

Performance of A Plate-Finned Thermoelectric Generator (TEG) Module for Industrial Waste Heat Recovery

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ABSTRACT

A thermoelectric generator (TEG) cell is a solid-state semi-conductor capable of converting thermal energy directly into electrical energy. Studies on specific designs for TEG modules are needed for an effective industrial waste heat recovery. Typical TEG systems apply direct heating or cooling without being assisted by heat transfer devices which makes it difficult to maintain high temperature difference between TEG cells surfaces for higher electrical power generation. To suit the TEG system with the industrial condition, a waste heat recovery (WHR) module was developed consisting of a Bismuth Telluride TEG cell and another module consisting of two TEG cells in a stacked configuration. The TEG cells were sandwiched between two copper blocks and connected to two plate-finned heat sinks and eight heat pipes. The two modules were tested on a dedicated test bench to study its performance based on an industrial WHR setup. The hot stream waste heat temperature was constant at 80 °C while the cooling air streams were set based on ambient conditions between 22 °C to 30 °C. The maximum power performance (MPP) varied from

10 mW to 153 mW where the effect of cooling is very significant on the power outputs. Under forced cooling condition, the MPP generated from the double stacking TEG configuration is significantly higher compared to single cell configuration, by approximately 250%.

Keywords: *Thermoelectric Generator; Waste Heat Recovery; Cooling Air Stream Temperature*

Introduction

Energy sustainability is central to modern industrialization. Approximately 50% of energy consumption in industries are released as heat and is expected to increase. Waste heat recovery (WHR) is a method to extract the heat energy generated from a system and reuse it for other purposes. About 20% of industrial thermal process has the potential to be reused to generate electrical and mechanical power. The quality of waste heat varies between different industries depending on the temperature grades. High grade waste heat is at temperatures greater than 400 °C, medium grade between 100 °C and 400 °C, while low grade is waste heat below 100 °C [1].

The solid-state technology of thermoelectric generators (TEG) is emerging as an alternative solution in WHR with the main benefits of no moving parts, long service life, low maintenance and zero pollution. TEG cells are built from materials with a high value of Seebeck coefficient, a property relating to the capability of a material to excite free electrons due to the flow of thermal energy [2]. It has the right criteria and potential to be applied for low grade waste heat recovery to improve the energy efficiency of a system. The use of TEG cells for medium grade WHR has been studied for a biomass dryer [3], automotive exhaust [4] as well as in carbonizing [5] and blast furnaces [6]. For low temperature WHR, case studies have been reported for fuel cells [7], mini fuel cell vehicles [8]-[9] and hybrid electric vehicles [10]. The uniqueness of TEG cell in encourage researchers to keep exploring the ability of the cell in different application, arrangement, and heat source. Mahdi et al. [11] tested three TEG cells to charge a 12 V battery and the system generated 12.2 W of electricity. Zhang et al. [12] integrated nanostructured TEG cells into a residential boiler system while Montecucco et al. [13] utilized the heat from stoves for continuous water heating and power supply.

The design of TEG WHR systems for specific applications is continuously studied due to the difference in waste heat grade, logistic constraints such as space, and practical limitations on the required cooling mechanisms. A TEG cell needs to be heated and cooled simultaneously on its opposite surfaces in order to create a temperature difference that leads to heat transfer through the semiconductor elements. Higher temperature difference leads to higher heat transfer and greater electrical power generation. It is

important for TEG system designs to have effective heat capture and dissipation mechanics to obtain an optimized power generation. The work of Mohamed et al. [14] on a fuel cell TEG WHR proved the higher sensitivity of power generation towards the TEG cooling rates compared to the heating rates.

To design effective TEG WHR modules, the use of heat exchangers and heat pipes has been proven to positively influence the rates of heat absorption and dissipation from the hot fluid stream towards the cooling fluid streams such as in the design for a factory oven by Remeli et al. [15] and a module for ultra-low grade WHR by Sulaiman et al. [16].

