IOP Conf. Series: Materials Science and Engineering **226** (2017) 012148 doi:10.1088/1757-899X/226/1/012148

Validation of a Waste Heat Recovery Model for a 1kW PEM Fuel Cell using Thermoelectric Generator

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Abstract. Fuel cell is a device that generates electricity through electrochemical reaction between hydrogen and oxygen. A major by-product of the exothermic reaction is waste heat. The recovery of this waste heat has been subject to research on order to improve the overall energy utilization. However, nearly all of the studies concentrate on high temperature fuel cells using advanced thermodynamic cycles due to the high quality of waste heat. The method, characteristics and challenges in harvesting waste heat from a low temperature fuel cell using a direct energy conversion device is explored in this publication. A heat recovery system for an open cathode 1kW Proton Exchange Membrane fuel cell (PEM FC) was developed using a single unit of thermoelectric generator (TEG) attached to a heat pipe. Power output of the fuel cell was varied to obtain the performance of TEG at different stack temperatures. Natural and forced convections modes of cooling were applied to the TEG cold side. This is to simulate the conditions of a mini fuel cell vehicle at rest and in motion. The experimental results were analysed and a mathematical model based on the thermal circuit analogy was developed and compared. Forced convection mode resulted in higher temperature difference, output voltage and maximum power which are 3.3ºC, 33.5 mV, and 113.96mW respectively. The heat recovery system for 1 kW Proton Exchange Membrane fuel cell (PEM FC) using single TEG was successfully established and improved the electrical production of fuel cell. Moreover, the experimental results obtained was in a good agreement with theoretical results.

1. Introduction

Hydrogen fuel cell is a green energy generator that produces electricity and water as by-product. It offers high electrical productivity about 50 to 60% and low gas emissions [1]. However, the reactions involved in fuel cell is highly exothermic that produces heat in addition to electricity [2]. Previously, the scope of thermal management for fuel cells has been limited to develop highly effective methods to remove excess heat from the stack as temperature is a governing parameter in fuel cell performance. An extended domain for thermal management is proposed in this work to include the utilization of the generated low grade waste heat from Polymer Exchanger Membrane (PEM) fuel cells for auxiliary electrical power generation using Thermoelectric Generator (TEG) as shown in figure 1 below; thus, improving the overall energy efficiency of the system.

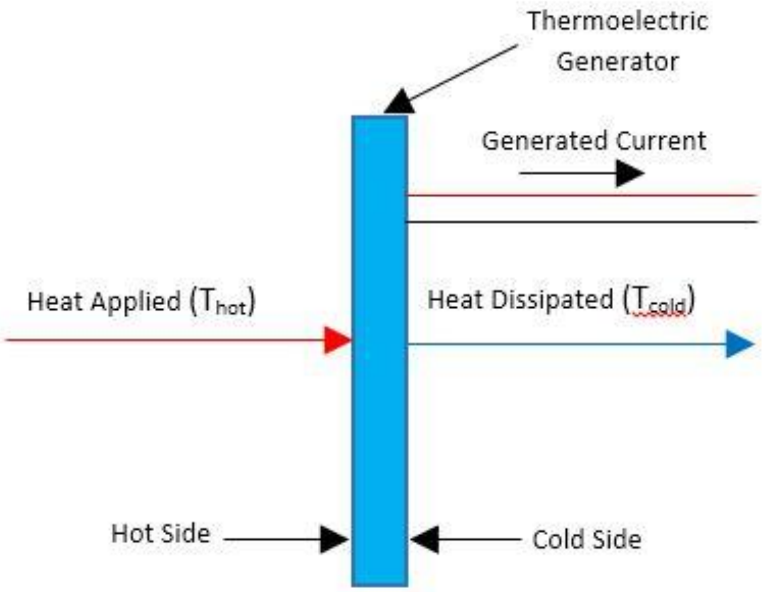

Figure 1: Diagram and Operation of a TEG

A TEG is a unique type of Carnot heat engine which uses electrons as the ‘working fluid’ [3]. It consists of no moving parts, low maintenance, lightweight, very reliable and most important is that it can produce energy as long as there is difference in temperature. TEG consists of n-type and p-type of semiconductor pellets that connects electrically in series and thermally in parallel. Common type of material used for TEG is Bismuth Telluride which enables a TEG to generate electricity higher and withstand high temperature operating condition. The basis of TEG is to force the flow of free electrons by inducing temperature difference between the two TEG surfaces. Waste heat as a high temperature source is highly compatible with TEG application [4]. In order to generate electricity, heat must be applied to the hot surface of a TEG, which is then dissipated using heat transfer devices such as heat sinks, coolants in pipes or even fans installed at the cold side of the TEG [5].

