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Laboratory and Field Tests of Thermoelectric Generators for Power Generation under Different Conditions

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ABSTRACT

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 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. Finally we tested the TEG apparatus at a geothermal well.

1. INTRODUCTION

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 power microgrids 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 can use 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. To make use of geothermal energy and other low-grade energy sources, many have carried out a series of studies on thermoelectric generation (Liu, et al., 2014; Erkan, et al., 2007). Technology using TEG can transform thermal energy into electricity directly by using the Seebeck effect. 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 due to the Seebeck effect when a temperature gradient is applied across the two ceramic plates and across the p- and n-type legs.

There have been many studies, both numerical and experimental, on TEGs (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). Suter, et al. (2012) made a numerical simulation of a 1KW thermoelectric module, and discussed the effect of different factors on TEG power output. Liu, et al. (2014) designed a thermoelectric generation system and conducted an experimental study. It was found that the power could reach 500 W at the temperature difference of 200°C.

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 was 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 the same. 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. EXPERIMENTS

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 source, 2) TEG modules and assembly, and 3) cold sink. Water served as the heat transfer fluid in this study.

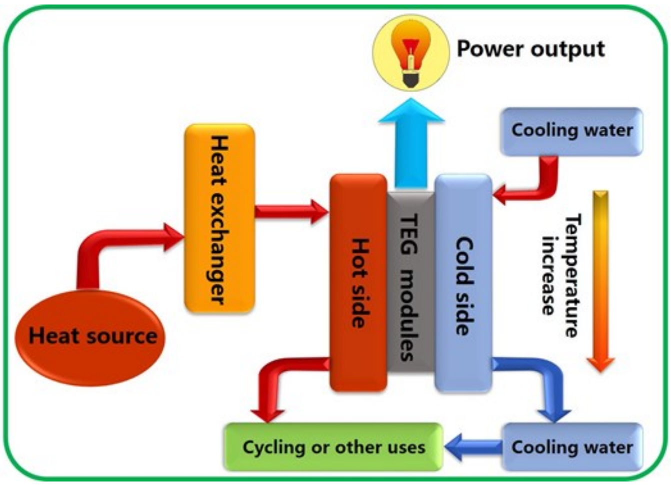

Figure 1: The process diagram of the lab-scale thermoelectric power generation system.

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.

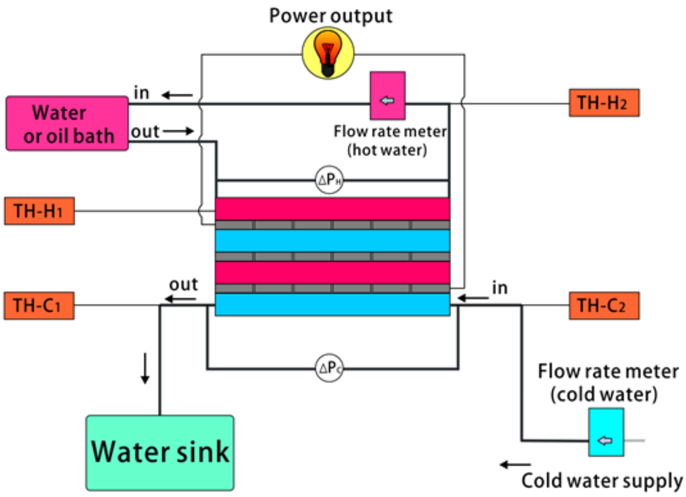

Figure 2: The schematic of the lab-scale thermoelectric power generation system.

It is usually useful 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.

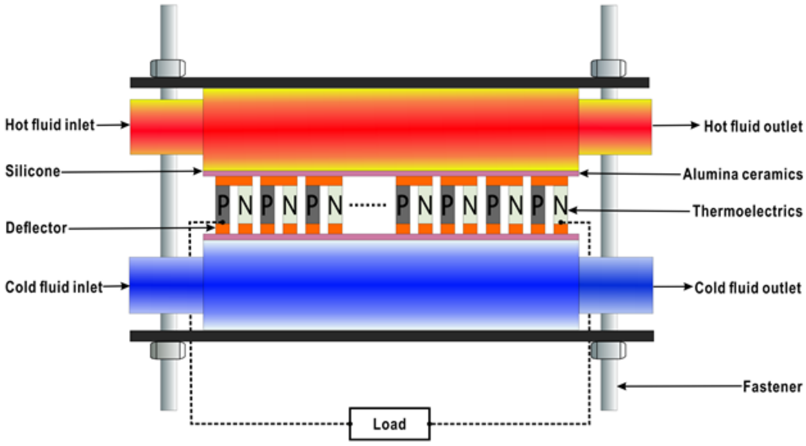

Figure 3: The schematic of single TEG module test (Chen et al., 2017).

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. 90 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.

