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Design and Laboratory Study of a Five-layer Thermoelectric Power Generator

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ABSTRACT

The application of low enthalpy thermal resources, especially power generation, has been one of the hot research areas in recent years. Most of the current commercialized thermal, including geothermal, power-generation technologies convert thermal energy to electric energy indirectly, that is, making mechanical work before producing electricity. Technology using thermoelectric generators (TEG), however, can transform thermal energy into electricity directly by using the Seebeck effect. TEG technology has many advantages such as compactness, quietness, and reliability because there are no moving parts. One of the great challenges for TEG to be used for power generation is large-scale utilization. It is difficult to manufacture a TEG system even at the scale of a few kilowatts (kW). To this end, we have designed a five-layer TEG apparatus that can be installed with modularized units. Such a system with a layered structure could be expanded in power, something similar to solar Photovoltaics (PV). In this study, laboratory experiments were conducted to measure the power output at different flow rates of water, different temperature, and different temperature differences between hot and cold sides. The five-layer TEG device could generate about 45.7 W electricity with a temperature difference of 72.2°C between cold and hot sides. The power of each module was about 0.51 W at this temperature difference. The experimental data can be applied to the design of commercial TEG systems.

1. Introduction

Utilization of geothermal energy is one of the solutions to reduce CO_2 and other greenhouse gas emissions. Thermoelectric generator (TEG) technologies can produce power without turbines or other moving parts. Because of these characteristics, TEG may make small-scale production and geothermally-sourced micro power grids both practical and affordable. Small (<5 MW) geothermal projects could provide consumers with the same distributed power flexibility provided by solar and wind production with the additional benefit of being a more reliable baseload source of electricity without intermittency. TEG technologies can also allow geothermal heat to provide balancing and grid support as well as using the earth's heat for storage.

While most storage technologies require power from the grid to charge, TEG power uses the stored heat in rock at depth and is thus independent of grid power. This not only means added flexibility, but also enables operation of geothermal-TEG to supply another major market segment: off-grid or island power. Communities in remote areas or areas with interruptible connection to the grid can benefit from the ability of geothermal-TEG to supply power on demand, dropping down to baseload at night and then ramping up to supply peak power when needed.

Attention has been paid to the application of low temperature thermal resources for power generation. Most of the current commercialized thermal, including geothermal, power-generation technologies convert thermal energy to electric energy indirectly, that is, making mechanical work before producing electricity. Technology using TEG, however, can transform thermal energy into electricity directly by using the Seebeck effect. This is because thermoelectric materials (TEM) are solid-state energy objects that combine thermal, electrical, and semiconducting properties simultaneously. TEG technology has many advantages such as compactness, quietness, and reliability because there are no moving parts.

A TEG module is usually constructed of many (usually 127 pair for a 4x4 cm size) p- and n-type thermoelectric legs fastened between two ceramic plates. A voltage is induced because of the Seebeck effect when a temperature gradient is applied over the two ceramic plates and across the p- and n-type legs. There have been many studies, both numerical and experimental, on TEGs (for example, Goldsmid and Nolas, 2001; Crane and Jackson, 2004; Maneewan and Chinadaruksa, 2009; Bélanger and Gosselin, 2011; Casano and Piva, 2011; Demir and Dincer, 2017; Twaha et al., 2017). The effects of the TEG dimensions and flow characteristics on the thermal conversion efficiency have been investigated by many researchers (for example, Yu and Zhao, 2007; Suter et al, 2012; Wang et al, 2014; Liu et al, 2014; Chen, et al., 2017).

One of the problems yet to be solved for TEG electricity systems is the expandability to large power capacity. In order to find a solution to this problem, in this project a five-layer TEG laboratory apparatus for electricity generation has been designed, built, tested, and optimized. The TEG system was designed such that it could be expandable in the number of layers while the temperature gradient across each layer (from inlet to the outlet) remains nearly constant. Using this device, laboratory experiments were conducted to measure the voltage and the power output at different flow rates of water, different temperature, and different temperature differences between the hot and cold sides.

2. Experimental

According to our review and analysis on some of the existing TEG technologies, we designed a lab-scale TEG apparatus. The process diagram is shown in Figure 1. The TEG power generator is composed of three parts: 1) heat sources, 2) TEG modules and assembly, and 3) cold sink. Water served as the heat transfer fluid in this study.