Application of TEG as a waste heat recovery device has been proven for industrial exhaust gases [5], internal combustion engines [6], ground-air thermoelectric power generator [7] and direct carbon fuel cell (DCFC) hybrid system [8]. Their findings prove a positive effect on the overall system efficiency. Furthermore, it was found that usage of heat pipe and finned type of heat exchanger at the cold side of TEG improves heat dissipation from TEG. Thus, it will produce higher temperature gradient which will contribute to higher power output from a TEG.

Research interest in waste heat recovery of fuel cells using TEG was initiated by Paris and Jones [9] where they simulated the effects of thermoelectric modules towards a fuel cell thermal management model. They found out that thermoelectric module maintains fuel cell operating condition in an acceptable range. Simulations done by Gao et al [10,11,12] have proven that the power output of a fuel cell system can be increased using more than one thermoelectric generator module, by dividing TEG modules into branches and using different type of heat exchangers.

Recently, an experimental study was reported by Hasani and Rahbar [2] to investigate the thermoelectric generator waste heat recovery system performance from a 5 kW PEM fuel cell. They have found that forced convection over the heat sink can be used to increase the heat transfer rate and temperature difference which leads to enhancement in the power output density.

To date, studies on the direct application of thermoelectric generator on PEM fuel cells are very limited due to the low grade waste heat generated and offer a wide range of opportunities in technical and modelling studies. From the available literature, the majority of the work were computational based [10,11,12,13,14,15] and only one published report on experimental [2]. Large temperature differences can be created to improve the TEG performance even for low temperature PEM fuel cells when the operational domain is related to vehicle applications. The movement of the vehicle provides a continuous air flow that is capable of inducing a large temperature difference across the TEG especially when moving at high speeds. From the perspective of application on fuel cell vehicles, the waste heat recovery potential is greater even at for low temperature PEM fuel cells.

Based on the background study, a preliminary research on the waste heat recovery of an open cathode 1kW PEM fuel cell using a single thermoelectric generator (TEG) unit was conducted towards improving the PEM fuel cell energy efficiency relative to vehicle application. Theoretical modelling of the waste heat recovery system was developed and experimentally validated for a fixed TEG orientation with variable fuel cell power and vehicle speeds. Findings from this research can be used as a benchmark for further study related to TEG arrangement and temperature difference improvements relative to low power PEM fuel cell stacks in vehicle applications.

2. System Setup

A PEM fuel cell system coupled with a TEG waste heat recovery system was developed. The main setup consist of a 1 kW PEM fuel cell (open cathode type), fuel cell controller, hydrogen supply, DC electronic loader, an insulated flow duct, a TEG module and a heat pipe attached to a cooling fan. Figure 2 shows the experimental setup of while figure 3 shows the schematic diagram for the system. Figure 4 shows a closer arrangement and configuration of the stack and TEG.