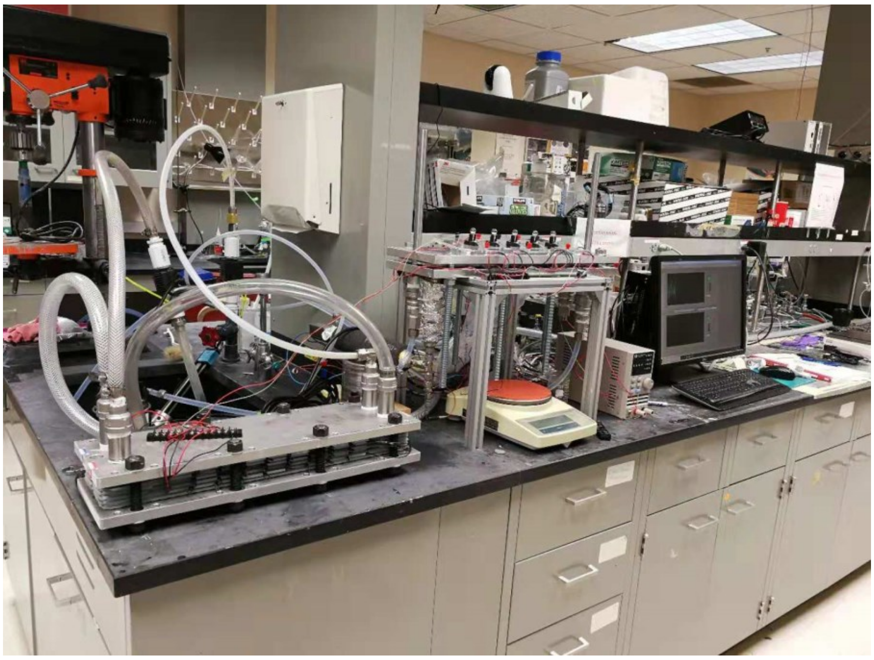

Figure 4: Photo of the lab-scale thermoelectric power generation system.

3. LABORATORY 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.

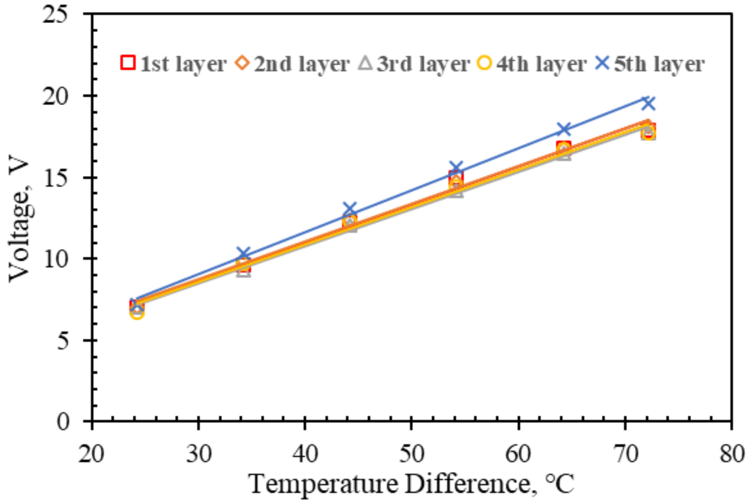

Figure 5: Voltage of each layer of the five-layer TEG lab apparatus at different temperature difference (water flow rates on the cold and hot sides were 103.9 and 205.7 L/hour respectively).

Another interesting observation is that the voltages and power outputs 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.

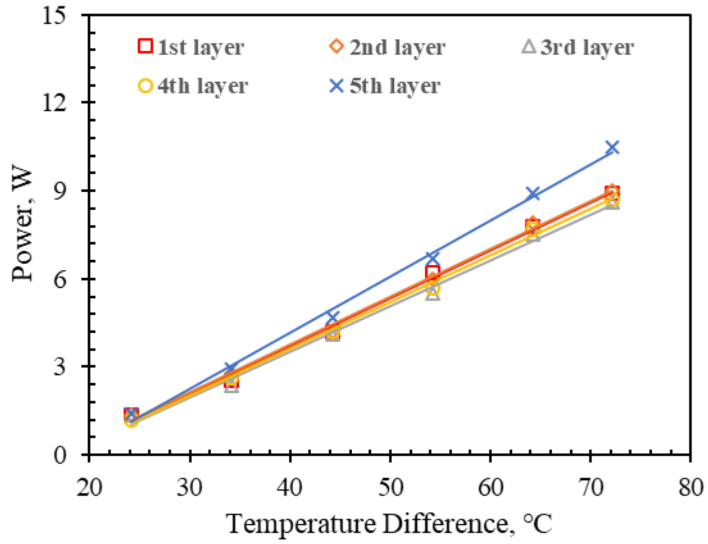

Figure 6: Power of each layer of the five-layer TEG apparatus at different temperature difference (water flow rates on the cold and hot sides were 103.9 and 205.7 L/hour, respectively).

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 72.2ºC between the cold and hot sides. The power of each module was about 0.51 W at this temperature difference.