Integrating TEG cell with heat transfer devices proved to increase the efficiency of the TEG system. Zhao et al. [17] combined TEG cell with heat pipes to avoid heat loss along the pipes for high end temperature of the thermoelectric module. Makki et al. [18] showed experimentally that the use of heat pipes and heat sinks improved TEG outputs by 12.2% due to the higher rates of heat transfer across the system. Heat exchange device normally applied in TEG module designs are plate-finned heat sinks. A heat pipe is a highly conductive thermal transport device for high heat transfer rates with rapid response and to minimize the heat loss to the surrounding. The combination of TEG cells, heat pipes and heat sinks are seen as the best combination for effective heat recovery especially for low grade waste heat.

This article reports the development of a new TEG module design with a single TEG cell and another module with two TEG cells in a stacked configuration. In the stacked configuration, the TEG cells are positioned in series where the cold surface of cell number 1 is in direct contact with the hot surface of cell number 2. The electrical performance and thermal characteristics of TEG cell stacking is not widely reported, and this provides a research gap to be addressed, especially for a specific TEG module design and application. The selected case domain is the bread-baking industry where the hot gas stream temperature from the main oven is at the borderline of the low grade and medium grade waste heat (70 °C to 150 °C). Through this study, the outputs for a new TEG module design were analysed and the relative performance of TEG cells stacking was evaluated. The presented information would be useful in future TEG module designs considering multiple TEG cells configuration.

Methodology

TEG module design

A TEG module was designed for fundamental characterization study. Figure 1(a) shows the developed TEG module and Figure 1(b) provides the full dimension of the module. The base design consists of one TEG cell sandwiched between clamping plates that is connected by heat pipes to two plate-finned heat sinks. High conductivity thermal paste was used to lower the

contact resistance between the TEG cell surfaces and the clamping plate surfaces. Heat sinks were used to enhance the heat capture and dissipation across the module. One heat sink functions as a heat absorber (hot side) while the other heat sink at the opposite end functions as a heat dissipater (cold side). Each plate-finned heat sink is made of fifty-five rectangular fins with eight embedded heat pipes to transfer thermal energy effectively between the heat sinks and the clamping plates. The details of the TEG module components are listed in Table 1.

The second TEG module design incorporated two TEG cells in a stack configuration. Each cell is positioned in series stack configuration where one surface of the TEG cell is in contact with the surface of the other cell without the use of any thermal paste. The other components of the module were unchanged.

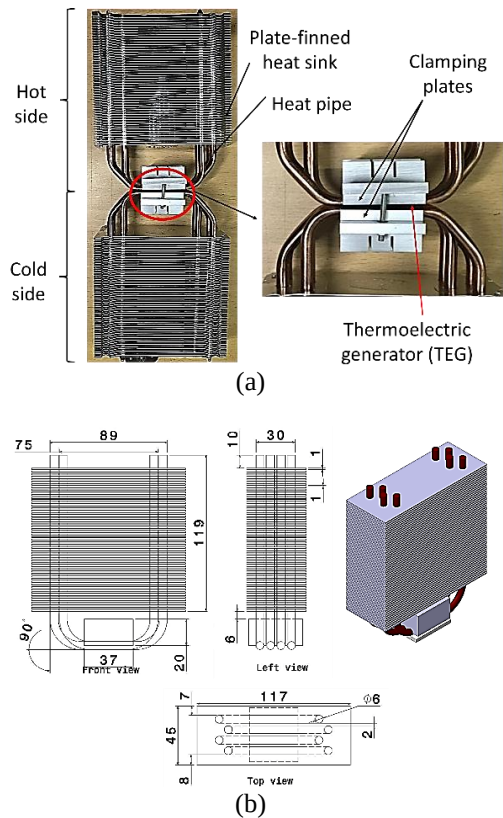


Figure 1: (a) The base TEM system design with a single TEG cell sandwiched between clamping plates and two heat sinks, (b) full dimension of the TEG module

Table 1: The component specifications of the TEG module

Component	Component	Description
Thermoelectric generator	Material	Bismuth Telluride
	Dimension	40mm x 40mm x 4mm
	Working temperature	<250°C
Heat pipe	Working fluid	Water
	Diameter/Length	6mm/148mm
Heat sink	Type	Plate-finned heat sink
	Dimension	117mm x 45mm x 1mm
	Number of fins/Gap between fins	55/1mm

Experiment setup

Figure 2 illustrates the industrial WHR process that is applied as a concept for the proposed plate-finned TEG system application. The TEG module is ideally positioned at the end of the waste heat exhaust chimney of a factory. The hot-side heat sink is exposed to the waste heat stream while the cold-side heat sink is exposed to ambient conditions. This creates a temperature difference between the TEG hot and cold sides and electricity is generated depending on the rate of conduction heat transfer across the TEG cell.