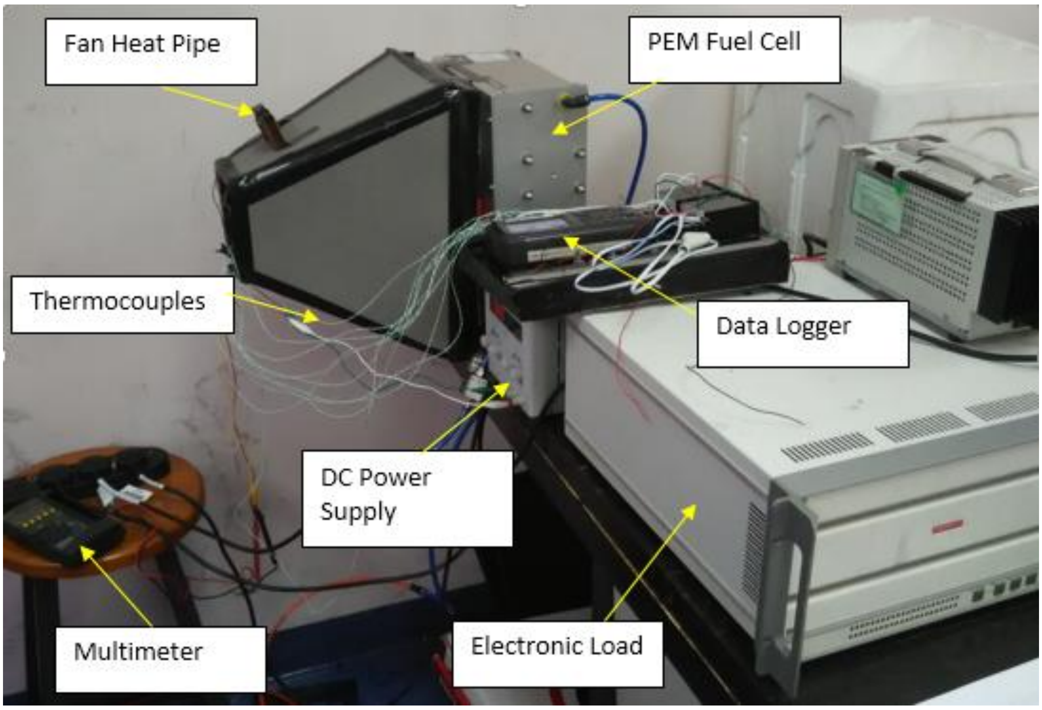

Figure 2: The experimental setup of the FC-TEG heat recovery system.

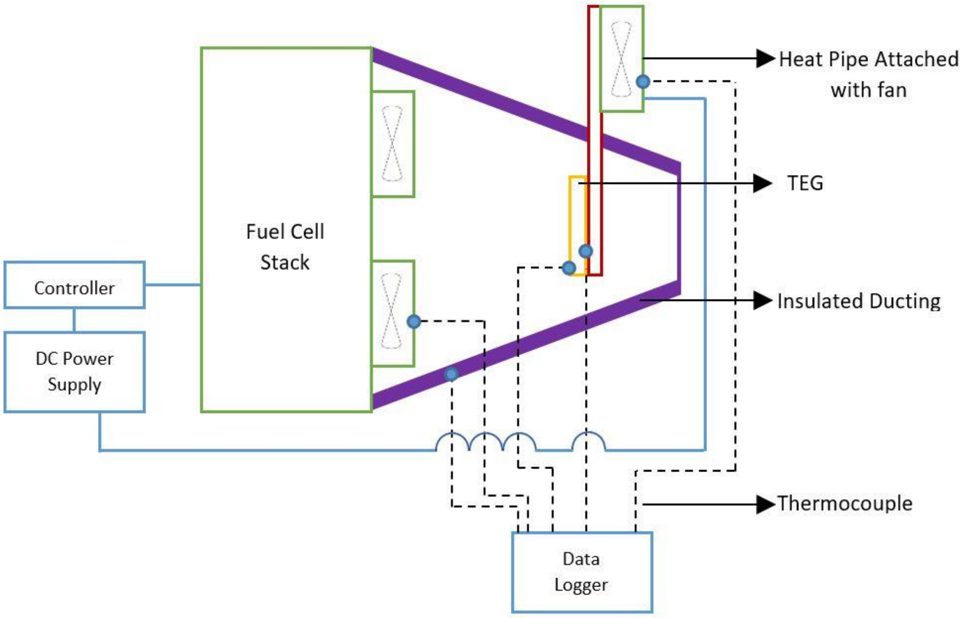

Figure 3: Schematic diagram of the FC-TEG heat recovery system.

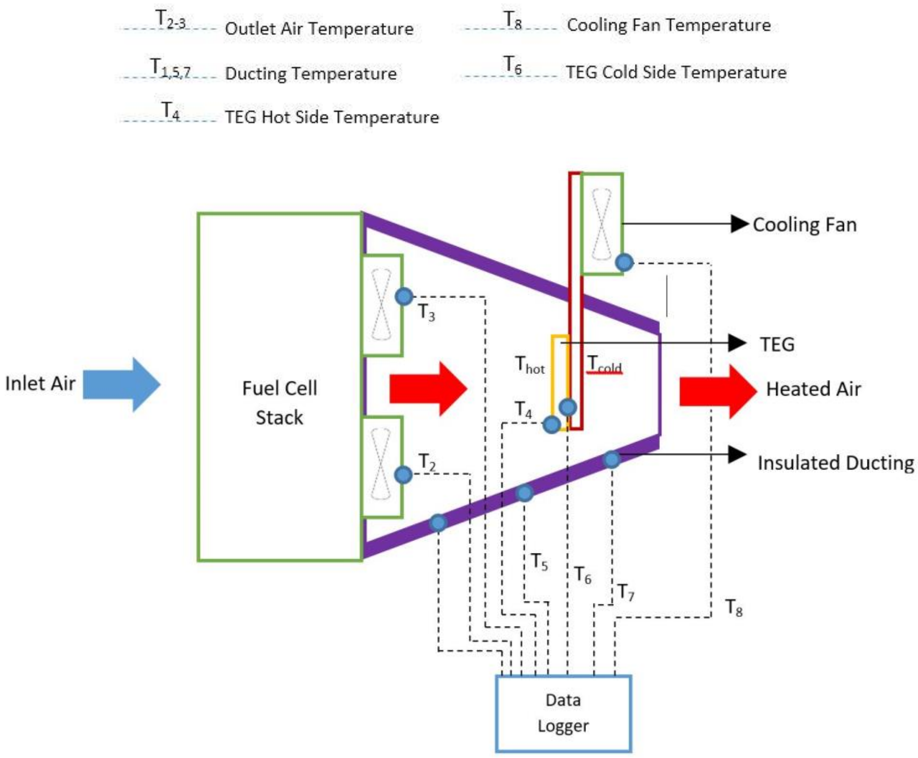

Figure 4: The arrangement of the fuel cell stack, TEG and heat pipe.