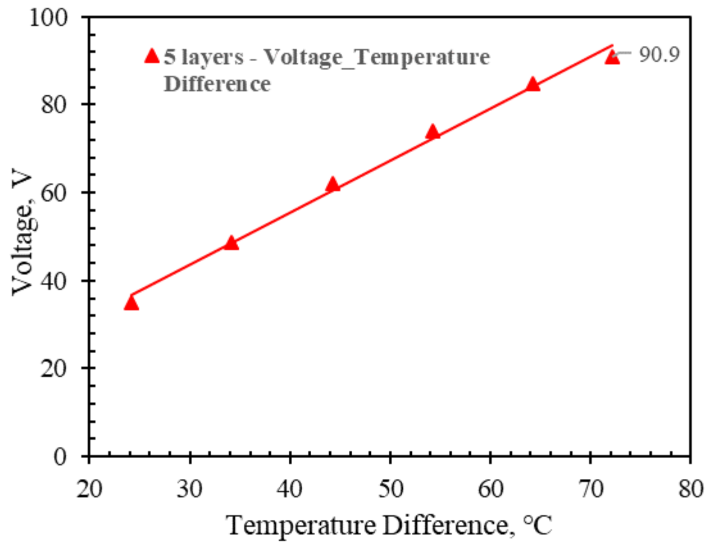

Figure 7: Voltage of the five-layer TEG apparatus at different temperature difference (water flow rates on the cold and hot sides were 654.55 and 1028.57 L/hour, respectively).

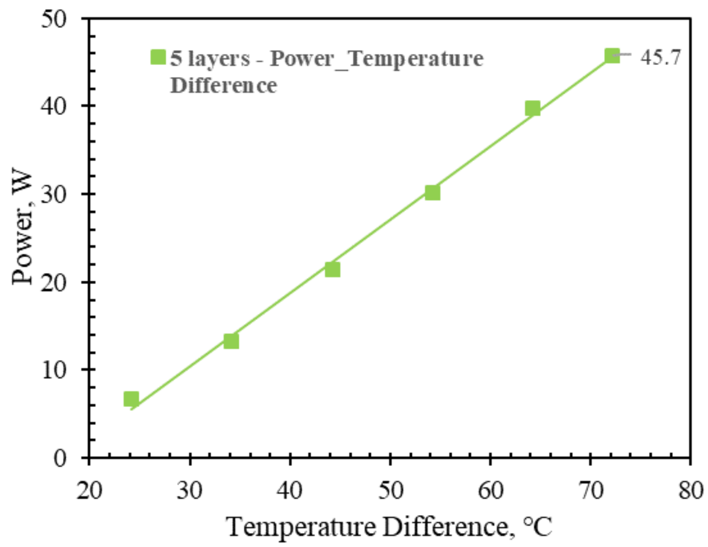

Figure 8: Power of the five-layer TEG apparatus at different temperature difference (water flow rate on the cold and hot sides were 654.55 and 1028.57 L/hour, respectively).

3. 2 Effect of Flow Rate

<u>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</u>

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

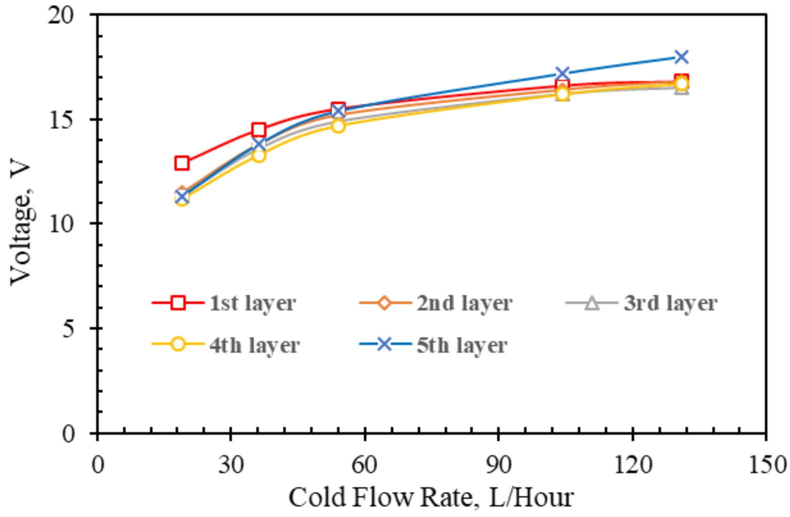

Figure 9: Voltage of each layer of the five-layer TEG lab apparatus at different flow rates on the cold side (water flow rate on the hot side was 133.33 L/hour and temperature difference between cold and hot sides was 64.2oC).

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^{o}C and was kept constant.

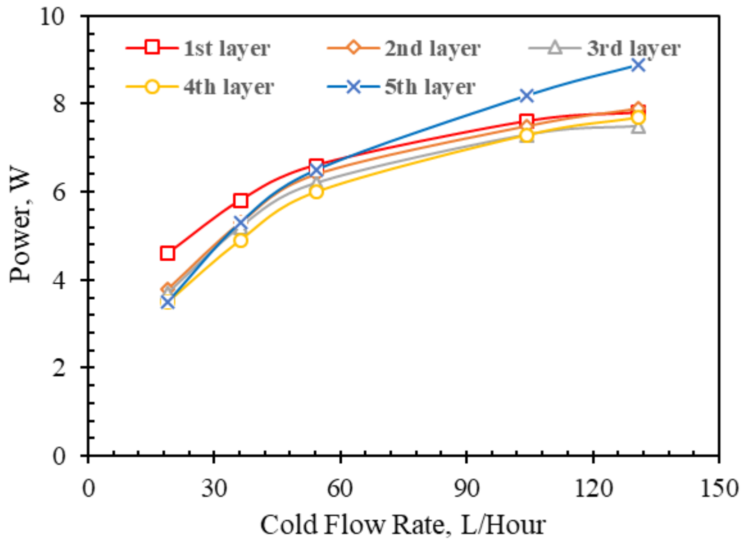

Figure 10: Power of each layer of the five-layer TEG lab apparatus at different flow rates on the cold side (water flow rate on the hot side was 133.33 L/hour and temperature difference between cold and hot sides was 64.2^{o}C).