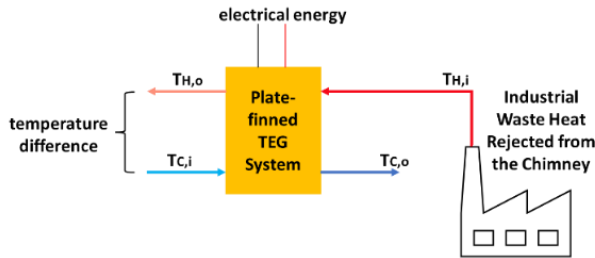


Figure 2: Concept of the TEM application for WHR from an industrial plant

A test bench was developed to replicate the industrial waste heat domain and its cooling mechanisms. Figure 3 shows the test bench design concept, adapted from the research by Remeli et al. [19]. It is fabricated by using acrylic plates with a thickness of 3 mm. The heating and cooling sections of the test bench are designed as rectangular ducts to channel and focus the flow of the hot and cold air streams across the heat sinks. The total length of the hot and cold ducting is 600 mm and 450 mm, respectively.

As shown in Figure 4, the TEG module is positioned at the test section, located at the centre of the test bench. Rubber insulators with 10 mm thickness is used to wrap the internal surface of the heating section to prevent heat loss

from the hot stream to the surrounding that would lead to a reduction in initial thermal energy availability. The TEG cell section is located externally, separated from the heating and cooling sections.

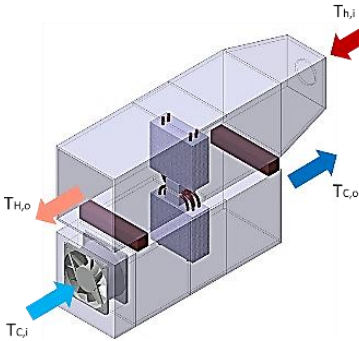


Figure 3: Plate-finned TEG system design concept

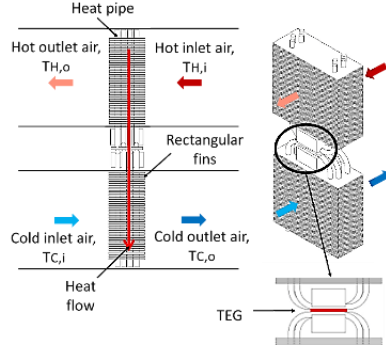


Figure 4: Process diagram of the TEG module for the experiment

In the heating section, the industrial waste heat is artificially produced by a heat gun. The heat gun allows control of the hot stream temperature and is located 35 cm (hydraulic length) from the TEG module to allow uniform flow towards the module. The test bench walls are fabricated using acrylic with a melting temperature of 130 °C. To avoid deformation, the operating temperature of the heat stream from the heat gun is limited to 100 °C. In this study, the hot stream temperature is constant at 80 °C based on the waste heat stream from the main oven of a bread-baking factory [15].

The cooling mechanism can either be influenced by forced (windy) or natural (still air) convection mechanics. Ambient air is supplied as the cooling medium for the TEG system by installing a variable-speed positive-pressure fan at the cooling section. The effects of natural convection (NC) and forced convection (FC) on the cold-side heat sinks is a test variable to compare the electrical power generation at different rates of heat dissipation. This condition replicates the possible cooling mechanics that would occur for an actual TEG module operation accounting for the changes in air stream patterns of the surrounding. The cooling temperatures are set between 22 °C to 30 °C, suitable with normal ambience temperatures during night and day. The parameters for the experiments are listed in Table 2.

