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Al_2O_3 and SiO_2 Nanofluids Performance in Thermoelectric Generator

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ABSTRACT

Thermoelectric generator, TEG, is a device that converts heat into electricity through the Seebeck effect. Nanofluids on the other hand are a fluid that contains suspension of nanoparticles in a base fluid. Nanofluids provide better heat transfer performance as compared to conventional coolants which is attributed to the presence of nanoparticle suspension in the base fluid. The purpose of this study is to observe the performance of a single TEG when subjected to nanofluids as the cooling medium. In this study, single Al_2O_3 and SiO_2 nanofluids at 0.5% volume concentration were used and circulated at different flowrates. The performance of TEG was then observed through the power output of TEG. The TEG used was the bismuth telluride, Bi_2Te_3, where temperature of 80°C is applied to the hot side of the TEG. Simultaneously, nanofluids were circulated at the cold side of the TEG with flowrates of 12, 49, 80 and 112 mL/s. The effect on the temperature difference in the TEG, thus producing different voltage was observed. Power is then calculated from the obtained voltage and current. SiO_2 nanofluids was able to increase the maximum power output by 45%, while Al_2O_3 nanofluids increased the maximum power output by 70%.

1. Introduction

Thermoelectric devices possess the ability to convert heat energy to electrical energy and vice versa [1]. The first thermoelectric effect was discovered by Thomas Johann Seebeck, in 1821 by demonstrating that electromotive force was able to produce as the result of introducing heat to the junction of two different electrically conductive material [2]. This effect became the basis for power generations. The second thermoelectric effect was discovered thirteen years later by Jean Charles Athanase Peltier, in 1834 [1]. However, Peltier observed that a small heating or cooling effect was produced from directing a current through a thermocouple [2]. This effect was the basis for thermoelectric cooling. The Peltier Effect is the reverse phenomenon of the Seebeck Effect as both effects requires a temperature gradient across a solid material. The mechanism behind a thermoelectric generator (TEG) is that a temperature difference is introduced between the hot side and the cold side of a thermoelectric material to produce electrical energy [2,3]. Materials that build

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up a TEG depends on the applications. The most common type is bismuth telluride, Bi_2Te_3, which is used for low temperature applications [4]. Other known materials are lead telluride, PbTe, Germanium Telluride, GeTe, and silicon – germanium alloys [4]. The characteristics that set these materials apart is the figure of merit, ZT. The dimensionless ZT is used to characterise a thermoelectric material efficiency in converting heat energy to electrical energy. Advantages provided by a thermoelectric generator is its sturdiness as it is a solid-state device that contains immobile components [1]. Moreover, other advantage of the TEG is that it is environment friendly, silent, reliable, and scalable [4,5]. However, the downside of TEGs is its low efficiency having an efficiency of 5% to 10% [5].

Nanofluids are defined as any base fluid, either organic or inorganic, that contains suspensions of nano – sized particles [6]. Nanofluids can be categorised as two – phase fluids due to its content of liquid and solid [6]. The nanoparticles used in nanofluids are generally metal, metal oxides, carbon nanotubes, and carbides. Common base fluids are distilled water, ethylene – glycol, mixture of water and ethylene – glycol, and engine oil [7]. Previous studies show that there is an enhancement in heat transfer coefficient when nanoparticles are introduced in base fluids. According to Xuan and Li, the heat transfer properties increase as the concentration of nanoparticles increase [8]. However, introducing nanoparticles to a base fluid will increase its viscosity [9].

Various research has been conducted on increasing the temperature difference in the TEG. The reason behind this is, as the temperature difference is high, the output voltage is also high [2,10,11]. In other aspect, manufacturers have been seeking a method to reduce the size of TEGs as the cost of raw materials is a significant factor to be taken into consideration. However, reducing the size of TEGs will lead to the issues associating with heat transfer as a small surface area will complicate heat transfer. This will lead to a small temperature difference being develop thus an inefficient TEG produced [2]. One of the strategies taken by researchers is introducing nanofluids coolant to overcome this issue. Nanofluids are known for its heat transfer enhancement and has been studied by various researchers for various applications. Generally, nanofluids are flowed over the cold side of the thermoelectric material thus introducing a forced convection environment which further increases heat transfer through convection. Hilmin *et al.,* [11], conducted a study on generating power from vehicle exhaust using TEG coupled with TiO_2 nanofluid. The authors concluded that the TiO_2 nanofluid has managed to increase the TEG power output when compared to water cooling [11]. Karana and Sahoo [12], conducted a theoretical analysis on TEG using MgO and ZnO nanofluid for the purpose of waste heat recovery in automobiles. The authors conclude that the MgO and ZnO nanofluids managed to enhance the power output by 11.38% and 10.95% respectively [12].This study will determine the effects of nanofluids on TEG performance through variation of fluid flow rates.

In this study, effect of adopting Al_2O_3 and SiO_2 nanofluids to TEG performance was observed. The experimental work has provided a comprehensive review on the effect of both flowrates and thermal conductivity properties of Al_2O_3 and SiO_2 nanofluids as coolant to the cold side as compared to the base fluid of water.

2. Methodology

2.1 Nanofluids Preparation

Nanoparticles used were Al_2O_3 and SiO_2, which were procured from Sigma Aldrich (M) Sdn Bhd. Al_2O_3 is in powder form with purity of 99.9% and it is in 13 nm size. Meanwhile, SiO_2 were in dispersion form with 33 nm size. Both nanoparticles were prepared in the based fluid of distilled water. For homogeneity, each solution was sonicated using an ultrasonic homogeniser at room biotemperature of 25 °C for 2 hours as practiced by other researchers [13,14].

