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Field Test of Thermoelectric Generators for Recovering Industrial Waste Heat

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Abstract—Waste heat recovery (WHR) based on thermoelectric generators (TEG) could improve energy efficiency and reduce carbon emissions. TEG could directly convert low-grade heat into electric energy. There have been many reports on laboratory experiments on evaluating the performance of TEG by measuring the power output at different conditions. However, there have been few field tests using waste heat with a temperature of less than 100 °C with TEG devices, which is of great significance because there is huge waste heat within this temperature range. TEGs were usually and mostly used for low-power microelectronic devices. In these cases, only one or several instead of hundreds of TEG modules were utilized. In this study, we conducted the field tests of TEG using the waste heat with a temperature of 80 °C at a gas power plant located in Shanxi province, China. We tested two TEG devices with 10 (240 TEG modules) and 20 layers (360 TEG modules), respectively. To our best knowledge, the number (20) of layers in one TEG device is the biggest so far reported in the literature. The field test results were analyzed and compared with laboratory experiments and other field tests at a high temperature of 170 °C. The power output and efficiency of TEG were measured and calculated at different temperature differences and flow rates. The TEG device could provide a power of 167.8 W for a flow rate of 3 cubic meter per hour at a temperature difference of 60 °C (the temperature of the heat resource was 80 °C). The cost of TEG device used in the field tests was estimated and compared with other power generation technologies. The field test results in this study demonstrate the feasibility of using TEG for recovering large scale waste heat.

Keywords—thermoelectric generators (TEG), field test, green power, waste heat recovery

I. INTRODUCTION

China aims to achieve the peak of CO_2 emissions in 2030 and become carbon neutrality before 2060 (the so-called "dual-carbon policy") to tackle climate change. This goal is driving rapid growth in the development of renewable energy utilization, while pushing heavily emitting industries to save energy and reduce emissions. Waste heat recovery (WHR) is commonly used in industrial applications. The launch of China Carbon Emission Trade Exchange (CCETE) brings huge economic benefits to companies in low-carbon industries. Companies seeking to become carbon neutral must reduce their own emissions rather than simply pay for emissions reductions elsewhere.

Internal combustion engines have two important resources of heat exhaust that account for about 65-70% of the energy input: the exhaust system (about 35-40%) and the radiator (about 30%) [1]. WHR based on thermoelectric generators (TEG) could convert low-grade thermal energy directly into high-grade electric energy based on Seebeck effect, which may be a solution to the problem of medium and low temperature power generation [2]. The potential of TEG for WHR has been studied and demonstrated in some laboratory and theoretical work. However, the practical or large-scale implementation of this technology in the related industries is still relatively rare. Investigations on the applications of TEG for WHR were mainly focused on automotive exhaust and industrial applications. According to a summary [3] of WHR using TEG for industrial applications, there were few studies with a power output of more than 100 W. Industrial WHR based on TEG requires more pilot tests at a larger scale.

Anderson and Brandon [4] compared the performance of TEG with the Rankine cycle and found that the Rankine cycle is able to achieve superior thermal efficiencies at power outputs above 100 kW. In the range of 10 to 100 kW, the thermal efficiency of TEG is comparable to that of the Rankine cycle. Below 10 kW, the efficiency of the TEG is higher than that of the Rankine cycle.

Waste heat is available in various forms such as flue gas, exhaust gas, sewage and heated water, etc. Yadav et al. [5] performed experiments to use TEG to utilize waste heat from the billet casting industry. During the billet (average temperature at 540 °C) cooling process, 12 TEG units were placed between the absorber copper plate and water cooling block, generating a total power output of 339 W. Børset et al. [6] implemented a 0.25 m^2 TEG at a silicon plant for WHR from silicon during the casting process. The maximum power output reached 40.5 W at an average temperature difference of about 100 °C. Punin et al. [7] investigated the heat transfer characteristics of a TEG system for low-grade WHR from the sugar industry. The average temperature of the outer surface of the sugar boiler is usually about 200 °C. When the temperature difference between the hot and cold sides of TEG was 95°C, the maximum power output reached 126.15 W and the system efficiency reached 11.5%. Meng et al. [8] proposed that the power out of TEG could reach about 1.47 kW/m^2 with a conversion efficiency of 4.5% for exhaust gas at 350 °C.