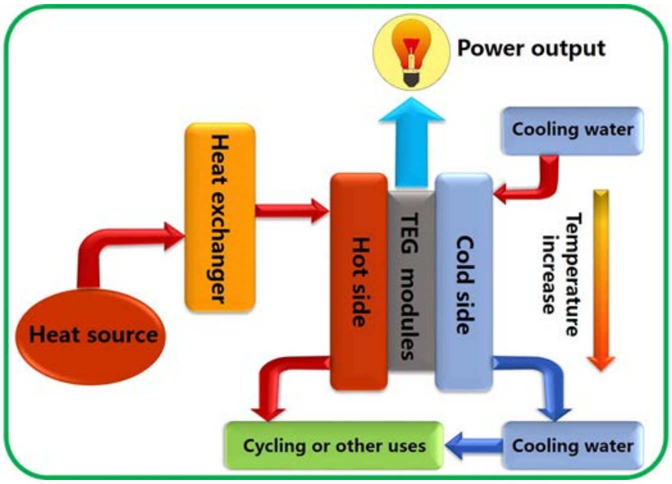

Figure 1: The process diagram of the lab-scale thermoelectric power generation system

The schematic of the lab-scale TEG apparatus is shown in Figure 2. The hot water was provided by an electric heater. The TEG modules were placed in between hot and cold sides in containers with hot and cold water. The temperature values at the inlet and outlet of the cold and hot sinks were measured. The power output of the TEG apparatus and its change with temperature differential and flow rate were also measured. All of the experimental data were sampled using LabView data acquisition hardware and software.

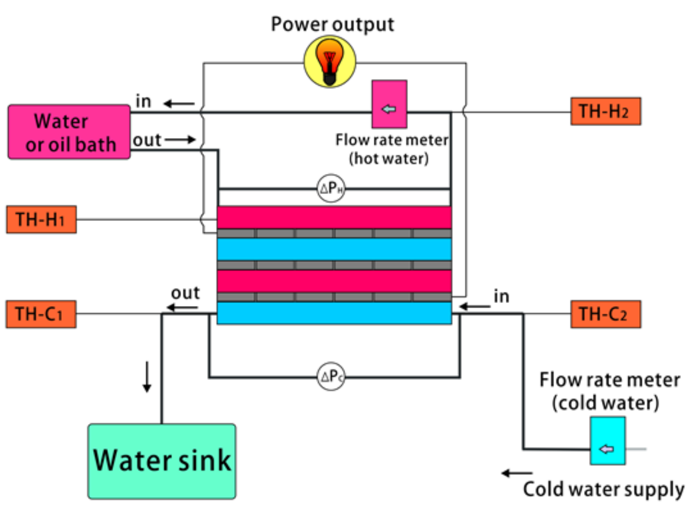

Figure 2: The schematic of the lab-scale thermoelectric power generation system.

It is usually necessary to test a single TEG module before assembling for quality check and other purposes. A schematic of the single TEG module test apparatus is shown in Figure 3.

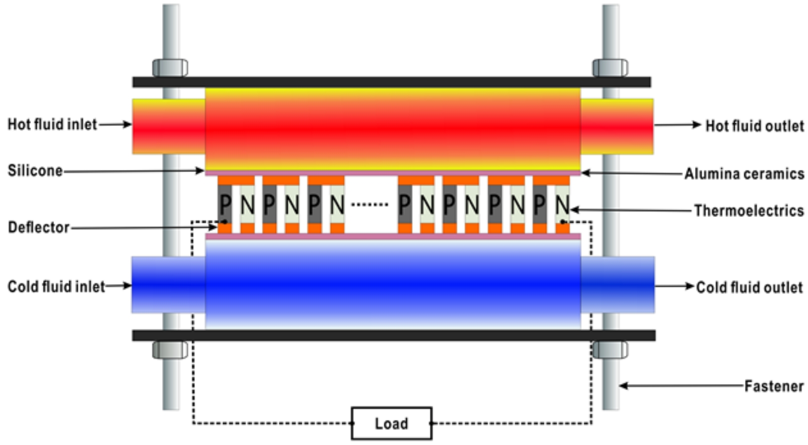

Figure 3: The schematic of single TEG module test (Chen et al., 2017).

One of the challenges for TEG to be used for power generation is large-scale utilization, even at the scale of kW. To this end, we designed a TEG system that can be installed with modularized units and expanded in power, something similar to solar PV. Such a system was constructed as a layered structure, expandable by adding more layers. We built a five-layer TEG apparatus, as shown in Figure 4. Ninety TEG modules with a size of 4x4 cm were assembled in the five-layer TEG lab apparatus (see Figure 4). Each layer had 18 TEG modules.

