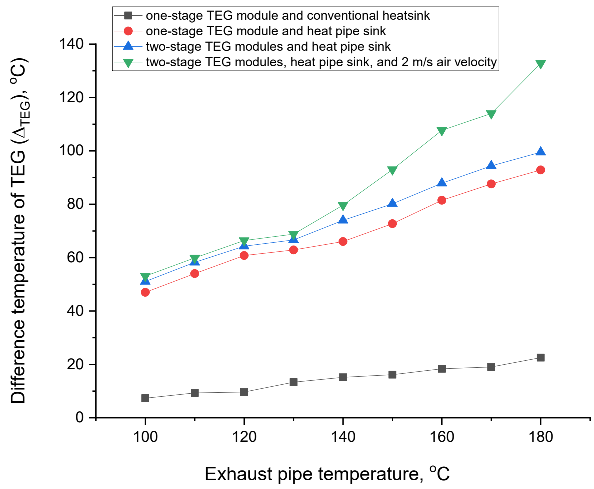


(a)

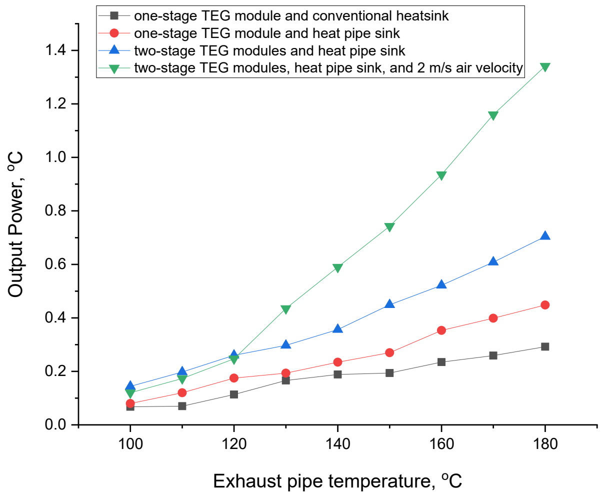


(b)

Fig. 8. Effect of exhaust pipe temperature to voltage and power output in TEG configuration with 1 module TEG and heatsink (a); with 2 module TEG, heat pipe sink, and 2 m/s air velocity (b)



(a)



(b)

Fig. 9. Comparison of exhaust pipe temperature and difference temperature in TEG module (a) Comparison of exhaust pipe temperature and output power (b)

On the exhaust pipe temperature conditions of 100 - 180°C and using heat pipe sinks, the temperature difference ranged from 47.0°C to 92.8°C. Adding TEG modules to two-stage TEG modules with heat pipe sinks increased the temperature difference from 22.5 to 99.5°C. Adding a fan on the exhaust side of the heat pipe sink increased the temperature difference from 22.5 to 132.8°C. The data showed that the addition of fans also further increased the temperature difference.

Two-stage TEG modules arranged in parallel increased the temperature difference compared to a one-stage TEG module, but the increase was found insignificant. The higher temperature difference between the two sides of the TEG module also increased the output power produced. The results showed that the TEG system working with the forced convection system had a significant impact on the temperature difference and the resulting power output. In short, the placement of the TEG system allowing the heat dissipation side to get exposure to air moving at a certain speed needs to be considered.

The power generation efficiency of the TEG system is an essential parameter for evaluating the performance of the TEG system in generating electrical power. The efficiency of the TEG system (η_{TEG}) is determined by comparing the net energy obtained to the amount of heat extracted from the source. Fig. 10 shows the TEG efficiencies of the four configurations tested in this study. At the exhaust pipe temperature condition of 100ºC, the TEG efficiency was still quite low. Then, starting from the exhaust pipe temperature of 120ºC, as the exhaust pipe temperature increased, the TEG efficiency also showed a significant increase. Maximum efficiency for each configuration occurred at 180ºC exhaust pipe temperature conditions. At the exhaust pipe temperature condition of 180ºC exhaust pipe, when using a single-stage module and heatsink, the TEG efficiency was 0.25%, when using a single-stage TEG module and heat pipe sink, 0.38%. Still, the exhaust pipe temperature condition at 180ºC with the two-stage TEG module and heat pipe resulted in a TEG efficiency of 0.60%. The configuration of two-stage TEG modules with heat pipe sinks and an air velocity of 2 m/s produced the greatest TEG efficiency compared to the other three configurations with an efficiency of 1.14% in exhaust pipe temperature of 180ºC. The increase in efficiency was proportional to the temperature difference between the two sides of the TEG module. The higher the temperature difference, the more power generated, increasing the TEG efficiency.

The increase in TEG efficiency was more determined by the performance of the heat pipe sink that could release large amounts of heat so that the temperature difference between the two sides of the TEG became more significant, and the power generated was greater. Generally, the TEG system configuration consisted of two-stage TEG modules, heat pipe sinks, and a fan with an air velocity of 2 m/s that gave the highest performance, resulting in the highest temperature difference, highest power generated, and highest efficiency. This indicates that the use of heat pipe sinks under forced convection conditions can be a reference for future energy and thermoelectric generation work. The addition of air velocity in forced convection in the heat pipe sink increases the convection coefficient, making the heat release on the cold side of the TEG even greater [44].