Casi et al. [9] built, installed and tested a TEG at a rockwool manufacturing plant using fumes (340 °C) flowing in the pipe as the hot side and heat pipe heat exchangers as the cold side. During the test period, the average power output was 4.6 W with an efficiency of 2.38%. The optimization of the TEG at the rockwool manufacturing plant was carried out by Araiz et al. [10] in terms of both power output and economic cost. The installation cost could minimize to 10.6 €/W and the Levelized Cost of Electricity (LCOE) estimated for their design was about 0.15 €/kWh. Their simulation results demonstrated the potential of using TEG for WHR at a reasonable cost.

Small-scale TEG are often used to directly supply power to low-power electronic devices, rather than to the power grid. Huang et al. [11] designed and tested a TEG for WHR from an atmospheric pressure plasma jet (APPJ) and powering a multi-functional monitoring system to monitor the temperature of APPJ and the surrounding air quality.

The design optimization of TEG lies mainly on the heat exchanger and advanced materials. Chen et al. [12] designed a variable converging angle in each part of the heat exchanger so that the temperature difference applied to the thermoelectric modules was approximately the same in all parts. Their design increased the power output of TEG by 12.5%. Khalil et al. [13] compared three cooling systems of a TEG installed on a chimney for WHR. TEGs with closed- and open-circuit liquid cooling systems could generate 8 and 45% more power output than those with heat pipes, respectively. Wang et al. [14] proposed a WHR system with potassium heat pipes and skutterudite TEGs for passive thermal management and power generation. Cui et al. [15] evaluated the power output of a porous annular TEG for WHR. This TEG consisted of p- and n-type porous thermoelectric foams (TEFs). The analysis showed that the porous structure could improve the performance of TEG compared to bulk TEG. Lee and Lee [16] improved the compactness of TEG with printed circuit heat exchangers. The power density of the TEG reached 233.1 kW/m^3 at the inlet temperatures of 175°C (hot side) and 20°C (cold side).

Li et al. [17] have conducted geothermal field tests with a 6-layer TEG apparatus which generated about 500 W electricity at a temperature of 176 °C. They demonstrated that the cost of TEGs is less than that of solar PV panels if capacity factor is considered. However, it is still a big question and a great challenge whether it is possible to use TEG devices to generate power at a relatively large scale for waste heat resources with a temperature of less than 100 °C. The waste heat resources within such a temperature range are huge around the world.

As reported by Li et al. [17] [18], the expandability of a TEG apparatus is important to generate power at a large scale but the maximum number of layers in their TEG systems was only 6.

In this paper, we manufactured two TEG devices with a maximum number of 20 layers and conducted the field tests using the waste heat with a temperature of 80 °C at a gas power plant located in Shanxi province, China.

The power output and the efficiency of the TEG devices were measured on-site at different temperatures and flow rates. The field test data were analyzed and discussed. The costs of the TEG devices were estimated at different temperatures.

II. Field Tests

A. Overview of the Gas Power Plant

The gas power plant is located in a coal mining area with abundant coal-bed methane resources. The gas power plant has three gas generators of 1.8 MW with a total installed capacity of 5.4 MW. The waste heat mainly exists in the exhaust gas emissions and the engine cooling closed-loop.

The overview of the WHR system with TEG at the gas power plant is shown in Fig. 1. The schematic and the arrangement of the TEG devices with the piping network from the gas generators at the gas power plant is demonstrated in Fig. 2.