Table 2: Operating parameters of the experiments

Parameter	Unit	Value
Hot air stream temperature (in), $T_{H,i}$	$^{\circ}\text{C}$	80, Re: 2827
Cold air stream temperature, $T_{C,i}$	$^{\circ}\text{C}$	22, 25 and 30
Cold inlet air velocity, v_c	m/s	0 (natural convection) 0.7 (forced convection), Re: 3712-3901
Electronic load resistance, R	Ω	0.1 - 1000

The equipment and instruments installed on the test bench are listed in . The main output to be measured are electrical power from the TEG cell and temperatures on specific positions. The electrical power is measured by using an electronic load (model BK Precision 8540DC) to obtain the output voltage and current by regulating the load resistance during the experiment. The performance tests are conducted by increasing the load resistance between $0\ \Omega$ to $1000\ \Omega$ and the output voltage and current are measured. The maximum power point (MPP) will occur when the internal resistance of the TEG cell matched the external load resistance applied [20].

Temperature measurement is needed to evaluate the heat transfer rates across the sub-components. A total of 20 K-type thermocouple wires are used to measure the hot air stream temperatures, surfaces of the rectangular fins, heat pipes, and the surfaces of the TEG cell. The thermocouple wires are connected to a 20-channel Graphtec GL840 data logger that enabled real-time temperature monitoring and recording. For the cold air stream, a hot-wire anemometer is used to measure the temperature and velocities.

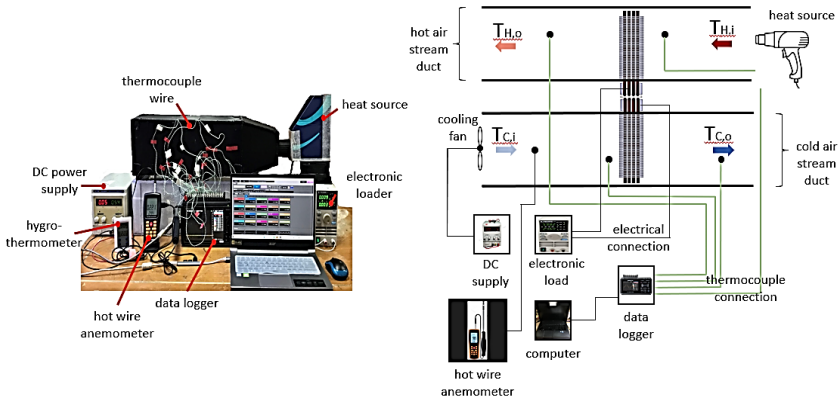


Figure 5: Experimental setup and equivalent schematic diagram of the plate-finned TEG system

Table 3: Specifications of the equipment and instruments for performance testing

Equipment and Instrument	Specifications	Descriptions/Values
Heat Gun (Heat Source)	Type	Steinel HG3000 SLE
	Temperature range	50 °C~650 °C
Data Logger	Model	Graphtec Midi Logger GL840
	Number and type of analog input channels	20 channels & multi-input type
Electronic Load	Model	BK Precision 8540DC
	Operating voltage range	0 V~60 V DC
	Operating current range	1 mA~30 A
DC Power Supply	Model	Atten APS3005D
		Regulated Power Supply
	Current range	0 A~5 A
	Voltage range	0 V~30 V
Hot Wire Anemometer	Model	Benetech Hot Wire Anemometer GM8903
	Velocity-temperature range	0 m/s~30 m/s – 0 °C~45 °C
Hygro-Thermometer	Temperature range	0 °C~50 °C (interior) & -50 °C~70 °C (exterior)
	Humidity range	20%~99%
Thermocouple Wires	Type	K-type & twin twisted
	Max operating temperature	250 °C
Thermal Paste	Type	RS 193-8248 Silicone Thermal Putty
	Thermal conductivity	3 W/mK
	Operating temperature range	-40 °C~200 °C

Electrical output analysis

The power law Equation (1) is used to obtain the power polarization of the TEG module as the circuit resistance varied where the values of current and voltage were obtained from the reading from the electronic load.

$$P = IV \quad (1)$$

where P is power in unit Watt (W), I is current in unit Ampere (A) and V is voltage in unit Volt (V).