For further research with field testing, installing the TEG system to be exposed directly to the wind at a certain velocity is essential so that the heat exchanger can work in forced convection without using an additional fan. Heat pipes increased the temperature difference by four times that of the conventional heatsink. However, with the temperature difference on both sides of the TEG already relatively high, the power generated and TEG efficiency were found still relatively low. Using six units of TEG configuration with two-stage TEG modules, heat pipe sink, and 2 m/s fan (12 TEG modules in total), the maximum power generated and TEG efficiency were found at 1.4 W and 1.14%, respectively. The efficiency of a TEG is the ratio of power generated to the heat supplied to its hot side from the car exhaust pipe. An efficiency of 1.14% indicates the ratio of power generated of 1.4 W to the heat supplied to the TEG hot side of 117.3 W. This low efficiency aligns with previous studies where the average TEG efficiency was below 5%, as conducted by Asaduzzaman et al. [26] by 4.63%, it was obtained at 297◦C exhaust temperature. Zhao et al. [30] conducted an exergy analysis to determine the cause of low TEG efficiency, where it was found that there was an exergy loss of over 52% in exhaust heat transfer and PN couple heat conduction.

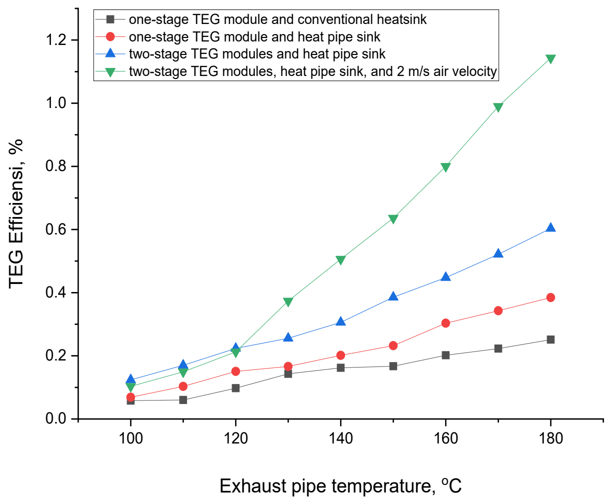


Fig. 10. TEG Efficiency

Therefore, in the future, continuous research to improve the efficiency of TEG is still needed. Although the results of TEG efficiency and power generated are still low, this research can provide some essential findings.

Using heat pipes as heat exchangers effectively increased the temperature difference between the two sides of the TEG module. Then, the increase in temperature difference significantly improved power output around 200%, compared to a conventional heatsink. This research provides exciting implications for using TEG systems in vehicles, where they could serve as an alternative for harnessing exhaust heat from internal combustion engines (ICEVs) and offer practical guidance for designing and optimizing these systems for energy-harvesting applications.

To see the investment feasibility of using the TEG waste heat energy recovery system, an economic or feasibility analysis was carried out in this study [45]. The feasibility analysis was conducted using the payback period (PB), which was determined by dividing the total investment of the TEG waste heat energy recovery system by the annual electricity cost savings, as shown in Eq. (4) [46].

$$\text{PB} = \frac{Total\ Investment\ Cost\ (IDR)}{Annual\ Electricity\ cost\ saving\ (IDR/year)} \tag{4}$$

For payback period calculation, the TEG-based waste heat energy recovery system on a pickup car was assumed to be used for 6 hours per day, 26 days per month, annually, and the electricity cost was assumed of IDR 1,467 for every kWh [46]. With the maximum power obtained of 1.4 W and use for 2496 hours per year, the total kWh was 3.5 kWh, and the cost savings obtained for one year was IDR 5,135 on the use of a two-stage TEG module and heat pipe configuration with 2 m/s air velocity. If the investment cost of the waste heat energy system in the configuration of the two-stage TEG module and heat pipe configuration is IDR 1,280,000, then the payback period from the use of heat pipe-based recovery tools will be very long. This means that the use of a TEG-based waste heat energy recovery system has not produced optimal power, so improvements are still required in the future to reach the investment feasibility limit.

3.4. Uncertainty analysis

In this experiment, the temperatures were measured with the K-type thermocouple, connected to the ADAM 6018+ data acquisition system. The temperature calibration was conducted, and the error associated with temperatures was ±0.1°C. The output voltage (V) and current (I) of TEG were measured by the data acquisition system made by Arduino, and after calibration, the uncertainty was ±0.1 V and ±0.01 mA, respectively. The uncertainties of the power generated by TEGs (SP_{el}/P_{el}) can be estimated as Eq. (5) [33,47].

$$\frac{S_{P_{el}}}{P_{el}} = \sqrt{\left(\frac{S_V}{V}\right)^2 + \left(\frac{S_I}{I}\right)^2} \quad (5)$$

The maximum uncertainty of power generated by TEGs (SP_{el}/P_{el}) determined based on Eq. (5) and were found to be ± 6.05 % respectively.

4. Conclusion

This study presents a novel method of converting waste heat exhaust pipe from a pickup car to electricity using an energy recovery system based on a compact thermoelectric generator (TEG) coupled with a heat pipe sink. Some important conclusions from this study include (1) The higher the exhaust pipe temperature, the higher the electrical energy to be generated. The maximum power generated and TEG efficiency of 1.4 W and 1.14% were obtained at an exhaust pipe temperature of 180ºC with six units of two-stage TEG modules coupled to a forced convection heat pipe sink. (2). The use of a heat pipe as a heat exchanger placed on the cold side of the TEG module improved heat transfer performance, as shown with the increase in the temperature difference on both sides of the TEG module and the increase in the electric power generated. (3). The temperature of the exhaust pipe could reach about 100 - 500ºC at an ideal and affordable installation point. However, the limitation of this research is related to the ability of the TEG used that can work at a maximum temperature of 180ºC; hence, the electrical energy generated is still relatively low. Future recommendations that could be pursued based on the discussion above could be carried out through further experimental investigations in line with this research, with the applied and enhanced capability of thermoelectric modules with a higher temperature range. Another future recommendation is enhanced TEG system configurations and heat pipe heat exchanger performance on the cold side of the TEG module to improve overall TEG performance to produce higher electricity output and energy efficiency.

Acknowledgments

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