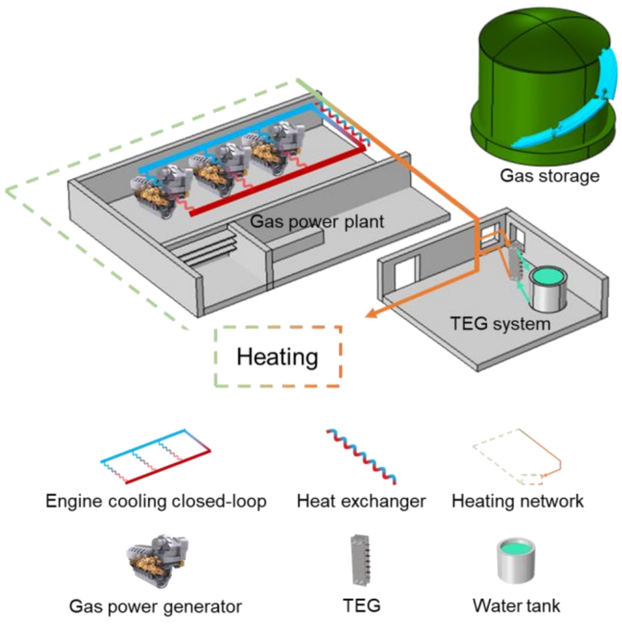

Fig. 1. The overview of the WHR system at a gas power plant.

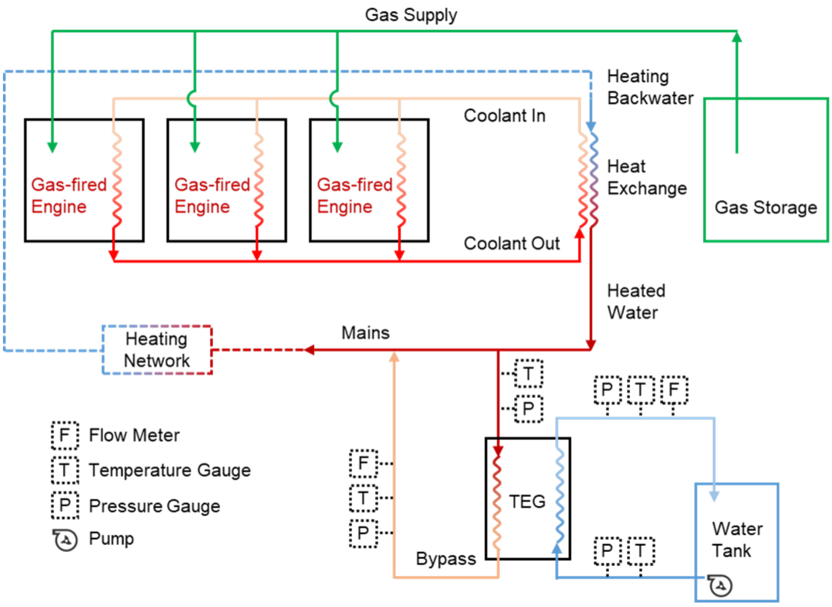

Fig. 2. The schematic and the arrangement of the TEG with the piping network from the gas generators at the gas power plant.

In order to maintain the operating temperature of engines, the inlet temperature of coolant (ethylene glycol) must be kept at 76 - 78 °C and the outlet temperature below 90 °C. A large amount of waste heat was carried out by the coolant flowing in a closed-loop. Especially in summer, the outlet temperature of coolant could reach 92 - 93 °C, close to the shutdown temperature of 95 °C. The coolant of engines was cooled by an external heat exchanger and then flowed back to the gas generators. The heat in the engine cooling closed-loop was transferred to the heating network through the external exchanger for external use. The working fluid in the heating network was water. The TEG was installed in a bypass channel parallel to the mains of heating network, as shown in Fig. 2.

Fig. 3. The selected part of the heating network.

Fig. 4. One of the TEG devices (20 layers) installed for field tests.