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 64.2 ^{o}C), 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.

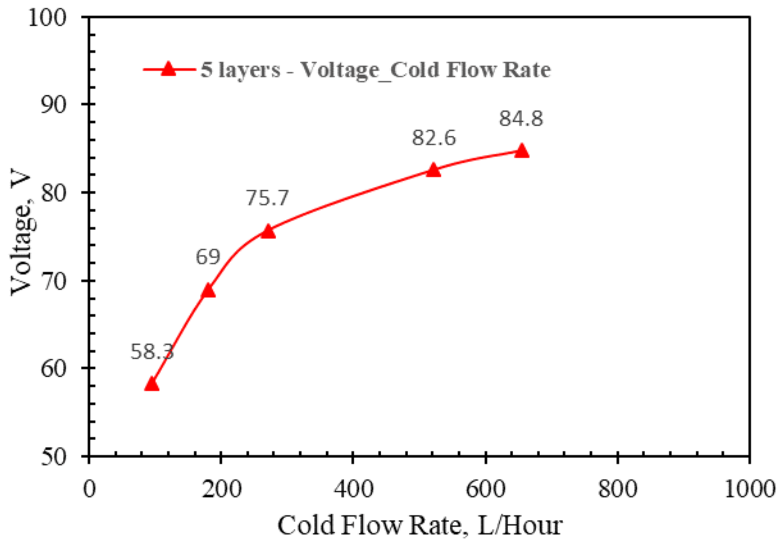

Figure 11: Voltage at different flow rates of water on the cold side of the five-layer TEG apparatus when water flow rate on the hot side is constant (water flow rate on the hot side was 666.67 L/hour and temperature difference between cold and hot sides was 64.2°C).

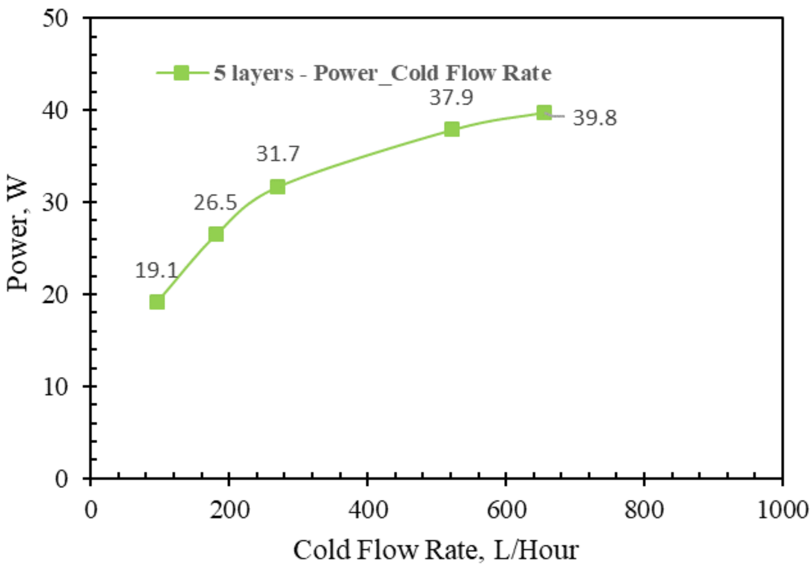

Figure 12: Power output at different flow rates of water on the cold side of the five-layer TEG apparatus when water flow rate on the hot side is constant (water flow rate on the hot side was 666.67 L/hour and temperature difference between cold and hot sides was 64.2°C).

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.

<u>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</u>

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°C and was kept constant.

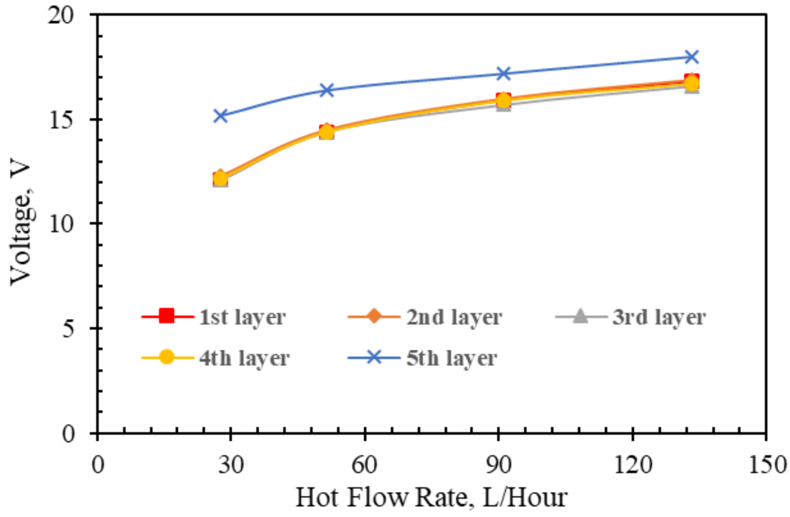

Figure 13: Voltage of each layer of the five-layer TEG apparatus at different flow rates on the hot side (water flow rate on the cold side was 130.91 L/hour and temperature difference between cold and hot sides was 64.2°C).