The thermoelectric generator (TEG) was attached to a heat pipe where a variable speed fan was used to cool the fluid within the heat pipe. The position of the TEG module was at the centre-line of the stack at a distance of 22.5 cm from the fuel cell stack. The position was chosen based on a background numerical analysis using ANSYS Fluent that simulated the temperature distribution within the duct at various fuel cell thermal power generation and is not provided in this paper.

Eight k-type thermocouples (T1-T8) as shown in figure 4 above; were used to measure the temperatures of the air at the stack exit, duct surfaces, thermoelectric generator surfaces and cooling. All data were collected using midi LOGGER GL200A data logger with a frequency of 5 seconds. A DC electronic load was connected to the fuel cell to provide artificial current loads to the fuel cell while a DC power supply is used to apply load to the TEG. Then, a multimeter and anemometer were used to obtain the TEG output voltages and air velocities respectively. The specifications of the devices and instruments are provided in Table 1.

Table 1: Specifications of experiment setup.

Parameter	**Value**
PEM fuel cell	
Rated Power	2kW
Fuel Cell Stack type	Open Cathode
Current	33 A
Electrical Efficiency	45%
No of fuel cell stack	48
Thermoelectric Module	
Model	Peltier Effect
Dimension	40 mm x 40mm x 3.9 mm
Seebeck Coefficient	190 µV/K
Operating Temperature	T<200 °C
Merit	$2 \times 10^{-3} K^{-1}$
No of Thermo Element	127

3. Experimental Methodology

The framework of the research was to imitate a mini fuel cell vehicle operating on a 1kW PEM fuel cell (based on developed prototypes for Shell Eco Marathon Asia competitions) coupled with a TEG module and heat pipe. In principal, the heat pipe will be exposed to fast flowing air as the vehicle moves and this variable speed airstreams are artificially provided by the cooling fan.

The objectives of the study is to analyse the output of a single TEG used in the waste heat recovery of a 1kW PEM fuel cell under variable fuel cell power and cooling air conditions. There were 2 different cooling modes which are natural convection and external forced convection. During natural convection (imitating the vehicle at rest or idling condition), the cooling fan was switched off. In forced convection cooling mode, the velocities of the cooling air was varied at 1.14 m/s (4.1 km/h), 1.90 m/s (6.8 km/h) and 2.30 m/s (8.3 km/h). These air velocities were applied due to the limitations of the cooling fan performance.

Before the experiment was conducted, the output air temperature from fuel cell stack fan were mapped in order to find and record the average temperature and speed for each of fuel cell load current. Then the experiment were setup according to schematic diagram in figure 3. After that, load current from DC electronic load was initially fixed to 100 watt and the cooling mode were set up to natural convection (fan in rest condition). When the temperature output from fuel cell had stabilized less than a minute, the data was recorded. Then the experiment were conducted using force convection at different speed (1.14 m/s, 1.90 m/s and 2.30 m/s). The experiment were conducted using different fuel cell load current. Finally, all the data was recorded and tabulated to be analyze. Table 2 lists the variables and range of value used for the experiment.

Table 2: Experimental variables.

Parameter	**Value**	**Unit**
PEM Fuel Cell		
Current,I	0-30	A
Fan		
Velocity,V	1-2.30	m/s
Room Conditions		
Temperature	23.5	°C

4. Theoretical Model

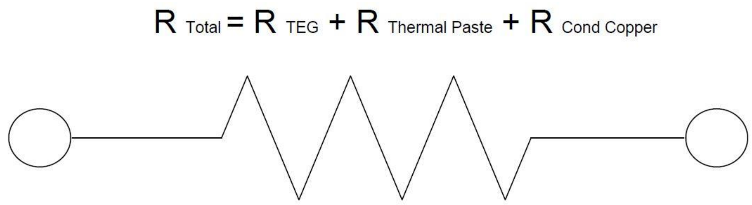

Figure 5: Thermal resistance modelling of the FC-TEG system.

The theoretical model is based on the thermal resistance network as shown in Figure 5 where 3 resistances consisting of thermal paste, copper heat pipe and TEG were used to calculate TEG power output.