B. Installation of TEG

The external heat exchanger between the engine cooling closed-loop and the heating network was well suited for installing TEG. Considering the safety issues and in order not to interfere with the operation of gas generators, we didn't choose to install the TEG to replace the external heat exchanger. The installation site of TEG was chosen in an area where the heating network passed through and near a water tank. The selected part of heating network is shown in Fig. 3.

As shown in Fig. 4, one of the TEG devices (20 layers) was installed by the windows. The hot flow channel of TEG was connected to the pipelines via two heat insulated tubes. The valves allowed to control the pressure and flow rate of hot water in the tubes. The cold flow channel was connected to a water tank. Another TEG (10 layers) was connected in the same way in the field tests. The 10-layer TEG contains 24 modules per layer and the 20-layer TEG contains 18 thermoelectric modules per layer.

C. Test Setup

Fig. 5 shows the photos of TEG devices ready for field tests. The size of the 20-layer TEG was about 0.3 m × 0.2 m × 0.55 m, and the size of the 10-layer TEG was about 0.18 m × 0.2 m × 0.7 m. The schematic of the test setup of the TEG is shown in Fig. 6. The selected part of the pipelines was fitted with pressure gauges, temperature gauges, control valves, and multiple outlets. Two flow meters (FLOWSTAR, Yancheng, China) were installed at the outlets of the hot and cold sides respectively. An electronic load (IT8211, ITECH, Nanjing, China) was used to provide external load and measure the voltage, current, and power output. Depending on the thermoelectric modules contained in each TEG device, the

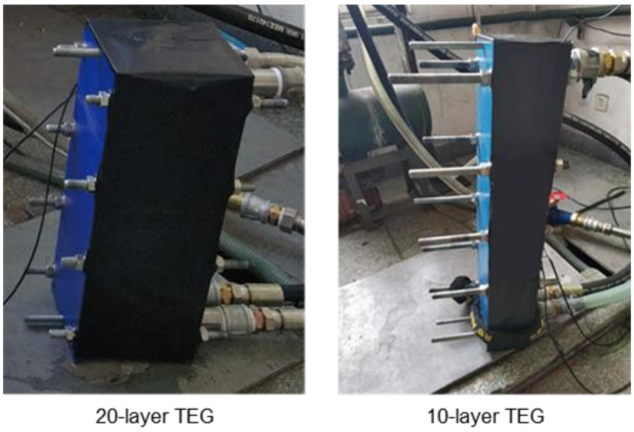

Fig. 5. Photos of the TEG ready for the field tests.

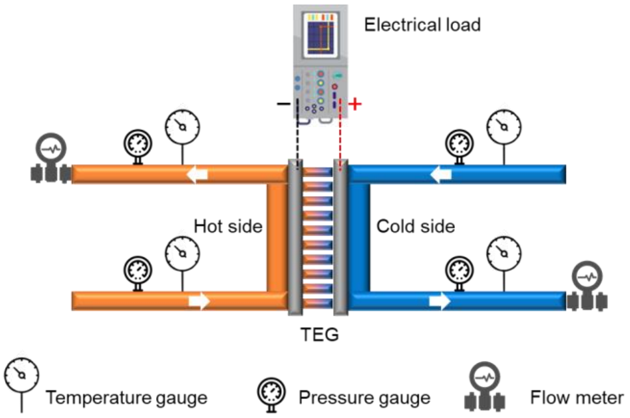

Fig. 6. The schematic of the experimental setup of the TEG devices.

electronic load was set to the appropriate values corresponding to the internal resistance of each TEG to obtain the maximum power output.

III. Results and Discussions

A. Effect of Temperature Difference on Power Output

Temperature difference is one of the most important factors influencing the performance of TEG. In the laboratory experiments reported by Li et al. [18], the power output of TEG was directly proportional to the temperature difference. In field tests, it is usually not convenient to adjust the water temperature at will. Because of this reason, the results measured at different temperature differences in this study were relatively few and did not vary much from each other. We quoted the data from a geothermal field test [17] for comparison. The TEG apparatus used in the geothermal field test had 6 layers, which is different from the TEG devices in the field tests conducted on the site located in Shanxi. So the average power output per layer was used instead of the total power output to investigate the power output at different temperatures.