The basic properties of nanoparticles and base fluids used are tabulated in Table 1. The Al_2O_3 and SiO_2 nanoparticles were added with diluted water to reach the required volume concentration of 0.5% by adopting Eq. (1) - (3) in the preparation of the single nanofluids. Nanoparticles were initially dispersed in base fluid using magnetic stirrer and then subjected to ultrasonic homogenization for 2 hours using Fisher brand ultrasonic homogenizer (FB1501). This is important, as it will ensure a good dispersion of nanoparticles for better stability of the nanofluids prepared. Stability was confirmed through visual observations a

Table 1
Properties of nanoparticles and base fluids

Property	Al_2O_3	SiO_2	Distilled Water
Average particle diameter, nm	13 [15]	30 [15]	-
Density, kg/ m^3	4000 [16]	2220 [16]	996 [17]
Thermal conductivity, W/ m.K	36 [18]	1.4 [16]	0.615 [17]
Specific Heat, J/ kg. K	765 [19]	745 [20]	4178 [17]

$$\varphi = \frac{\omega \rho_{bf}}{\left(1-\frac{\omega}{100}\right)\rho_p + \frac{\omega}{100}\rho_{bf}} \tag{1}$$

$$\varphi = \frac{m_p}{\rho_p} \Big/ \left(\frac{m_p}{\rho_p} + \frac{m_{bf}}{\rho_{bf}}\right) \tag{2}$$

$$\Delta V = (V_2 - V_1) = V_1\left(\frac{\varphi_1}{\varphi_2} - 1\right) \tag{3}$$

where ω was the weight concentration of the nanoparticles provided by the supplier, and ρ was the density in kg/m^3 with the subscript *p* and *bf* signifying nanoparticles and base fluid, respectively. The ΔV is the required volume of distilled water added to the current base fluid volume V_1 with volume concentration of $\emptyset_1$ to achieve volume V_2 with the volume concentration $\emptyset_2$ of nanofluids.

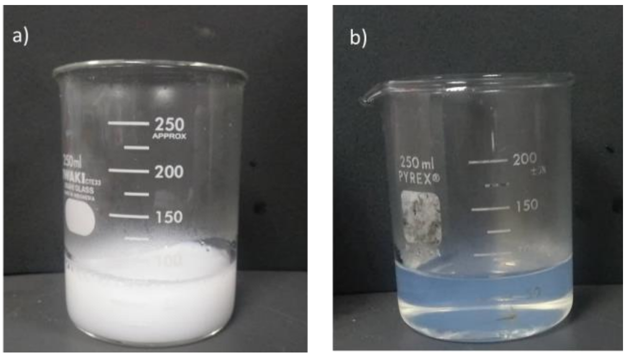

Fig. 1. Samples of nanofluids used in the study a) 0.5 vol % Al_2O_3 and b) 0.5 vol % SiO_2

2.2 Experimental Setup

Figure 2 shows the set up used for the TEG characterization experiment, focusing on the integration of hot side from heater cartridge in an aluminum block and the cold side of copper cooling jacket. The aluminum block houses two cylindrical shaped heaters that heat up the block thus supplying heat to the hot – side of the TEG. The cartridge heater was connected in parallel to the AC variable transformer. Output voltage of the AC variable transformer will determine the temperature input of the hot side which was set at 80°C. Meanwhile, the copper cooling jacket was located on top of the cold – side of the TEG, where the coolant flows through the cooling jacket. The TEG was then sandwiched between the copper cooling jacket and the aluminum block. Thermal paste was applied to the surface in between TEG and aluminium block to reduce the thermal contact resistance thus increasing the heat conduction. The TEG used was made of Bismuth Telluride material and is shown in Figure 3.

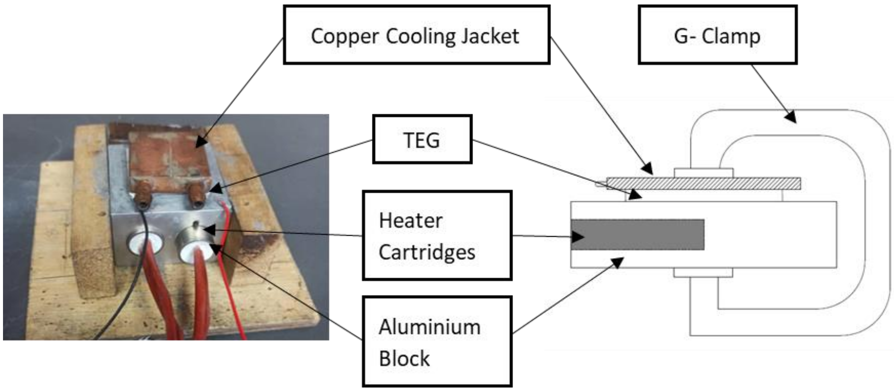

Fig. 2. TEG Characterization set up close view

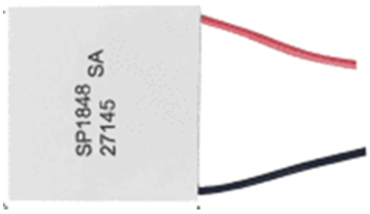

Fig. 3. Bismuth Telluride TEG

The test section was connected to a pump to circulate the fluids at the required flowrate in this close loop cooling circuit. Flowrate is controlled via manipulating the speed of the pump through the DC power supply. The flow rate was verified at the flowrate meter attached to the set up and four flowrates of 12 mL/s, 49 mL/s, 80 mL/s and 112 mL/s were used.