The rate of heat energy recovered from a TEG is

$$\dot{Q} = \frac{\Delta T}{R_{123}} = \frac{T_1 - T_2}{R_{123}} \quad (1)$$

where T_1 is the temperature of the TEG hot side, T_2 is the temperature of the TEG cold side and R_{123} is the total resistance of TEG, thermal paste and copper based on calculations for natural convection and forced convection. The value of TEG resistance is obtained experimentally by Singh et al. [16] which is 0.8°C/W. They conducted experiment by heating one side of the TEG and cooling the other side. By insulating the setup, the thermal energy across the TEG was specified by an external power source, Q_{th}. The temperature difference (ΔT) between the TEG and the specified thermal power input, Q_{th} allowed for R_{TEG} calculation, based on the formula

$$\dot{Q}_{th} = \frac{\Delta T}{R_{TEG}} \qquad (2)$$

as specified by the Singh et al. [16]. The thermal resistance of the thermal paste used to attach the TEG cold surface to the heat pipe copper surface is

$$R_{thermal\,paste} = \frac{L_{tp}}{k_{tp}A_{TEG}} \qquad (3)$$

The thermal resistance of the copper heat pipe,

$$R_{copper} = \frac{L_{copper}}{k_{copper}A_{copper}} \qquad (4)$$

where k_{copper} is thermal conductivity of copper, A_{TEG} is contact area surface of TEG and L_{copper} is the thickness of the copper heat pipe.

The TEG power output can be calculated using

$$P_{TEG\,theoretical} = \mu_{TEG}\dot{Q} \qquad (5)$$

where μ_{TEG} is TEG electrical power conversion efficiency and $\dot{Q}$ is rate of heat energy recovered from TEG. The electrical power conversion efficiency is unknown and needs to be calculated using

$$\mu_{TEG} = \frac{Q}{P_{TEG\,experiment}} \qquad (6)$$

where $\dot{Q}$ is rate of heat energy recovered from TEG and $P_{TEG\,experiment}$ is TEG power output from experiment. Table 3 show values of parameters used in formula above.

Table 3: Experimental parameter values.

Parameter	Value	Unit
Thermal Paste		
Thickness, L_{tp}	$1x10^{-3}$	m
Area, A_{TEG}	$1.6x10^{-3}$	m^2
Thermal Conductivity, k_{tp}	8.5	W/m.K
Copper		
Thickness, L_{copper}	$1x10^{-3}$	m
Area, A_{copper}	$1.6x10^{-3}$	m^2
Thermal Conductivity, k_{tp}	400	W/m.K

5. Results

The stack polarization curve inclusive of the electrical power and thermal power generated is shown in figure 6.

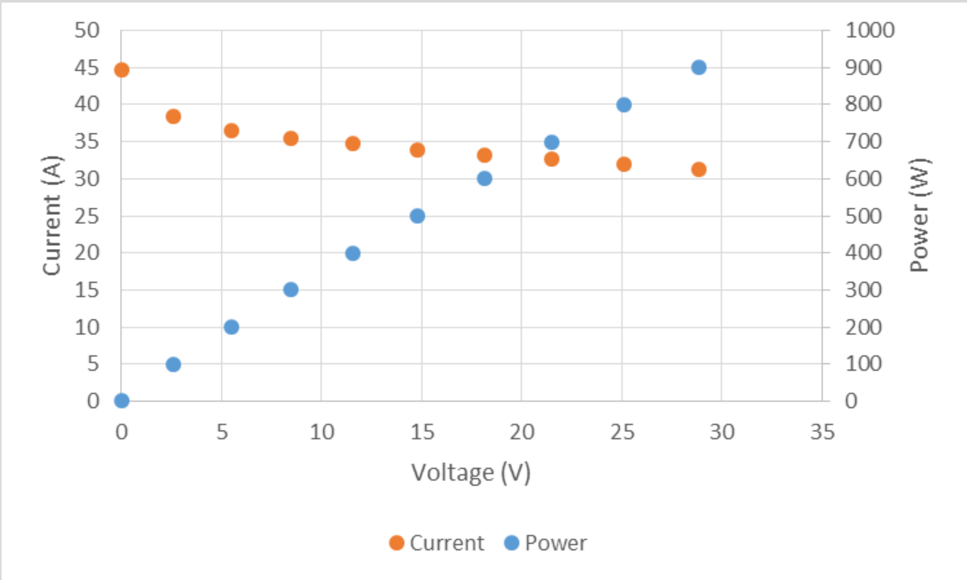

Figure 6: Stack polarization and thermal power generated for PEM fuel cell stack.