Figure 4: Photo of the lab-scale thermoelectric power generation system.

3. Results

We measured the voltage and power output of the five-layer TEG lab apparatus at different temperatures and flow rates. The results are listed and discussed in the following sections.

3.1 Effect of Temperature Difference

The voltages and power outputs of each layer of the five-layer TEG apparatus, measured at different temperatures and flow rates, are shown in Figure 5. Voltage and power increased linearly with temperature difference, which is consistent with the observation reported by Chen et al. (2017). Note that the water flow rate on the cold and hot sides were 103.9 and 205.7 L/hour, respectively. The linear phenomenon is interesting and may be used to predict the power output at higher temperatures.

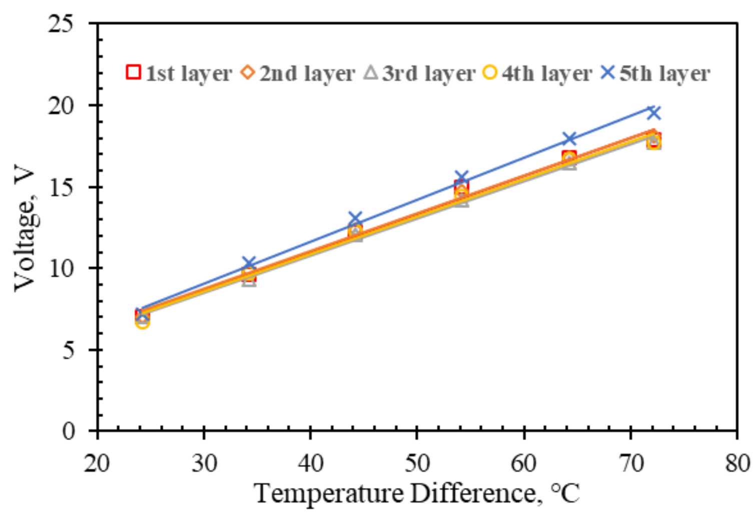

Figure 5: Voltage of each layer of the five-layer TEG lab apparatus at different temperature difference (water flow rates on the cold and hot sides were 103.9 and 205.7 L/hour respectively).

Another interesting observation is that the voltage and power of each layer of the five-layer TEG apparatus are close to each other, especially layer one to layer four. This implies that the heat transfer rates on different layers are almost the same, which makes the delivering of the electricity to the load easier, more uniform, and more stable.

The voltages and the power outputs of the entire five-layer TEG apparatus are shown in Figures 7 and 8, respectively. The water flow rates on the cold and hot sides were 654.55 and 1028.57 L/hour. The five-layer TEG device could generate about 45.7 W with a temperature difference of 72.2^{o}C between the cold and hot sides. The power of each module was about 0.51 W at this temperature difference.

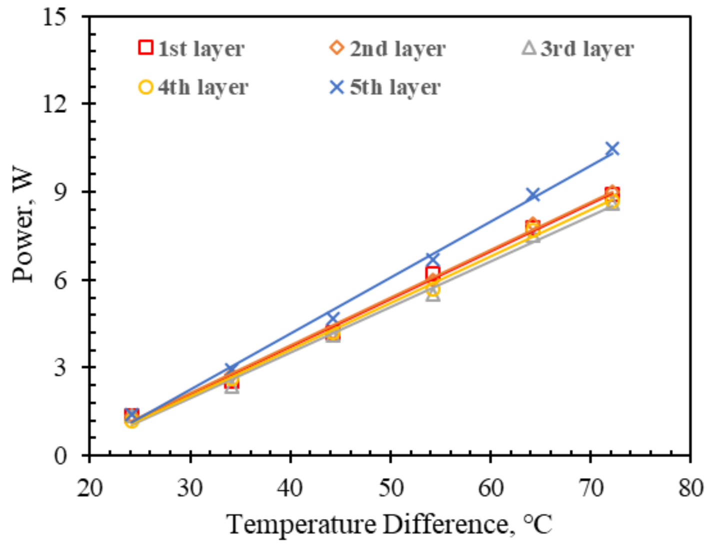

Figure 6: Power of each layer of the five-layer TEG apparatus at different temperature difference (water flow rates on the cold and hot sides were 103.9 and 205.7 L/hour, respectively).