The TEG was connected to a DC electronic load which serves to provide the testing conditions either in open circuit or variable load. The reading of current and voltage produced was taken from DC electronic load through variation of resistance from 900Ω to 0Ω. The value of Seebeck Coefficient for the TEG is 0.0241V/K [21, 22]. Two units of K– Type thermocouples are placed on the hot – side and cold – side of the TEG to monitor the temperature. The thermocouple was connected to a Graphtec Data Logger MiDi GL220 for temperature recordings.

The actual set up for the characterization experiment is shown in Figure 4. Figure 5 shows the schematic diagram of the set up with the corresponding circuits involved namely cooling circuit (nanofluids), electrical connections and also thermocouple connections.

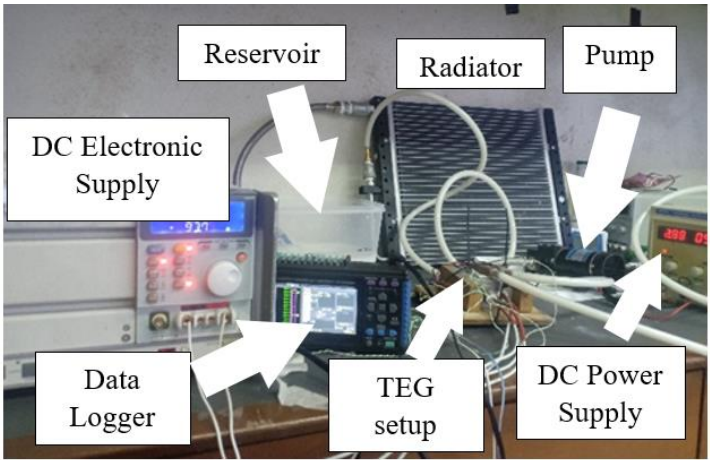

Fig. 4. Actual set up of TEG characterization experiment

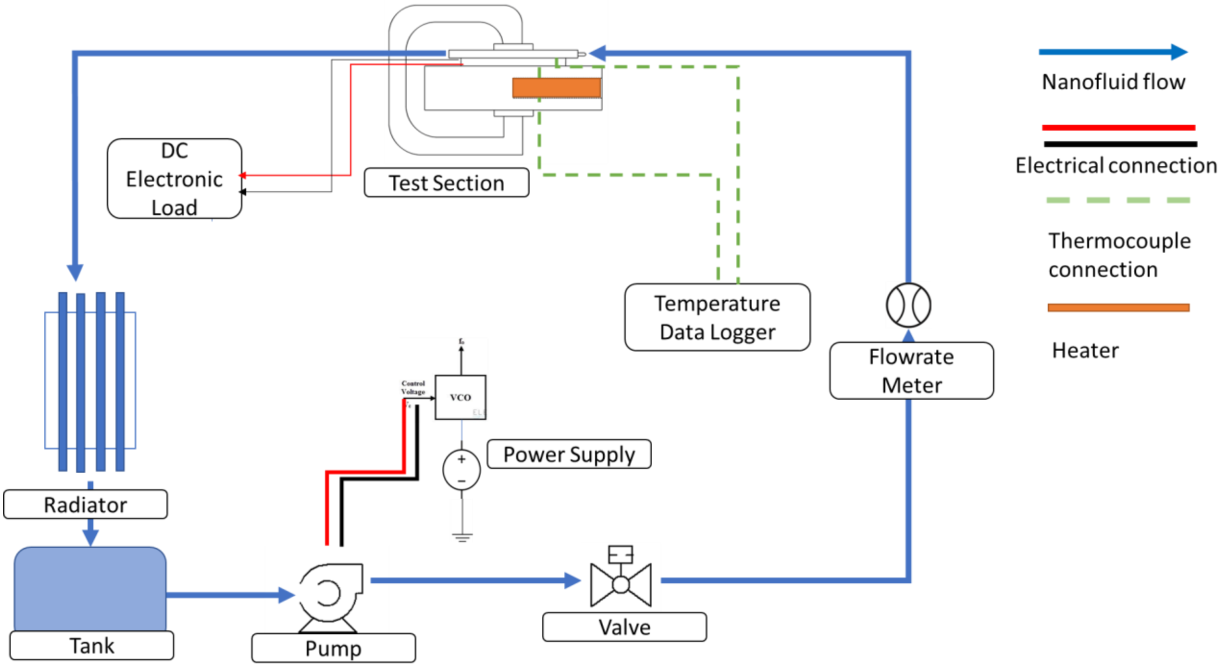

Fig. 5. Schematic diagram of TEG characterization experimental set up

2.3 Mathematical model

A mathematical model was established to study the performance of the TEG. For simplification purposes, several assumptions were made. These assumptions were obtained from Abu Bakar *et al.,* [22].

i. Thermal contact resistance between aluminium block, TEG, and copper cooling jacket were neglected.
ii. Heat transfer to environment either by convection or radiation was neglected.
iii. The Seebeck coefficient, thermal conductivity, and electrical resistivity remains unchanged throughout the experiment, with the effects of temperature to these values also neglected.