From the observation, the power output of fuel cell is increase when the fuel cell voltage is increase. Besides that, fuel cell current decrease as the voltage increase. When the power output of fuel cell increased from 100W-900W, electricity generated by TEG for a different speed is increased. By comparing graph with different power output of fuel cell, it shows that, the highest power output of fuel cell which is 900W produces the highest voltage output by TEG. Thus, a graph that summarized all the data is shown in figure 7 below.

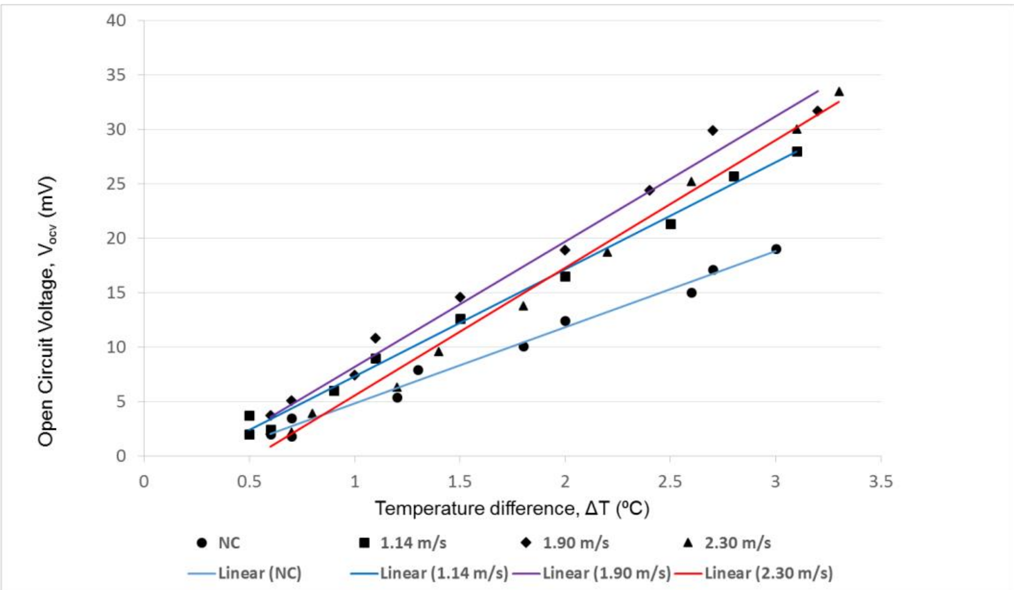

Figure 7: The effect of temperature difference towards TEG output voltage.

Figure 7 shows that the open voltage produced by a single TEG for different cooling air velocities increases as the temperature gradient is increased; in conjunction with a study done by Hasani and Rahbar [2] and Singh et al [16]. As observed, the highest value of power generated by TEG is the highest when the velocity of air was at 2.30 m/s, in which it generated 33.5 mV of electricity with temperature gradient of 3.3°C. Moreover, the lowest value of power generated by TEG is NC (natural convection), where TEG generated 18mV of electricity with temperature gradient of 3°C. Moreover, by observing to figure 8, higher temperature difference can be achieved at greater cooling air velocities due to the increased convection effects at the heat pipe leading lower TEG cold side temperatures which was suggested by Hasani and Rahbar [2]. If the test is performed using higher fuel cell power output, the temperature difference at the TEG will increase and consequently increase the TEG power output. The results obtained are in-line with the open voltage profile of TEG published by Baljit et al. [16] and Hasani and Rahbar [2].

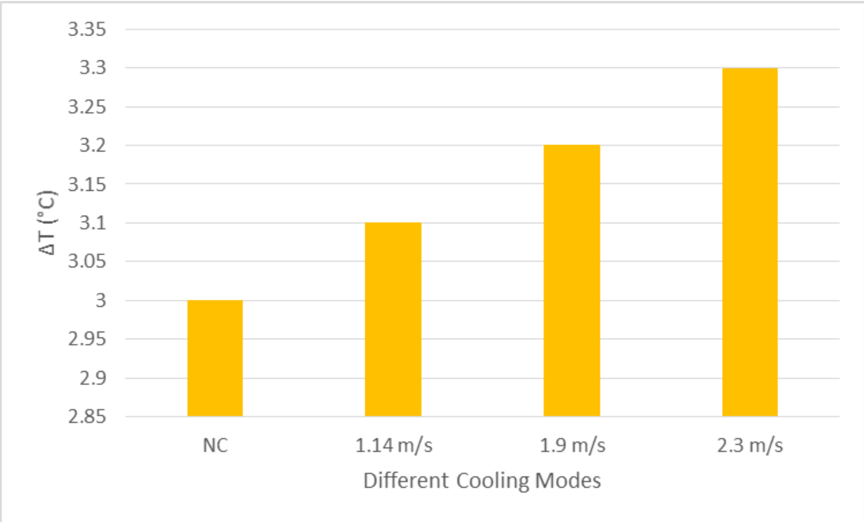

Figure 8: Temperature difference for different cooling modes.