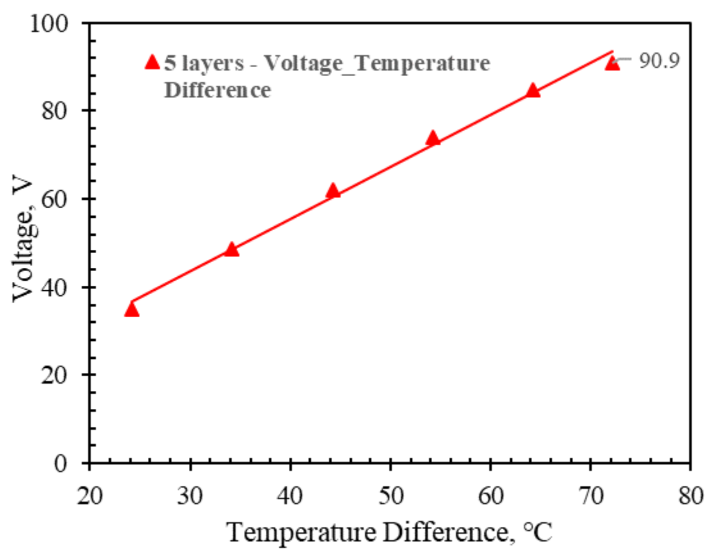

Figure 7: Voltage of the five-layer TEG apparatus at different temperature difference (water flow rates on the cold and hot sides were 654.55 and 1028.57 L/hour, respectively).

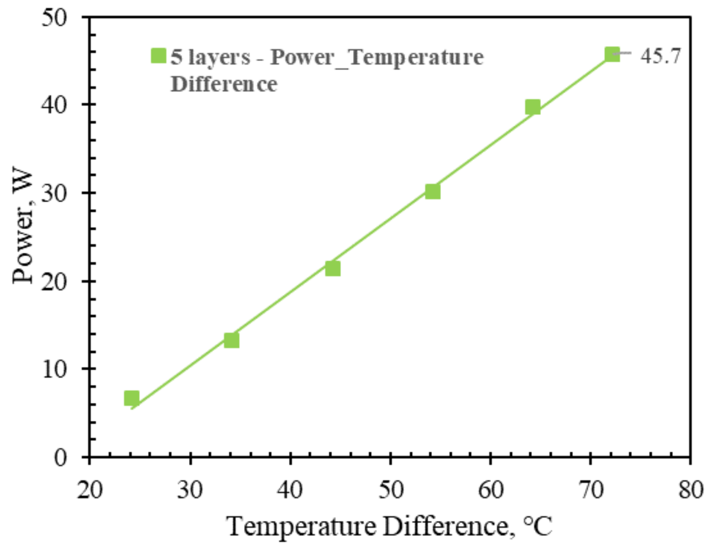

Figure 8: Power of the five-layer TEG apparatus at different temperature difference (water flow rate on the cold and hot sides were 654.55 and 1028.57 L/hour, respectively).

3. 2 Effect of Flow Rate

3.2.1 Voltage and Power Output at Different Flow Rates of Water on the Cold Side When Water Flow Rate on the Hot Side is Constant

Using the five-layer TEG apparatus, we measured the voltage and power output at different flow rates of water on the cold side of the TEG apparatus when water flow rate on the hot side is constant. The data are plotted in Figures 9 and 10 respectively.

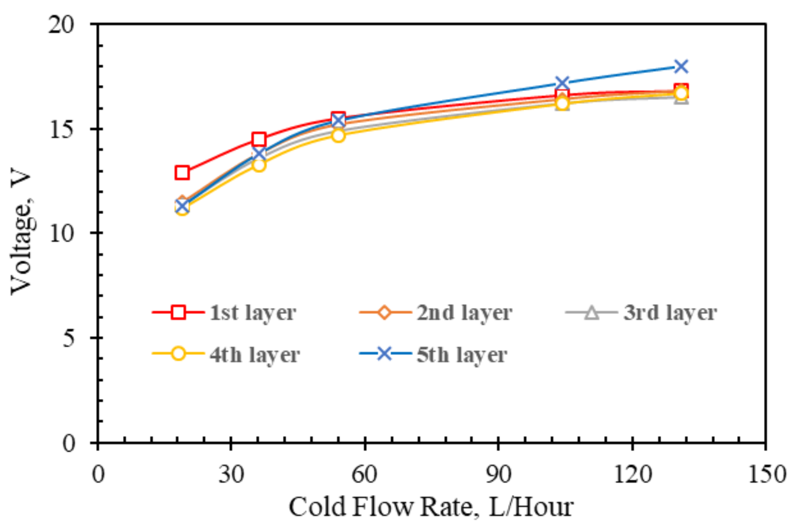

Figure 9: Voltage of each layer of the five-layer TEG lab apparatus at different flow rates on the cold side (water flow rate on the hot side was 133.33 L/hour and temperature difference between cold and hot sides was 64.2°C).