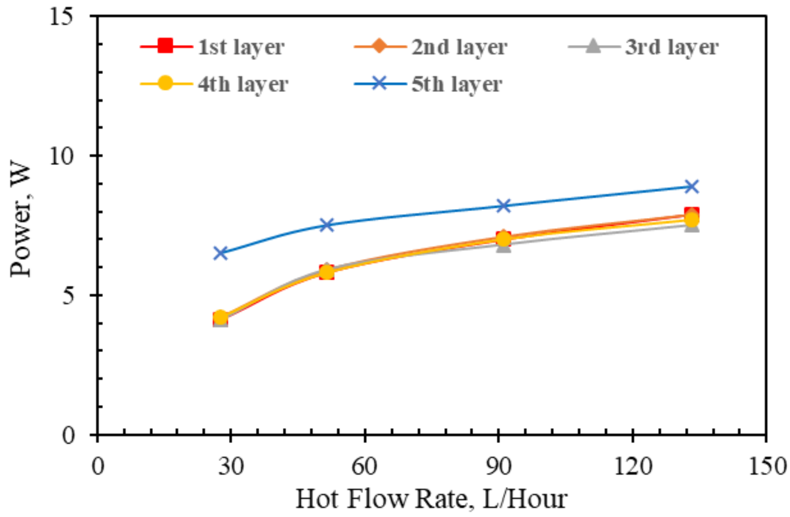

Figure 14: Power of each layer of the five-layer TEG apparatus at different flow rates on the hot side (water flow rate on the cold side was 130.91 L/hour and temperature difference between cold and hot sides was 64.2°C).

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.

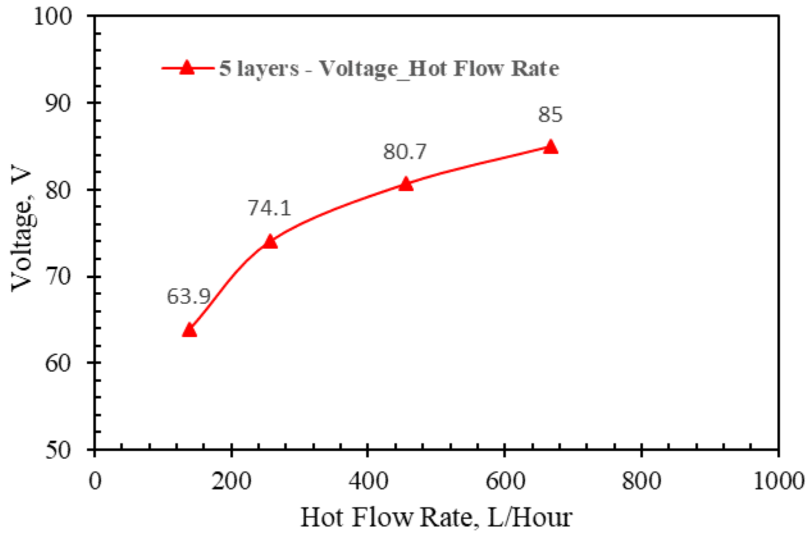

Figure 15: Voltage at different flow rates of water on the hot side of the five-layer TEG apparatus when water flow rate on the cold side is constant (water flow rate on the cold side was 654.55 L/hour and temperature difference between cold and hot sides was 64.2°C).