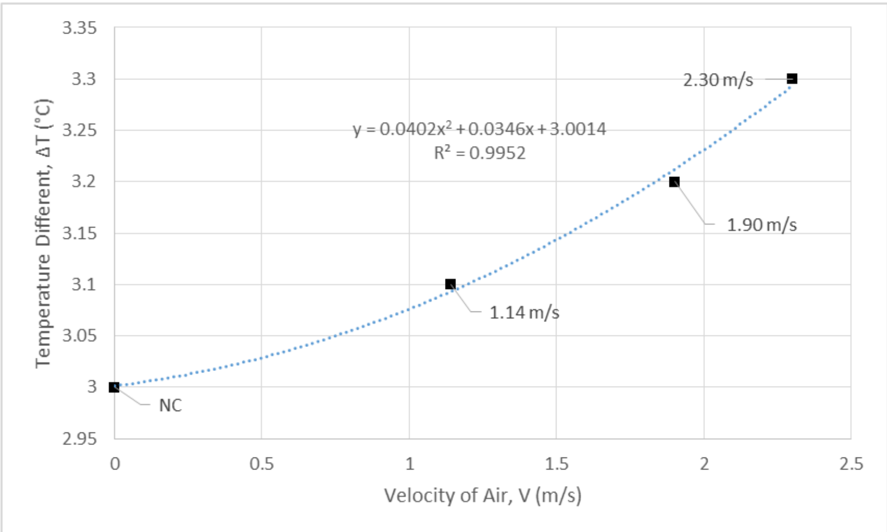

Figure 9: The effect of air velocity towards temperature difference of the TEG at 900W stack power.

Figure 9 shows the effect of cooling air speed towards the temperature difference between the hot and cold side of the TEG. A polynomial trendline was obtained with an increase of 0.135°C for every 1 m/s increase of cooling air velocity. Based on the 900W fuel cell power output, the output voltage produced using natural convection cooling compared to the highest applied 2.4 m/s cooling air velocity is approximately 45% due to the lower convection coefficient for natural convection currents.

5.1 TEG Output Power with Model Validation

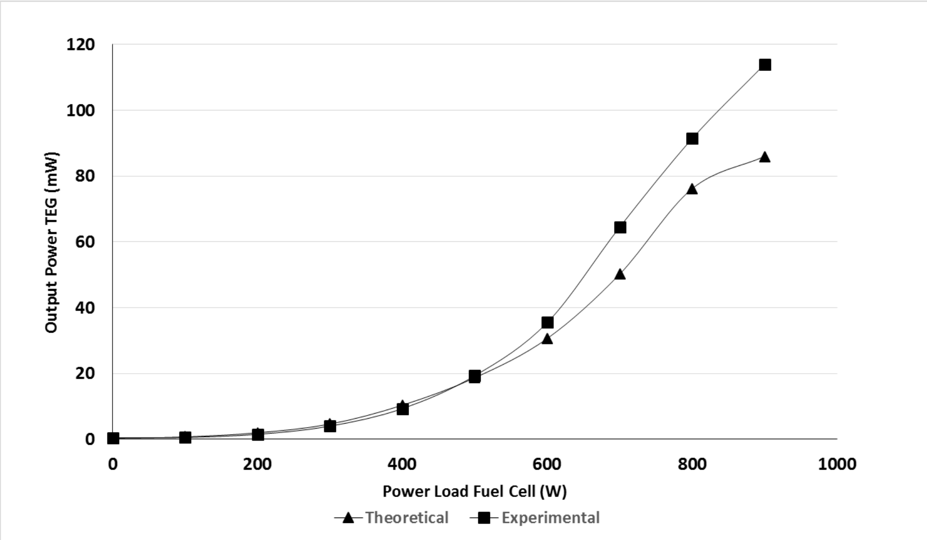

Figure 10: The output power of TEG at different fuel cell electrical power.

Figure 10 explains the theoretical model and experimental results show similar exponential profiles for the TEG output power. When the fuel cell power increases, the TEG power output also increases due to increasing temperature gradients. At low fuel cell power loads, the TEG output increase is very small. A sharp increase in TEG power output was obtained starting from the 500W fuel cell load. Also, results from the theoretical model and the experimental diverge at the 500W fuel cell load and the difference increases at increasing fuel cell power. At 900W fuel cell power, the difference is approximately 30%. This is because the effect of heat sink in the thermal resistance was neglected. It was suggested that the inclusion of heat sink thermal resistance will improves the theoretical results.