Fig. 7 shows the comparison of the average power output per layer of TEG in the field tests and laboratory experiments, including the data from this study and those reported by Li et al. [17] [18]. The power output increased with the temperature difference. And the values of the power output from the field tests were greater than those from the laboratory experiments, especially when the temperature difference is high. The reasons caused the difference of the power output between the

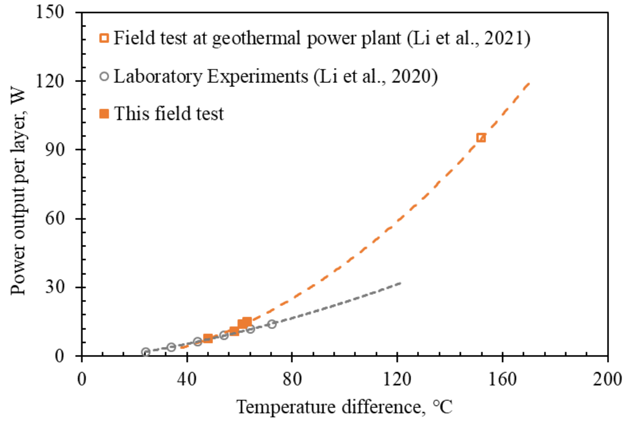

Fig. 7. The power output per layer vs. temperature differences.

field tests and laboratory experiments were not only the temperature difference, but also the fluid pressure. The pressure in industrial pipelines is often higher than the pump pressure in the laboratory. At higher fluid pressures, the thermoelectric modules installed between the fluid channels could have better contact with the fluid channel walls and less thermal resistance, which could improve the performance of TEGs.

B. Effect of Flow Rate on Power Output

We measured the voltage, current, and power output of the TEG devices at different flow rates of both hot and cold fluids. Although the flow rate on the hot side was adjustable, the range was very limited, only from 0 to 7 m^3/h. The flow rate on the cold side was adjustable from 0 to 5 m^3/h. During the tests, the flow rate was variable on only one side and constant at 3 m^3/h on the other side, and the temperature difference was around 60 °C (± 1 °C).

The power output of the TEG device at different hot and cold flow rates are plotted in Figs. 8 and 9, respectively. The power output increased with the flow rates on both hot and cold sides, and the growth rate decreased gradually. The 20-layer TEG device had higher total power output than that of the 10-layer TEG, especially at greater flow rates. After the flow rate increased to some extent, expanding the number of layers of TEG could be more efficient to enhance the power output than continuing to increase the flow rate. The TEG devices designed and manufactured in this study were hierarchically modular and easily expandable, which is suitable for coping with complex industrial heat resources.

C. Effect of Temperature Difference on Efficiency

The efficiency of TEG η is defined by W_{TEG}/Q_h, where W_{TEG} is the power output of TEG (W), and Q_h is the heat flux on the hot side (W).

Fig. 10 shows the efficiency of the TEG devices at different temperature differences. In these field tests, the efficiency of TEG was similar to the laboratory results measured and reported by Li et al [18]. Overall, the efficiency increased with temperature difference. The highest efficiency of the TEG devices in this field test was about 1.72% at a temperature difference of 60 °C. It is interesting to observe that the efficiency of TEG fluctuates in a lower range (around 1%) until the temperature difference reaches 60 °C. In contrast, the efficiency of TEG in the geothermal field test [17] rose to more than 5% at a temperature difference of 152°C (the exact