The mathematical model was obtained from Hilmin *et al.,* and Abu Bakar *et al.,* [11,22]. This mathematical model will be used to compare the results between theoretical analysis and experimental analysis.

The rate of heat transfer from the hot side, Q_{hot}, can be calculated using

$$Q_h = \alpha_{TEG} I_L T_h - \frac{{I_L}^2 R_{TEG}}{2} + k_{TEG} \Delta T_{TEG} \tag{4}$$

The rate of heat transfer from the cold side, Q_{cold}, can be calculated by [9]

$$Q_{cold} = \dot{m} C_{p\ nanofluid} \Delta T \tag{5}$$

where ṁ is the mass flow rate of the nanofluid, $C_{p\ cold}$is specific heat capacity of the hot gas, and ΔT is the temperature difference between $T_{cold\ in}$ and $T_{cold\ out}$. Applying the energy conservation principle with the assumption of no heat loss to surrounding, Output power by TEG, P_{TEG} can be obtain by Eq. (6)

$$Q_{hot} = Q_{cold} + P_{TEG} \tag{6}$$

With further arrangement of Eq. (6), Eq. (7) can be expressed as

$$P_{TEG} = Q_{hot} - Q_{cold} \tag{7}$$

Obtaining the rate of heat transfer through TEG, Q_{TEG} can be done through

$$Q_{TEG} = \frac{\Delta T_{TEG}}{R_{TEG}} \tag{8}$$

where ΔT_{TEG} is the temperature difference across the TEG and R_{TEG} is the thermal resistance of the TEG. The value of R_{TEG} is similar to load resistance when maximum power, P_{max} is achieved [11].

Theoretical Power Output of the TEG can be expressed as

$$P_{TEG} = \alpha_{TEG} I_L \Delta T_{TEG} - IL^2 R_{TEG} \tag{9}$$

The values of I_L was obtained by varying R_L via electronic load. The experimental value of Seebeck coefficient then can be calculated using Eq. (10)

$$\alpha_{TEG\ EXP} = \frac{V_{OC}}{\Delta T_{TEG}} - \alpha_{WIRE} \tag{10}$$

However, for simplification purpose, α_{WIRE} is assumed to be negligible and the equation reduced to

$$\alpha_{TEG\ EXP} = \frac{V_{OC}}{\Delta T_{TEG}} \tag{11}$$

3. Results and discussion

3.1 Experimental Validation Against Theoretical Data

Figure 6 shows the I-V curve and P-V curve for water flowed at 49 mL/s with experimental value and theoretical value of Pmax as shown. The I-V curve is displayed as an inverse linear relation whereas the P-V curve is shown as a polynomial. The quadratic function of, $y = -162.52x^2 + 114.54x + 0.9962$, where y represents Current, A, and x equals to Voltage, V, obtained from the polynomial is differentiated to obtained the first order derivative. The first order derivative is then used to find voltage, V, which in this case equates to 0.352 V. The obtained Voltage value is then substituted into the straight-line equation, obtained from the I-V curve to calculate the current, A, which equals to 0.061 A. R_{TEG} can be calculated by dividing the calculated value of voltage, V, and current, A which gives out 5.77 Ω. R_{TEG} is substituted into Eq. (9) with the value of ΔT equals to 31.5, to calculate the theoretical maximum power. The theoretical maximum power, $P_{theoretical}$ is equal to 16.29 mW whereas the experimental maximum power, $P_{experimental}$ is 14.93 mW. The percentage difference between these two values is 8.7% which is acceptable. The small deviation is probably due to the negligence effect of the heat loss to the surroundings.