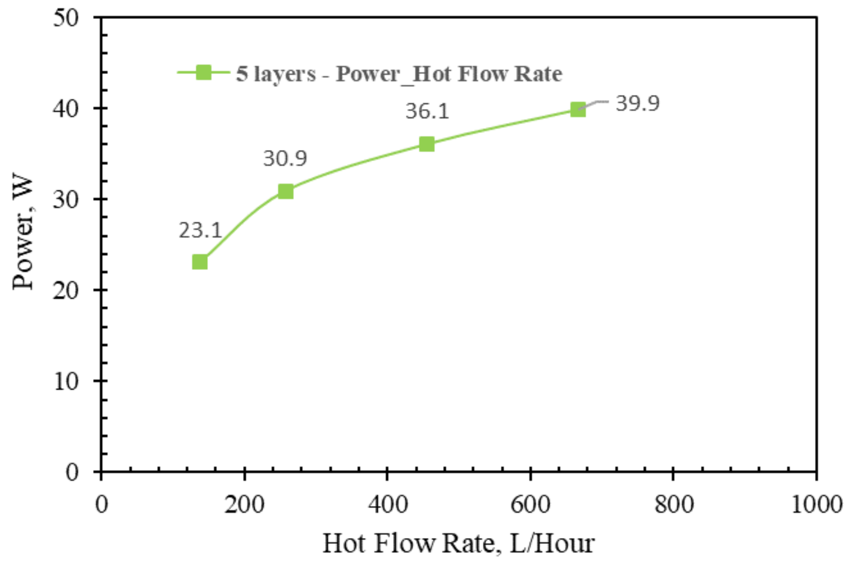

Figure 16: Power output at different flow rates of water on the hot side of the five-layer TEG apparatus when water flow rate on the cold side is constant (water flow rate on the cold side was 654.55 L/hour and temperature difference between cold and hot sides was 64.2°C).

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 °C.

4. FIELD TESTS

4.1 First Field Test

We moved the five-layer TEG apparatus, which could be fit in a small box, to the geothermal well pad located in Bottle Rock, California, USA (see Figure 17). In order to connect the five-layer TEG lab apparatus to the geothermal well head system, pipes, adapters, and manifolds were built to adapt the different dimensions between the TEG lab apparatus and the geothermal well, as shown in Figures 18 and 19.

The field test was run on July 27, 2019 after the installation of the five-layer TEG apparatus. It was not possible to control the inlet pressure and steam flow rate into the five-layer-TEG apparatus because no pressure control valve (PCV) was installed. The five-layer TEG apparatus leaked due to the high pressure and high temperature. It was not possible to measure any power output. We learned a lot from this field test even though the output could not be obtained.

Figure 17: The five-layer TEG apparatus could be fit in a small box and was moved to the geothermal well pad in Bottle Rock, California, USA.

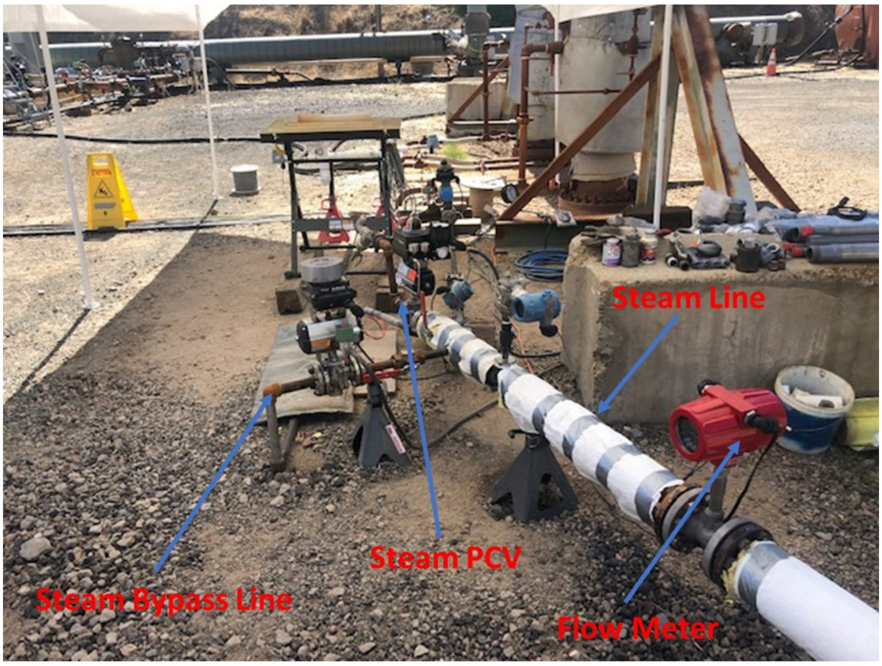

Figure 18: The geothermal well head in Bottle Rock, California, USA (pipes and manifolds were adapted to connect to the five-layer TEG lab apparatus).

Figure 19: The five-layer TEG lab apparatus, ready to be tested at the geothermal well in Bottle Rock, California, USA.

4.2 Second Field Test

We redesigned the structure and made a new six-layer TEG apparatus (see Figure 20). The new six-layer apparatus has a dimension of 75 cm (length) X 24 cm (width) X 18 cm (height). The TEG device can withstand high pressure better, without leak, if the pressures on the cold and hot sides of the TEG chips are approximately equal to each other.

The schematic and the flow configurations of the six-layer TEG apparatus used for the field tests were the same as that for the first field test. A pressure control valve (PCV) was installed this time in order to control the inlet pressure and steam flow ratesix-layer TEG. With the PCV, the power output as a function of steam pressure or steam flow rate could be measured.

A steam by-pass line parallel with the six-layer TEG apparatus was installed in order to protect the TEG device if any unexpected situation occurred. The pressure and the flow rate of the cold water flowing through the cold side could also be controlled. The purpose was to balance the pressure on the cold and hot sides of the TEG chips in order to withstand higher pressure without leaks.

The new six-layer TEG apparatus was installed at Bottle Rock geothermal field for testing, as shown in Figure 20. We then conducted the tests and measured the power output at different steam pressures (or steam flow rate) and at different pressures of cold water (or water flow rate). The field test began on September 27, 2019 and ended on September 29, 2019.