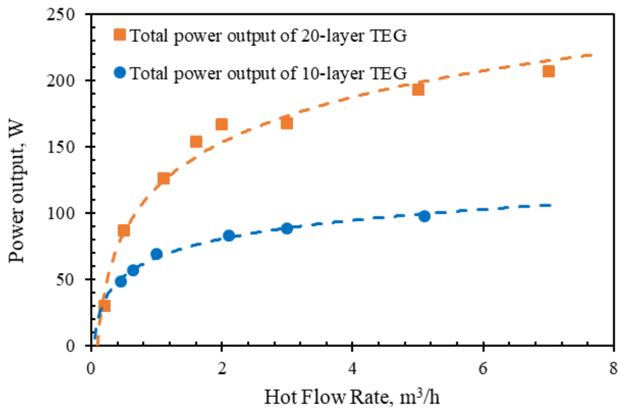

Fig. 8. The total power output of the TEG devices at different flow rates on the hot side (water flow rate on the cold side was 3 m^3/h and the temperature difference was 60 °C (± 1 °C)).

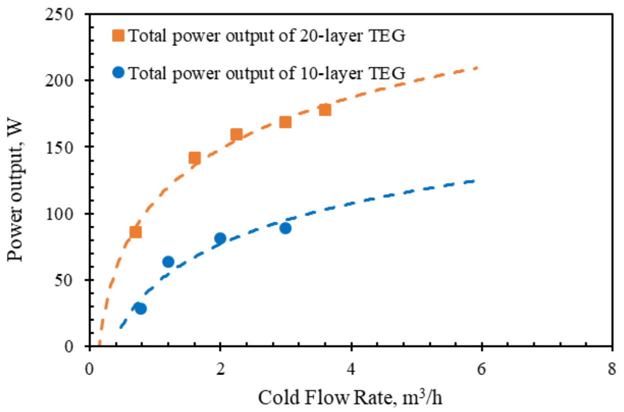

Fig. 9. The total power output of the TEG devices at different flow rates on the cold side (water flow rate on the hot side was 3 m^3/h and the temperature difference was 60 °C (± 1 °C)).

value was related to the flow rate). The results of the field tests and laboratory experiments suggested that the temperature difference of 60 °C (or a heat resource of 80 °C when the coolant temperature is 20 °C) may be an important turning point for the efficiency of TEG in industrial applications.

D. *Effect of Flow Rate on Efficiency*

Fig. 11 shows the efficiency of TEG at different flow rates on the hot side when the water flow rate on the cold side was 3 m^3/h and the temperature difference was 60 °C (± 1 °C). The overall trend in efficiency decreased gradually with the increase in hot flow rate. For a heat resource at a specific temperature, a greater flow rate means more heat input to the TEG. If the power increase couldn't match the increase in hot flow rate, the efficiency will decrease. It is worth to note that there is a peak phase of efficiency at hot flow rates between 2 and 3 m^3/h. As can be seen in Fig. 8, the power output had also increased to a higher range at hot flow rates between 2 and 3 m^3/h. The hot flow rate range of 2-3 m^3/h might be a reasonable range to achieve high power output and high efficiency of the TEGs at the same time in these cases. The efficiency of TEGs gradually decreased after the hot flow rate exceeded 3 m^3/h, and the efficiency of the 20-layer TEG was higher than that of the 10-layer TEG.

The efficiency of the TEG devices at different flow rates on the cold side is plotted in Fig. 12 when the water flow rate on the hot side was 3 m^3/h and the temperature difference was

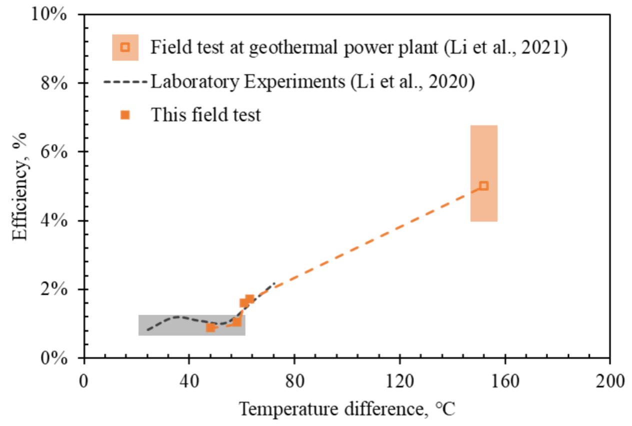

Fig. 10. The efficiency of the TEG devices at different temperature differences.