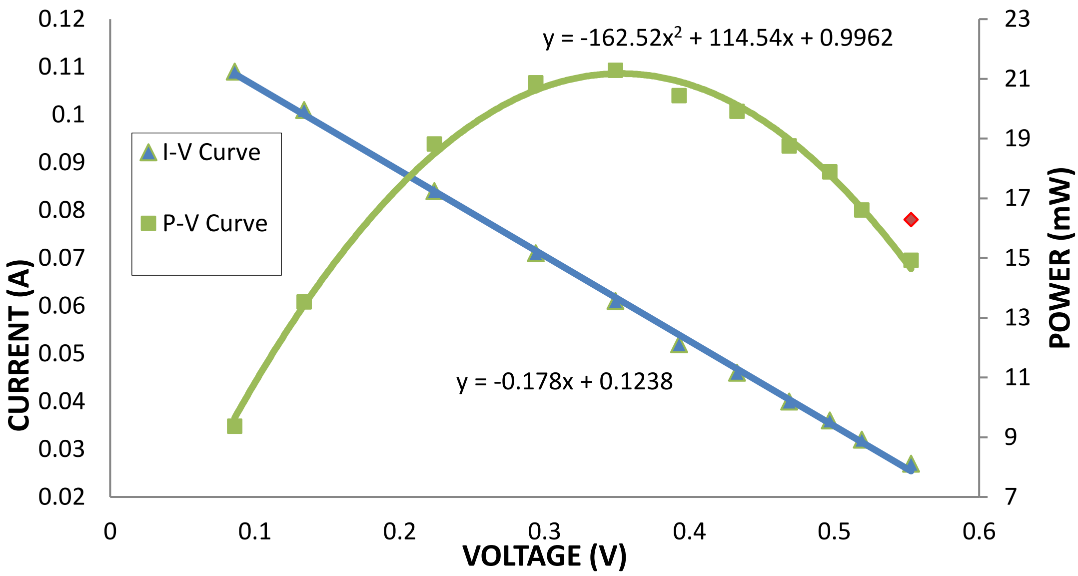

Fig. 6. Validation curve for current versus power at water, 49 mL/s

3.2 Effect of Flowrate to The Performance of TEG

The effect of flow rates to the performance of the TEG are observed through the I-V curve and P-V curve of each fluid. The values of current and voltage was obtained from the electronic DC load by varying resistance from 900Ω to 10Ω. The P-V curve is derived from multiplying current and voltage to obtain current. Figure 7 shows the I-V curve and P-V curve for water upon adoption as cooling medium in TEG studed. The effect of flow rate variation to the power output can be observed through these curves. In general, the power output increases as the flowrate is increased. However, in the case of water, minimal effect on the power is observed by increasing the flowrate from 49 to 112 ml/s. It was observed that Pmax in water at 49mL/s is 21.3mW while Pmax at 80mL/s and 112mL/s is 20.6mW and 19.6mW consecutively which translates to 3.3% and 8% decrease, respectively.

As for water, the optimal flowrate is 49mL/s. Figure 7 shows the relation between water flowrate and power output at TEG hot side of 80°C. It was observed that the higher flowrate does not necessarily equate to an increase of TEG performance. It can be observed that 49mL/s brings out the best power output as compared to 12mL/s, 80mL/s, and 112mL/s. This finding agrees with the findings of Abu Bakar *et al.,* [22], where the authors stated that a further increase of flowrate from the optimal value will not enhance the power output and more likely demanding more pumping power to circulate fluid. The maximum power obtained from the 49mL/s was 0.021 W and the lowest value recorded was 0.009 W.

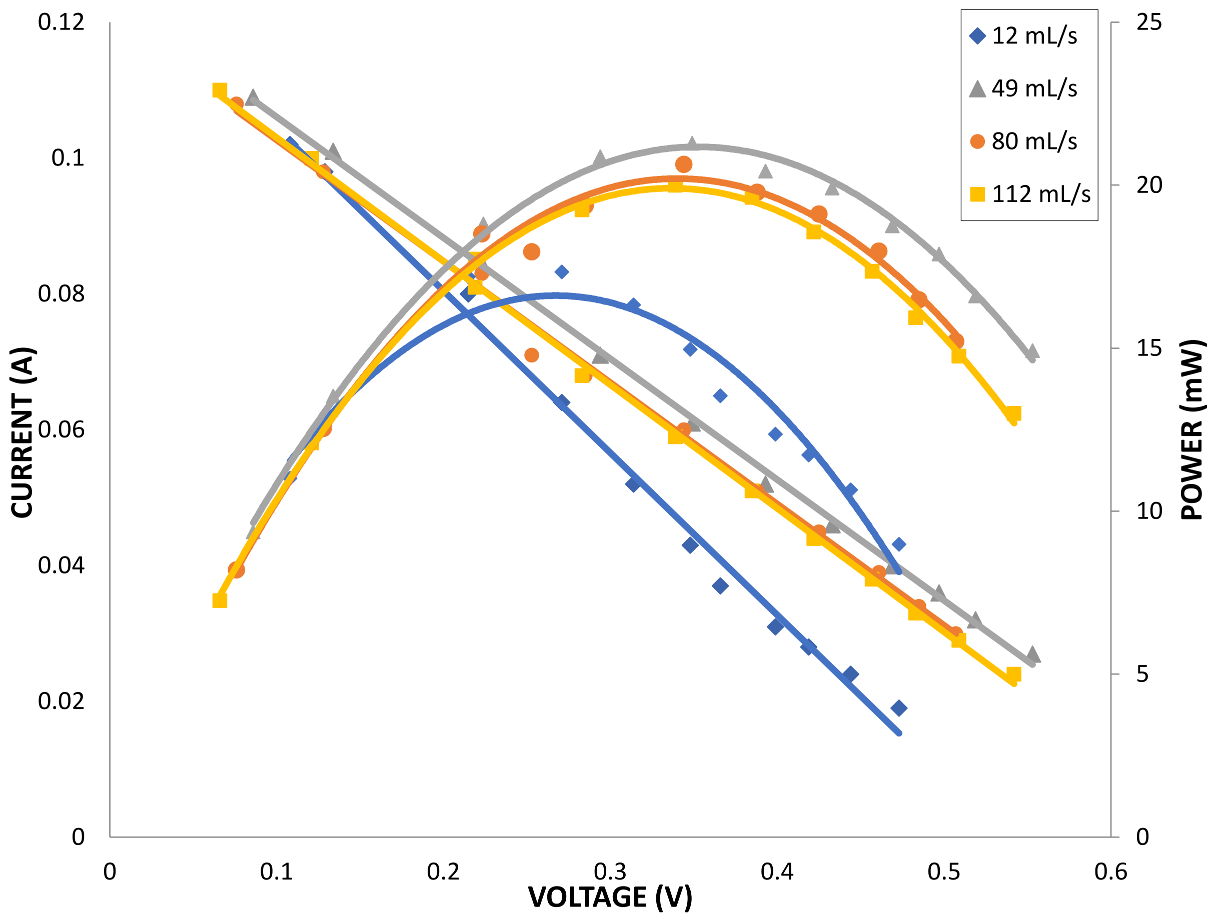

Fig. 7. Effect of flowrate of water to TEG performance

In the case of Al_2O_3 and SiO_2 nanofluids, it was observed that for both fluids, 112 ml/s was the optimal flow rate. This condition may be attributed by the viscous nature of nanofluids which demands more pumping power to circulate in the system [9,23]. In a separate study, Talib *et al.,* [24] has attributed the higher viscosity of nanofluids to the dispersion of nanoparticle which closes the gap between fluid layers. The higher flowrate requirement by nanofluids was caused by the higher viscosity of the nanofluids as reported by Sahin *et al.,* [9] and Muhammad *et al.,* [25], that adding nanoparticles in a base fluid will increase its viscosity.