Figure 20: The new six-layer TEG apparatus installed for field test at Bottle Rock geothermal field

The new six-layer TEG apparatus had no leak when the inlet steam pressure was less than 100 psi and leaked a little when fully open to the maximum pressure from the geothermal production well (Coleman 3-5). The steam pressure at the inlet of the six-layer TEG apparatus was about 122 psi, close to the wellhead pressure of 125 psi at the geothermal producer (Coleman 3-5). The apparatus stopped leaking when the pressure of the cold water was increased to about 80 psi.

A data acquisition system was developed to record the values of pressure, temperature, and flow rate at both inlet and outlet on cold and hot sides of the TEG apparatus. A typical screen shot of the data acquisition system is shown in Figure 21. The new six-layer TEG device could generate about 93.6 W per layer (about 500 W total) without any leak at the wellhead pressure of 125 psi and the temperature over 176°C (349 °F).

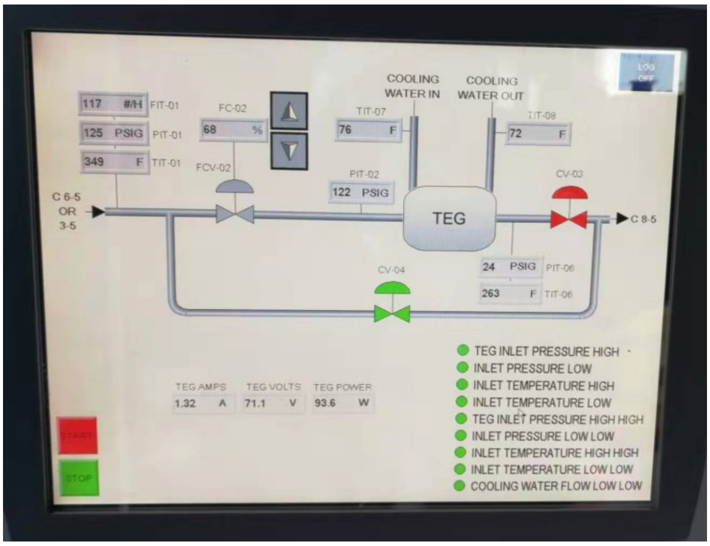

Figure 21: The screen shot of the power output and other parameters measured using the modified six-layer TEG apparatus at Bottle Rock geothermal field

Figure 22 shows the voltage measured from each layer except for the first layer because it had failed mechanically during shipping to the site. The values of the voltage from each layer did not vary significantly, which follows the trend of the experimental results as shown previously in Figure 15. Layer 6 had the highest voltage.

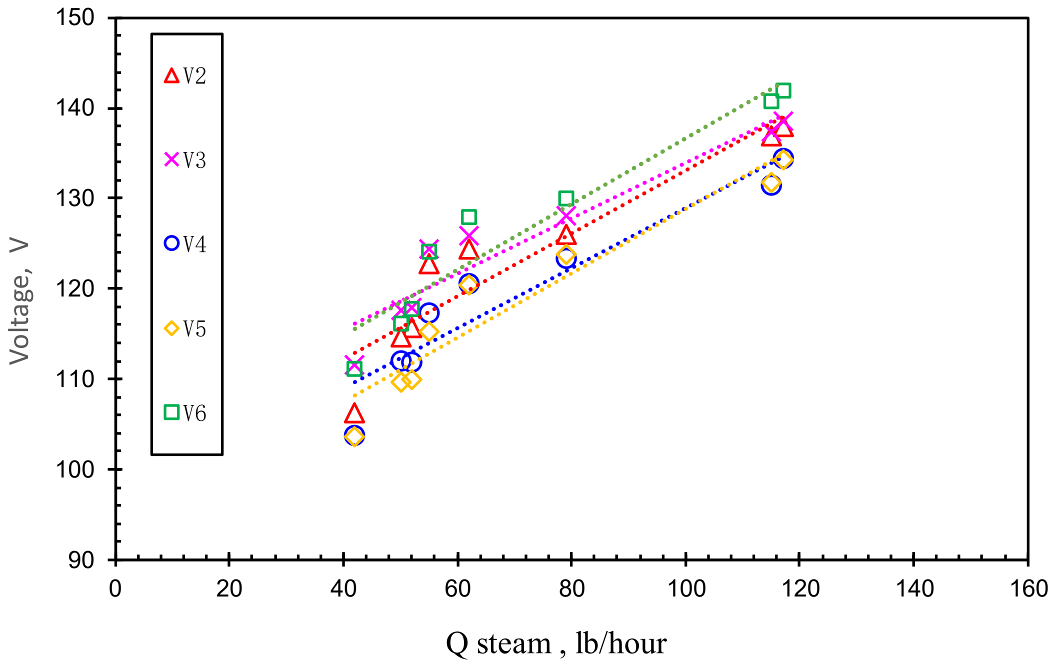

Figure 22: Voltage measured from each layer as a function of steam flow rate.

We measured the power of Layer 6 manually because the data control and sampling system failed at one point and the results are shown in Figure 23. As expected, the power increased with the steam flow rate. This also follows the trend of the experimental results as shown previously in Figure 16.