The resistance of the TEG cell is determined from the Ohm's law Equation (2).

$$V=IR \quad (2)$$

where V is voltage in unit Volt (V), I is current in unit Ampere (A) and R is resistance in unit Ohm (Ω).

Results and Discussion

The responses of the TEG module design under different cooling conditions and configurations are discussed according to the following sequence:

1. The temperature distribution and electrical power generation characteristics,
2. The comparison of outputs between the TEG configurations.

Temperature distribution and electrical power generation characteristics

Figure 6 shows the steady-state temperature distribution across the TEG module (referring to dimensionless distance) under different cooling conditions. All cases have similar trend of temperature changes from the heat source to the cold-side heat sink. The heating air stream was at 80 °C. The hot-side heat sink and heat pipe temperatures were 79 °C and 77 °C. As heat is transferred through the components, the temperature decreased due to internal thermal resistance. The largest temperature drop was observed to be across the TEG cell while between other components, the temperature changes were small due to the effectiveness of the heat sink and heat pipes in transferring heat. Comparable behaviour can be seen from a modelling conducted by Børset et al. [21] where the higher temperature drop is beneficial for power generation. For NC cooling, the temperature difference between the TEG hot and cold surfaces is 20 °C while for FC, the difference varied between 39 °C and 45 °C depending on the cooling air stream temperature. Applying lower cooling air stream temperature enhances rapid cooling, increases the rate of heat transfer through the TEG module and creates higher temperature difference between TEG surfaces which results in higher electricity generation.

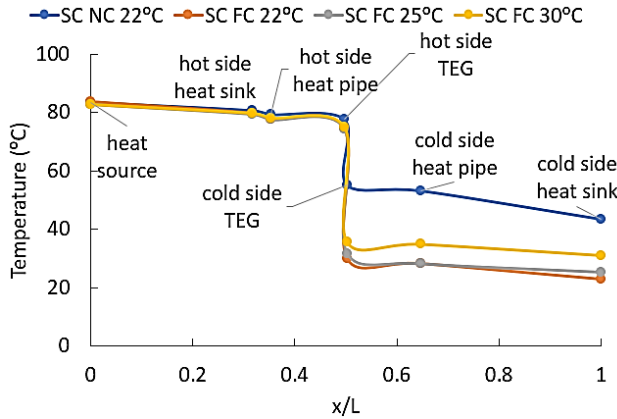


Figure 6: Dimensionless temperature profile for the TEG module design

Figure 7(a) shows the relationship between the voltage and current output from the TEG for single and double stacked TEG configuration, under various cooling conditions. The profiles show similar trend between the electrical current and voltage output produced. This behaviour satisfies the Ohm's Law that stated the current and voltage is inversely linear as external resistances are applied. Similar I-V profiles are also shown in studies conducted by Remeli et al. [15] and Wan et al. [22]. Figure 7(b) shows the electrical power output profiles from the TEG calculated from Equation (2). The parabolic profiles reveal that the cooling condition applied to the system have a strong impact on the performance. The peak of the P-V curve shows the maximum power point (MPP) generated which ranges between 10 mW to 153 mW. MPP is achieved when the external load applied equals the internal resistance of the TEG cell and delivers the highest electrical power.

NC cooling generated the lowest electrical power, a 10 mW output for single TEG and 35 mW for double stacked TEG configuration. FC cooling method clearly increased the generated electrical power from the TEG for both single and double stacked TEG configuration. FC cooling increased the rate of heat dissipation from the heat sink and created a higher temperature difference at the TEG cold surface. Lower cooling air stream temperature also created higher temperature difference at the TEG surfaces, leading to greater power outputs.