At flowrate of 112 mL/s, it is observed that for Al_2O_3 nanofluids, the maximum power obtained was 34.1mW as shown in Figure 8. At 12 mL/s, 49 mL/s, and 80 mL/s, the observed Pmax was 23.8 mW, 23.7 mW, and 24.4 mW respectively. The Pmax difference between 12 mL/s, 49mL/s, and 80 mL/s against 112 mL/s, if translated to percentage drop, is approximate to 30.2%, 30.5%, and 28.4% reduction against Al_2O_3 nanofluids at 112 mL/s respectively.

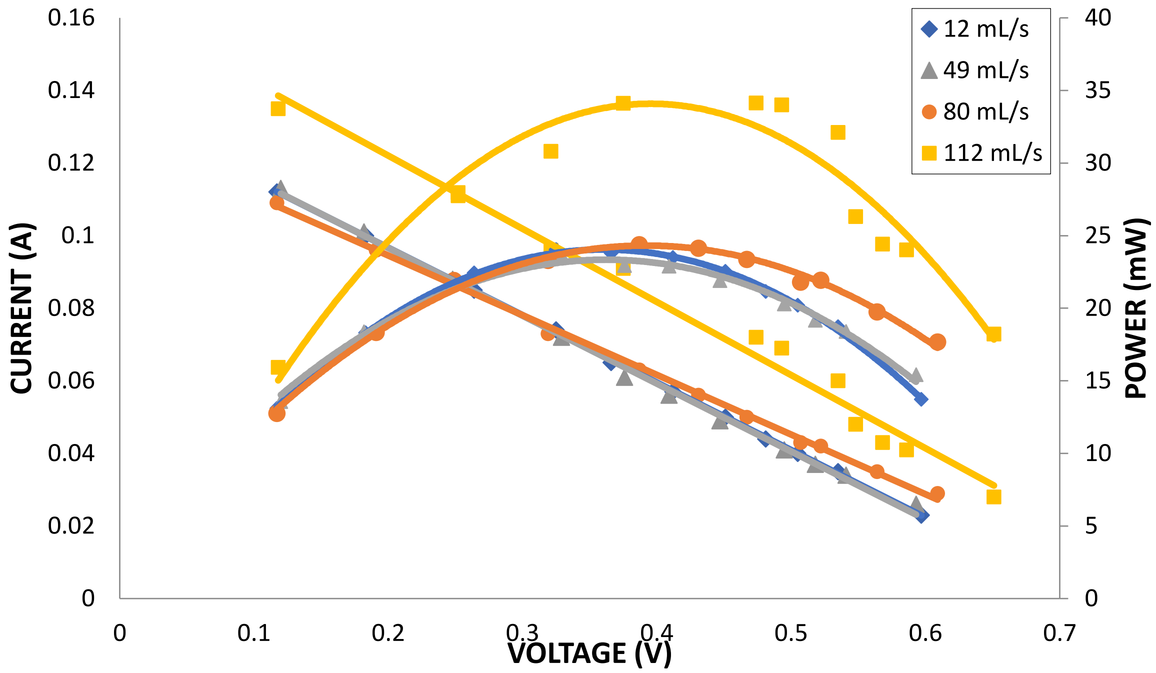

Fig. 8. Effect of varying flowrate of Al_2O_3 nanofluids to TEG performance

Meanwhile, as for SiO_2 nanofluids, the maximum power observed was 28.6 mW which was also obtained at 112 mL/s as shown in Figure 9. At flowrates 12 mL/s, 49mL/s, and 80 mL/s, the Pmax observed was 21.3 mW, 23.2 mW, and 27.9 mW respectively. Comparing against 112 mL/s, the Pmax of flowrates 12 mL/s, 49mL/s, and 80 mL/s can be represented with 28.4%, 18.9%, and 2.4% reduction respectively.

When comparing the Pmax at 112mL/s for both nanofluids, it was observed that TEG was able to generate a higher Pmax when the hot side of the TEG is exposed the flow of Al_2O_3 nanofluids which has a higher thermal conductivity as compared to SiO_2 nanofluids. The distinction of Pmax between the two nanofluids can be portrayed in the form of percentage difference which equates to 16.1%. These two results are in a good agreement with Khalid *et al.,* [26], who reported that the thermal conductivity of Al_2O_3 nanofluids is higher than SiO_2 nanofluids which translated to a better heat transfer performance.