The water flow rate on the hot side was 666.67 L/hour and was kept constant. The temperature difference between cold and hot sides was 64.2°C and was kept constant.

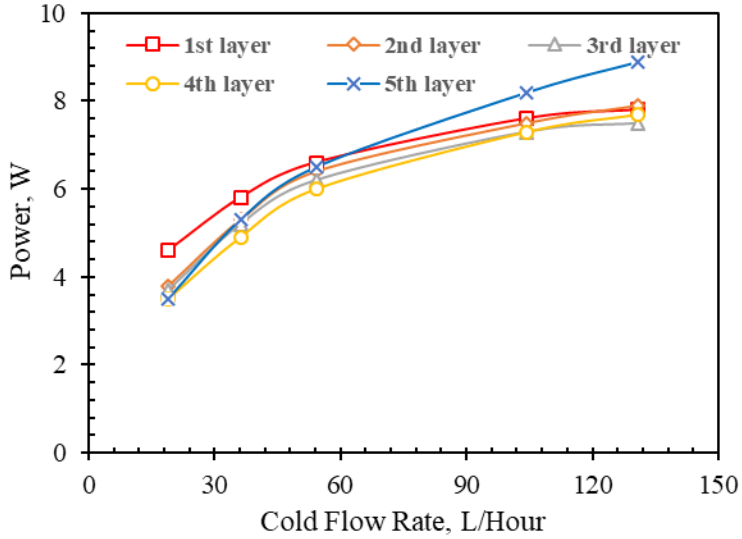

Figure 10: Power of each layer of the five-layer TEG lab apparatus at different flow rates on the cold side (water flow rate on the hot side was 133.33 L/hour and temperature difference between cold and hot sides was 64.2°C).

When water flow rate on the hot side was constant (666.67 L/hour) and the temperature difference between cold and hot sides was kept at 64.2oC), the voltage and the power output of the entire five-layer TEG apparatus at different rates on the cold side varied as shown in Figures 11 and 12, respectively. The five-layer TEG device could generate about 39.8 W at this temperature difference between cold and hot sides.

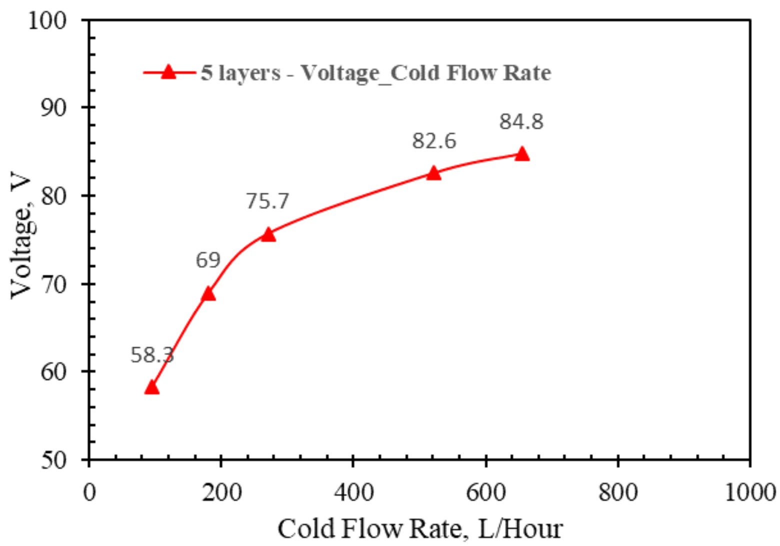

Figure 11: Voltage at different flow rates of water on the cold side of the five-layer TEG apparatus when water flow rate on the hot side is constant (water flow rate on the hot side was 666.67 L/hour and temperature difference between cold and hot sides was 64.2°C).