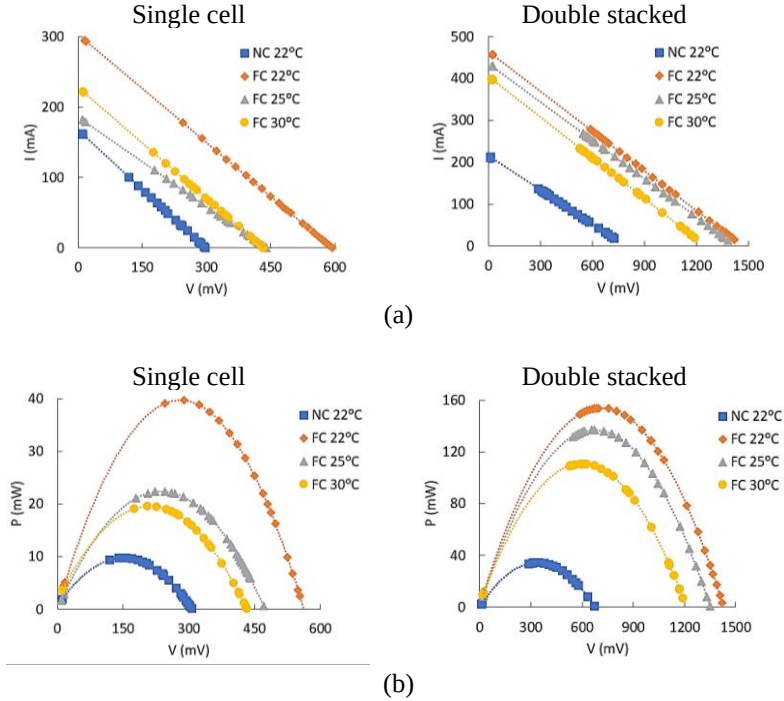


Figure 7: (a) Current-voltage characteristics, (b) Power output profile, of the TEG module design for single and double stacked TEG cell under various cooling conditions

Figure 8 displays the power output from the TEG module relative to the applied resistance. The single TEG cell configuration gives a response when the resistance reached 1.5Ω . However, the response for double stacked TEG configuration only occurred at 2.2Ω for NC and 2.1Ω for FC. For the single cell, the suitable resistance range for the TEG module is between 1.5Ω and 3Ω while for the double stacked cell, it is between 2Ω and 3.5Ω . Applying resistance beyond this range causes power loss and lower MPP.

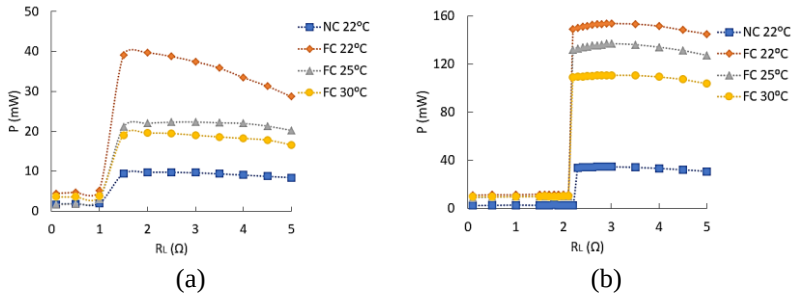


Figure 8: Power-resistance characteristics for (a) single cell TEG, (b) double stacked TEG

Comparison of MPP

Figure 9 compares MPP between the single and double stacked TEG configurations under different cooling conditions. Across all cooling air stream temperature, double stacked TEG configurations generated higher electrical output compared to single cell. Under NC, the MPP was 10 mW for a single TEG and 34 mW for double stacked TEG. Significant increases in MPP, at approximately 250%, are shown as FC cooling are applied to both cell configurations. Higher MPP was also generated with lower cooling air stream temperature. This is due to higher rates of heat transfer that caused higher temperature difference between the TEG surfaces.