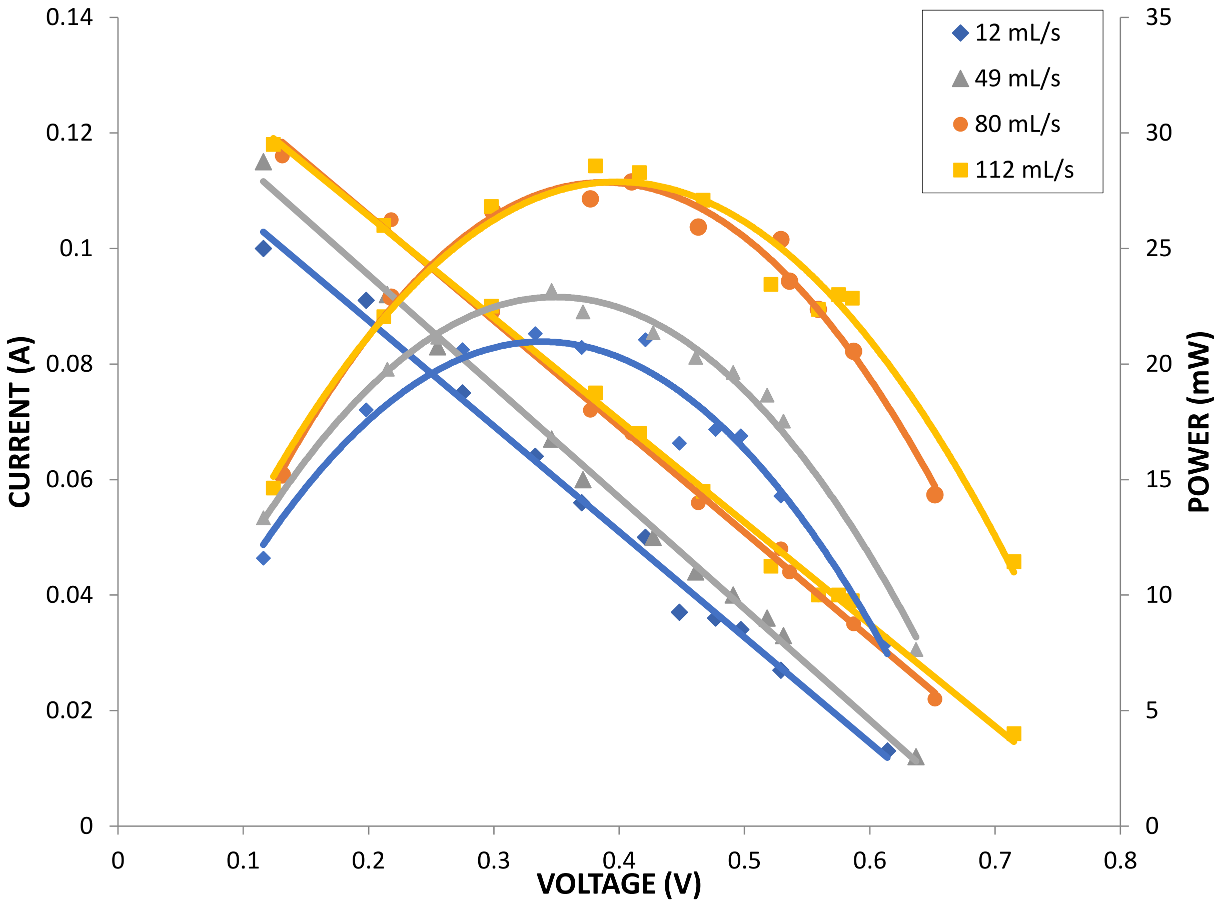

Fig. 9. Effect of varying flowrate of SiO_2 nanofluids to TEG performance

3.3 Effect of Thermal Conductivity to TEG Performance

Figure 10 shows the Current – Voltage Curve (I-V Curve) and Power – Voltage Curve (P-V Curve) for a similar flowrate of 112mL/s. It can be observed that nanofluids dominates its base fluids counterpart with Al_2O_3 nanofluids sitting above the other fluids. It can be said that Al_2O_3 nanofluids was able to bring out the highest maximum power. For water, the maximum power is 0.02W while SiO_2 nanofluids and Al_2O_3 nanofluids has a maximum power of 0.029W, a 45% increase and 0.034W, a 70% increase, respectively. This finding agrees with the observation made by Khalid *et al.,* [26] and Zakaria *et al.,* [27], who both concluded that the introduction of nanoparticles to a base fluid increases the base fluid's thermophysical properties with Al_2O_3 nanofluids giving out the highest thermal conductivity value when compared to SiO_2 nanofluids and its base fluid.