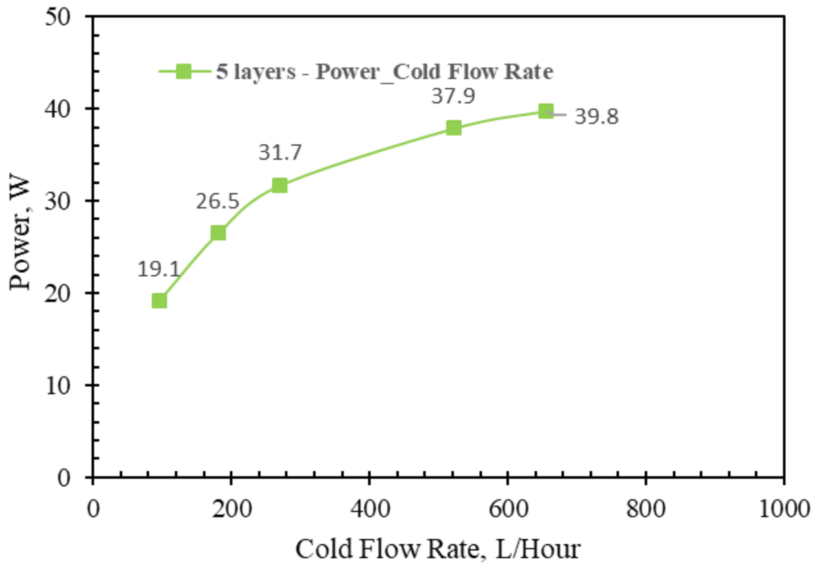

Figure 12: Power output at different flow rates of water on the cold side of the five-layer TEG apparatus when water flow rate on the hot side is constant (water flow rate on the hot side was 666.67 L/hour and temperature difference between cold and hot sides was 64.2^{o}C).

One can see from Figures 11 and 12 that the voltage could reach as high as 84.8 V. Both the voltage and power output increase with the flow rate of water on the cold side. The effect of flow rate is very significant, which is reasonable. This is because the higher the flow rate, the faster the heat transfer between liquid and TEG modules.

3.2.2 Voltage and Power Output at Different Flow Rates of Water on the Hot Side When Water Flow Rate on the Cold Side is Constant

We also measured the voltage and power output at different flow rates of water on the hot side of the TEG apparatus when water flow rate on the cold side was held constant. The data of each layer are plotted in Figures 13 and 14. The results demonstrate that both the voltage and power output increase with the flow rate of water on the hot side, which follows the same trend for the effect of flow rate on the cold side, as shown in Figures 9 and 10. Note that the water flow rate on the cold side was 130.91 L/hour for each layer and was kept constant. The temperature difference between cold and hot sides was 64.2^{o}C and was kept constant.

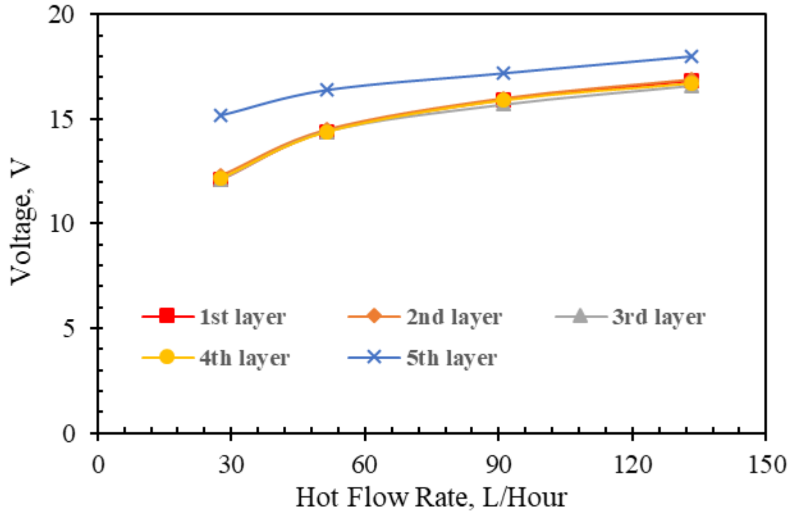

Figure 13: Voltage of each layer of the five-layer TEG apparatus at different flow rates on the hot side (water flow rate on the cold side was 130.91 L/hour and temperature difference between cold and hot sides was 64.2^{o}C).