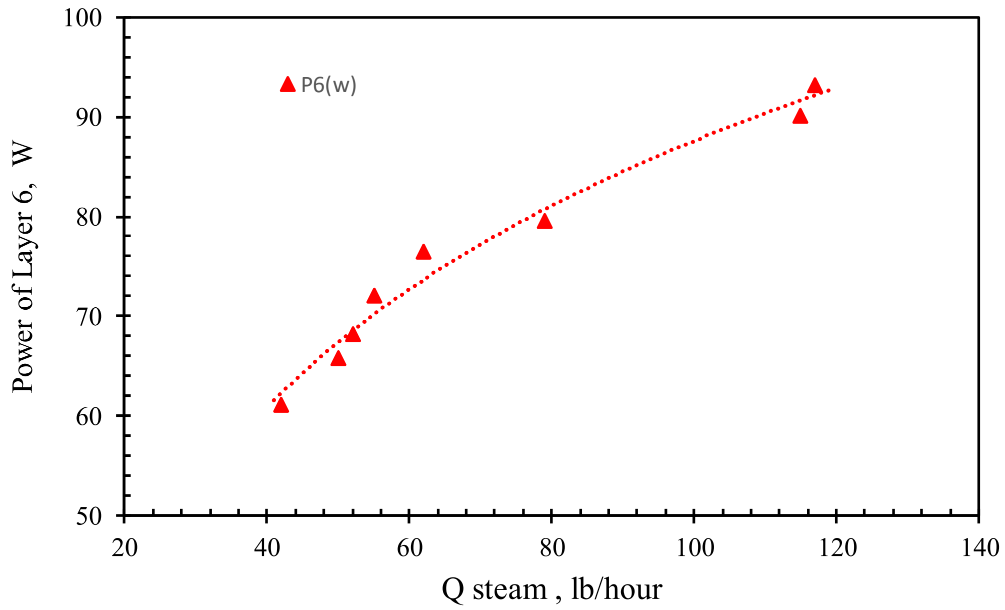

Figure 23: Power vs. steam flow rate measured from the sixth layer

The values of the voltage from each layer did not vary significantly, as shown in Figure 22. We know that the power is directly proportional to the voltage. The total power for the six-layer TEG apparatus was then estimated. The results are shown in Figure 24. The total estimated power reached about 560 W at a steam flow rate of 120 lb per hour.

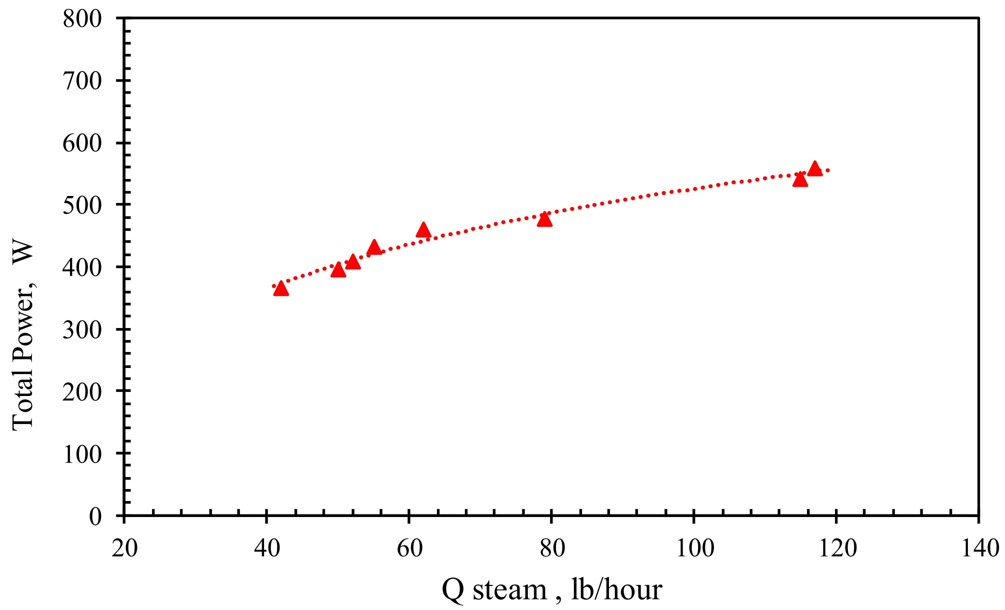

Figure 24: The total power estimated for the Six-layer TEG apparatus in field tests

The volumetric power density of the TEG apparatus was estimated based on the field test results. A device with a physical volume of 50 cubic meter could generate about 1 MW of electric power, which is very attractive.

In summary, the second field test of the six-layer TEG apparatus conducted at the Bottle Rock geothermal facility in California, USA was successful.

5. 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 72.2^{o}C 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.
(4) The second field test of the six-layer TEG apparatus conducted at the Bottle Rock geothermal facility in California, USA was successful and the results had a trend similar to the experimental data.
(5) A volume of 50 cubic meter TEG system could generate about 1 MW electric power.

ACKNOWLEDGEMENT

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