6. Conclusion

A waste heat recovery of a 1 kW PEM fuel cell using thermoelectric generator (TEG) where thermoelectric generator thermal and electrical behaviour performance was experimentally assessed. Moreover, a typical heat pipe with a fan is installed on the thermoelectric generator cold side improved power output of TEG. This study have successfully established a waste heat recovery of 1 kW PEM fuel cell using a single TEG which generates 113.96 mV of power output. Both experimental and theoretical results were in similar trendline until 500W before it deviates. Thus, this proves that, thermoelectric generator can improve the electrical production of PEM fuel cell by converting waste heat from PEM fuel cell to electricity.

References

[1] C. Rayment, "Introduction to Fuel Cell Technology," 2003.
[2] M. Hasani and N. Rahbar, "Application of thermoelectric cooler as a power generator in waste heat recovery from a PEM fuel cell - An experimental study," *Int. J. Hydrogen Energy*, vol. 40, no. 43, pp. 15040–15051, 2015.
[3] M. F. Remeli, L. Tan, A. Date, B. Singh, and A. Akbarzadeh, "Simultaneous power generation and heat

recovery using a heat pipe assisted thermoelectric generator system," *Energy Convers. Manag.*, vol. 91, pp. 110–119, 2015.

[4] J.-P. Fleurial, "Thermoelectric power generation materials: technology and application opportunities," *J. Miner. Met. Mater. Soc.*, vol. 61, no. 4, pp. 79–85, 2009.

[5] S. B. Riffat and X. Ma, "Thermoelectrics: A review of present and potential applications," *Appl. Therm. Eng.*, vol. 23, no. 8, pp. 913–935, 2003.

[6] J. Martins and F. P. Brito, "Heat-Pipe Assisted Thermoelectric Generators For Exhaust Gas Applications," pp. 12–18, 2010.

[7] S. Kim, S. Park, S. Kim, and S. H. Rhi, "A thermoelectric generator using engine coolant for light-duty internal combustion Engine-Powered Vehicles," *J. Electron. Mater.*, vol. 40, no. 5, pp. 812–816, 2011.

[8] J. W. Stevens, "Performance factors for ground-air thermoelectric power generators," *Energy Convers. Manag.*, vol. 68, pp. 114–123, 2013.

[9] M. Zhao, H. Zhang, Z. Hu, Z. Zhang, and J. Zhang, "Performance characteristics of a direct carbon fuel cell/thermoelectric generator hybrid system," *Energy Convers. Manag.*, vol. 89, pp. 683–689, 2014.

[10] X. Gao, S. J. Andreasen, M. Chen, and S. K. Kær, "Numerical model of a thermoelectric generator with compact plate-fin heat exchanger for high temperature PEM fuel cell exhaust heat recovery," *Int. J. Hydrogen Energy*, vol. 37, no. 10, pp. 8490–8498, 2012.

[11] X. Gao, M. Chen, S. J. Andreasen, and S. K. Kær, "Potential usage of thermoelectric devices in a high-temperature polymer electrolyte membrane (PEM) fuel cell system: Two case studies," *J. Electron. Mater.*, vol. 41, no. 6, pp. 1838–1844, 2012.

[12] X. Gao, S. J. Andreasen, S. K. Kær, and L. A. Rosendahl, "Optimization of a thermoelectric generator subsystem for high temperature PEM fuel cell exhaust heat recovery," *Int. J. Hydrogen Energy*, vol. 39, no. 12, pp. 6637–6645, 2014.

[13] R. J. Parise and G. F. Jones, "Fuel cell thermal management with thermoelectric coolers," *IECEC '02. 2002 37th Intersoc. Energy Convers. Eng. Conf. 2002.*, no. 20096, 2002.

[14] M. Chen, S. J. Andreasen, L. Rosendahl, S. K. Kær, and T. Condra, "System modeling and validation of a thermoelectric fluidic power source: Proton exchange membrane fuel cell and thermoelectric generator (PEMFC-TEG)," *J. Electron. Mater.*, vol. 39, no. 9, pp. 1593–1600, 2010.

[15] X. Chen, L. Chen, J. Guo, and J. Chen, "An available method exploiting the waste heat in a proton exchange membrane fuel cell system," *Int. J. Hydrogen Energy*, vol. 36, no. 10, pp. 6099–6104, 2011.

[16] B. Singh, L. Tan, A. Date, and A. Akbarzadeh, "The Effects of Temperature Difference and Compressive Force to the Electrical Characterization of Peltier Cell for Artificial Concentrated Solar Power Thermoelectric Application," *J. Mech. Eng.*, vol. 1, 2015.