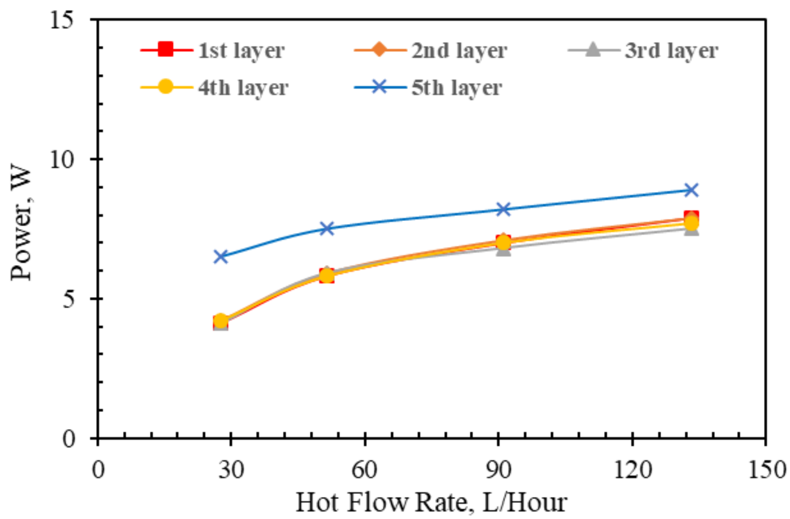

Figure 14: Power of each layer of the five-layer TEG apparatus at different flow rates on the hot side (water flow rate on the cold side was 130.91 L/hour and temperature difference between cold and hot sides was 64.2^{o}C).

When the water flow rate on the cold side and the temperature difference were kept constant at 654.55 L/hour and 64.2°C, respectively, the voltage and the power output of the entire five-layer TEG apparatus varied as shown in Figures 15 and 16. The results demonstrate that both the voltage and power output increase with the flow rate of water on the hot side. Note that the water flow rate on the cold side was 654.55 L/hour and was kept constant. The temperature difference between cold and hot sides was equal to 64.2°C and was kept constant.

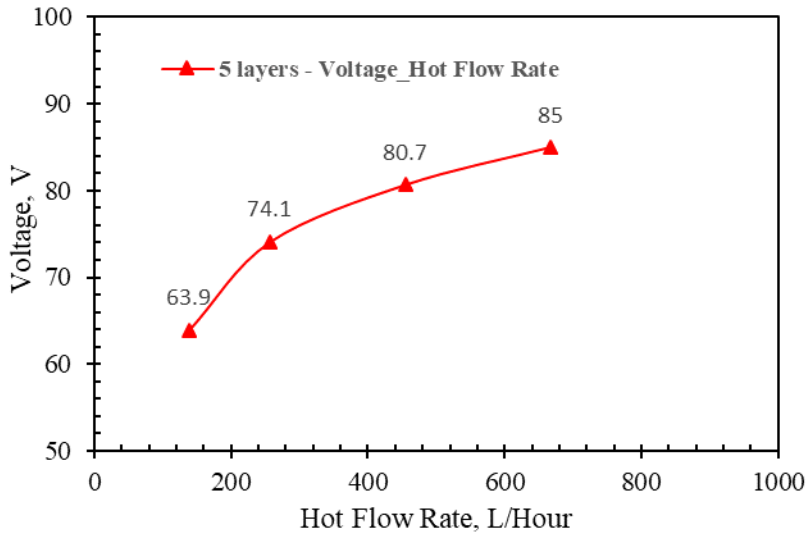

Figure 15: Voltage at different flow rates of water on the hot side of the five-layer TEG apparatus when water flow rate on the cold side is constant (water flow rate on the cold side was 654.55 L/hour and temperature difference between cold and hot sides was 64.2°C).