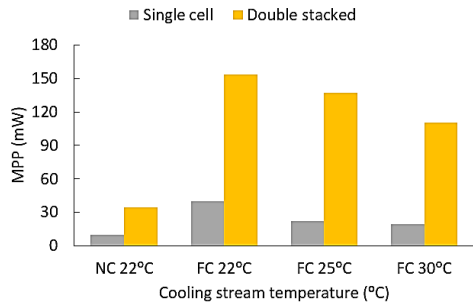


Figure 9: MPP comparison between single cell and double cell TEG configurations

The TEG cell reached MPP at different voltages (V_{MPP}). As shown in Figure 10(a), V_{MPP} is higher as double stacked TEG is applied and lower cooling air stream temperature is set. For NC, V_{MPP} is between 160 mV and 335 mV and V_{MPP} is higher with double stacked configuration. Under FC cooling method, the effect of double stacked TEG also depends on the cooling air temperature applied. The highest V_{MPP} produced is 700 mV, with double

stacked TEG cells and lowest cooling air stream temperature. The electrical power responses are obtained by varying the external load (RL) applied to the TEG cell. The resistances where MPP occurred for every case is found to be in a small range of values, as provided in Figure 10(b). Overall, the R_{MPP} is between $2\ \Omega$ to $3\ \Omega$ and the TEG cell is able to produce electrical output at a constant range of external load.

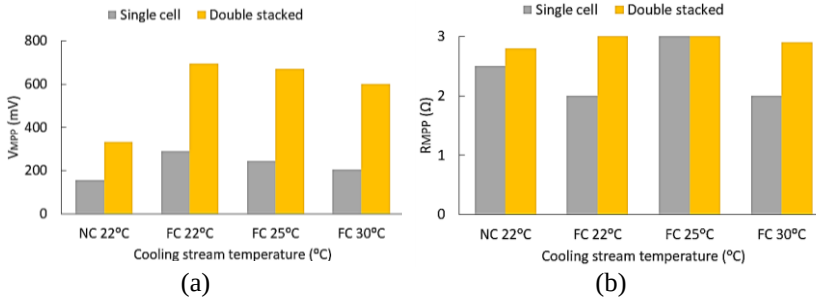


Figure 10: (a) V_{MPP} and (b) R_{MPP} comparison between single and double stacked TEG configurations

Figure 11 displays the MPP difference as cooling air stream temperature is varied for both single and double stacked TEG configurations. Both configurations show a decreasing MPP trend as the applied cooling air temperature increased. From single TEG configuration responses, the MPP shows a decrement of 2.5mW for every 1°C temperature drop. For double stacked TEG cases, the decrement is 5mW. Hence, even though the double stacked TEG generated higher MPP from the TEG module design, the configuration is more sensitive towards cooling air stream temperature changes.

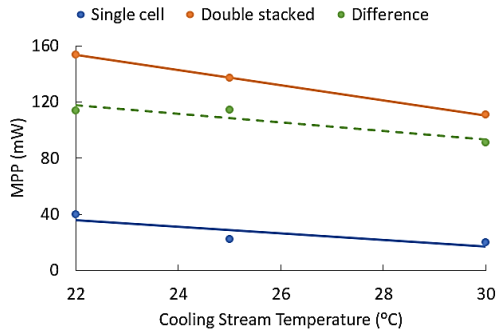


Figure 11: Difference between MPP for various cooling air stream temperature for single and double stacked TEG configurations

Conclusion

The development of a new TEG module design is an effort in recovering industrial waste heat for electrical power generation. The performance evaluation was performed for single and double stacked TEG configurations under different cooling method and condition. The module has a high potential in recovering industrial waste heat, depending on the TEG cell configurations, and supplied cooling air stream temperature. The module successfully generated the highest MPP of 153 mW at 245 mA, 694 mV and 3 Ω . These were achieved with double stacked TEG configuration, when the waste heat was at a constant temperature of 80 °C, and forced convection cooling at 22 °C.

From the analysis, few important observations were found:

1. The MPP is highly dependent on the cooling method and condition. Forced convection cooling with lower cooling air stream temperature significantly improved the MPP as it enhanced the heat transfer through the TEG module.
2. Stacking the TEG cells with series connection gives the TEG module higher potential in generating electrical power due to higher heat transfer across the TEG.
3. Even though double stacked TEG produced higher electrical output, the application was more sensitive towards changes in cooling air stream temperature.
4. Considering the effect of TEG configuration and cooling air stream temperatures, the optimum range of load resistance to achieve MPP is between 2 Ω and 3.5 Ω .

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