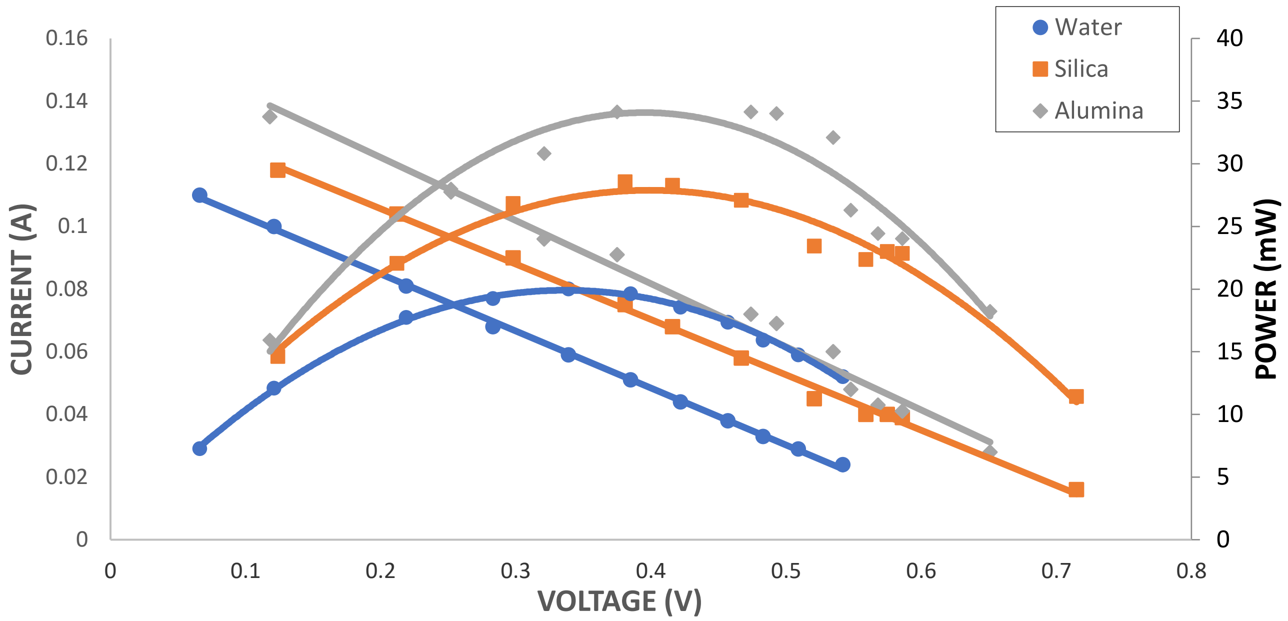

Fig. 10. Effect of thermal conductivity of the cooling medium to the performance of TEG

3.4 Experimental Seebeck Coeff Vs Temp Gradient Across TEG

Figure 11 shows the range of experimental Seebeck Coefficient against ΔT TEG for all three fluids. The experimental Seebeck coefficient values were obtained from Eq. (11) as mentioned in the mathematical model. The experimental Seebeck coefficient for water is in the range of 0.0244 V/K to 0.029 V/K. For the case of Al_2O_3 nanofluids and SiO_2 nanofluids, the range falls between 0.0204 V/K to 0.0223 V/K and 0.0199 V/K to 0.0222 V/K, respectively. In comparison, Abu Bakar *et al.,* [22], reported the values of 0.0215 V/K to 0.0236 V/K. The inconsistency of the Seebeck Coefficient for this experiment is probably due to the temperature change. However, the obtained values from the experiment approaches the theoretical Seebeck Coefficient of 0.0241 V/K.

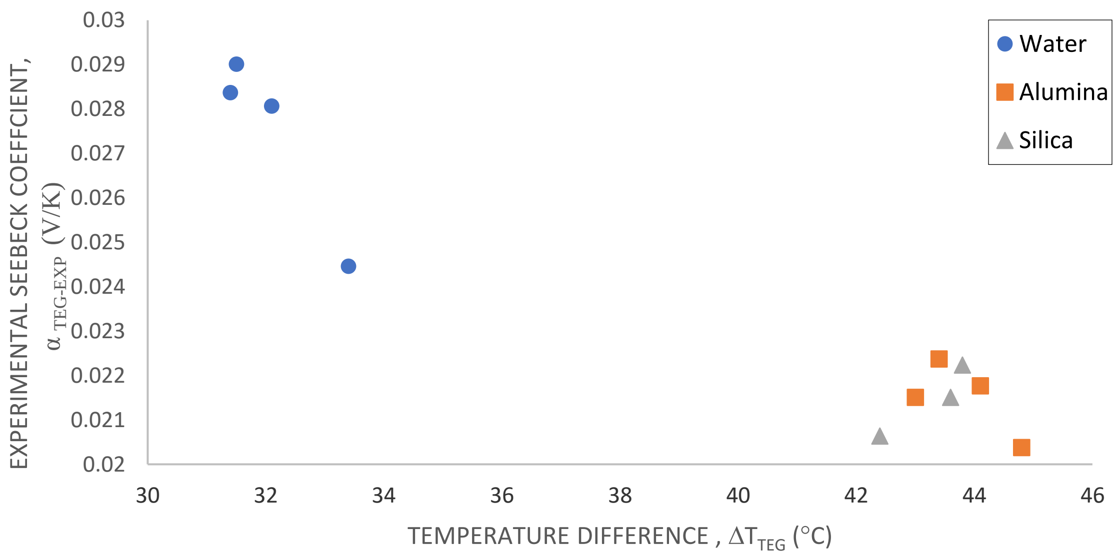

Fig. 11. Seebeck Coefficient of water, Al_2O_3 nanofluids and SiO_2 nanofluids

4. Conclusions

From the graph obtained, it is justified that nanofluid outperforms its base fluid of water. The power output by TEG increases along with the temperature applied at the hot side of TEG. It can also be concluded that for water, as the flowrate is increased, the power output was also increased, up to a certain value, which is 49mL/s in this study. However, both nanofluids reported an optimum flow rate of 112mL/s. It is also observed at 112mL/s, SiO_2 nanofluids was able to increase the maximum power output by 45%, while Al_2O_3 nanofluids increased the maximum power output by 70%. Although the experiment was done in temperature controlled and indoor space, the variables of surroundings may affect the data obtained from the experiment. Further study on the actual application of the combination of nanofluids and heat recovery via TEG is recommended as it shows improvement in the performance of TEG.

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