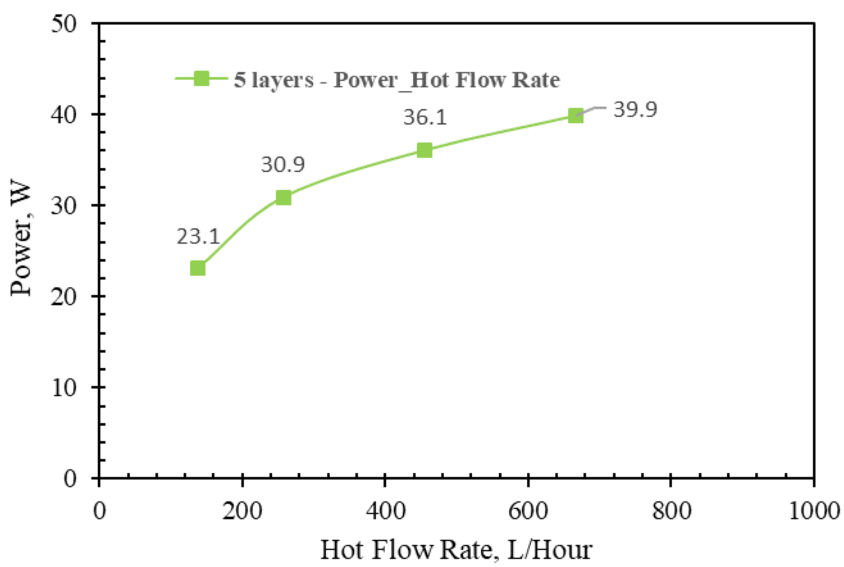

Figure 16: Power output at different flow rates of water on the hot side of the five-layer TEG apparatus when water flow rate on the cold side is constant (water flow rate on the cold side was 654.55 L/hour and temperature difference between cold and hot sides was 64.2°C).

Because 90 TEG modules have been assembled in the five-layer TEG lab apparatus, the power of each module was about 0.45W at a temperature difference between cold and hot sides of 64.2^oC.

4. Conclusions

According to our experimental results, the following conclusions were reached:

(1) The five-layer TEG device designed and built in this study could generate about 45.7 W with a temperature difference of 72.2oC between cold and hot sides. The power of each module was about 0.51 W at this temperature difference.

(2) The voltage and power output of each layer is almost the same, which makes the delivering of the electricity to the load easier, more uniform, and more stable.

(3) The effects of flow rate, temperature, and temperature difference between hot and cold sides on the voltage and power output have been investigated experimentally. The voltage and power increase with temperature difference almost linearly. The voltage and power also increase with the water flow rate on both cold and hot sides, but not linearly.

Acknowledgement

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REFERENCES

Bélanger, S., Gosselin, L. “Thermoelectric generator sandwiched in a crossflow heat exchanger with optimal connectivity between modules.” *Energy Conversion & Management*, 52, (2011), 2911-2918.

Casano, G., Piva, S. “Experimental investigation of the performance of a thermoelectric generator based on Peltier cells.” *Experimental Thermal & Fluid Science*, 35, (2011), 660-66.

Chen, J., Li, K., Liu, C., Li, M., Lv, Y., Jia, L., & Jiang, S. (2017). Enhanced efficiency of thermoelectric generator by optimizing mechanical and electrical structures. *Energies*, 10(9), 1329.

Crane, D.T., Jackson, G.S. “Optimization of cross flow heat exchangers for thermoelectric waste heat recovery.” *Energy Conversion & Management*, 45, (2004), 1565-1582.

Demir, M. E., & Dincer, I. (2017). Performance assessment of a thermoelectric generator applied to exhaust waste heat recovery. *Applied Thermal Engineering*, 120, 694-707.

Goldsmid, H. J., & Nolas, G. S. (2001). A review of the new thermoelectric materials. *In Thermoelectrics*, 2001. *Proceedings ICT* 2001. *XX International Conference* on (pp. 1-6). IEEE.

Liu, C., Chen, P., and Li, K. “A 500W low-temperature thermoelectric generator: Design and experimental study.” *International Journal of Hydrogen Energy*, 39, (2014), 15497-15505.

Maneewan, S., & Chindaruksa, S. (2009). Thermoelectric power generation system using waste heat from biomass drying. *Journal of electronic materials*, 38(7), 974-980.

Suter, C., Jovanovic, Z. R., & Steinfeld, A. (2012). A 1 kWe thermoelectric stack for geothermal power generation–Modeling and geometrical optimization. *Applied energy*, 99, 379-385.

Twaha, S., Zhu, J., Yan, Y., Li, B., & Huang, K. (2017). Performance analysis of thermoelectric generator using dc-dc converter with incremental conductance based maximum power point tracking. *Energy for Sustainable Development*, 37, 86-98.

Wang, T., Luan, W., Wang, W., & Tu, S. T. (2014). Waste heat recovery through plate heat exchanger based thermoelectric generator system. *Applied Energy*, 136, 860-865.

Yu, J., Zhao, H. "A numerical model for thermoelectric generator with the parallel-plate heat exchanger." *Journal of Power Sources*, 172, (2007), 428-434.