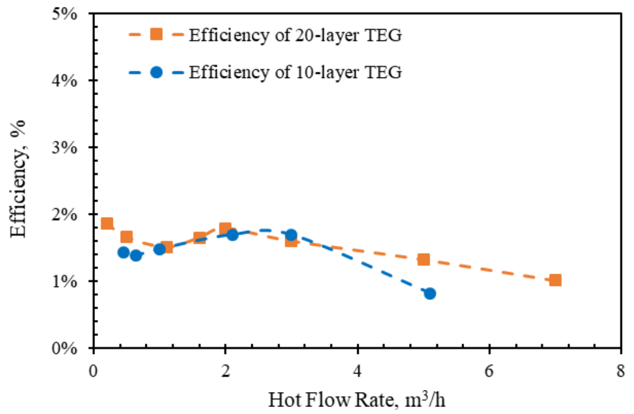

Fig. 11. The efficiency of the TEG devices at different flow rates on the hot side (water flow rate on the cold side was 3 m^3/h and the temperature difference was 60 °C (± 1 °C)).

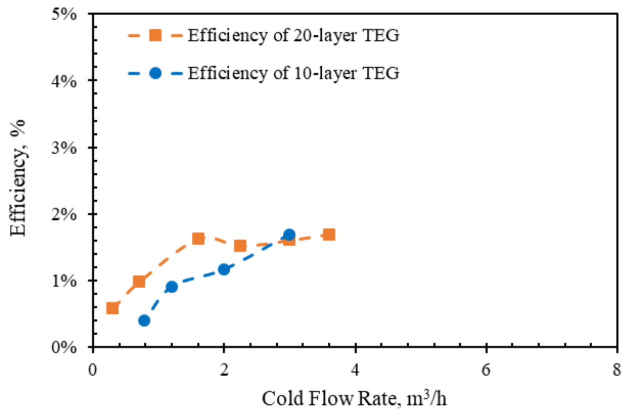

Fig. 12. The efficiency of the TEG devices at different flow rates on the cold side (water flow rate on the hot side was 3 m^3/h and the temperature difference was 60 °C (± 1 °C)).

60 °C (± 1 °C). The efficiency of the 20-layer TEG increased with the cold flow rate until the cold flow rate reached 2 m^3/h. The efficiency of the 10-layer TEG also increased with the cold flow rate and slightly exceeded the efficiency of 20-layer TEG at a cold flow rate of 3 m^3/h. When the thermal energy was fed into the TEG at a constant rate, a greater cold flow rate could help the TEG absorb more thermal energy and convert it into electricity, while also obtaining a higher efficiency. The TEG could have a maximum efficiency at a cold flow range from 2 to 3 m^3/h in these cases.

As discussed above, the proposed 10-layer and 20-layer TEG devices could achieve high power output and high efficiency at the same time when the flow rates on both the hot and cold sides were simultaneously in the range of 2-3 m^3/h.

E. Cost Estimation

Based on the results of the field tests conducted in this study and the geothermal field tests [17], the installation cost ($/kW) and the Levelized Cost of Electricity (LCOE) of TEG at different temperature differences were calculated with reference to the cost data of geothermal power generation (from International Renewable Energy Agency). The estimated cost data are shown in Fig. 13. The LCOE of TEG could be comparable with the average cost of fossil fuels when the temperature difference reaches 150 °C. As reported by Li et al. [17] [19], the cost of TEG is also attractive compared with PV panels if the capacity factor were considered.

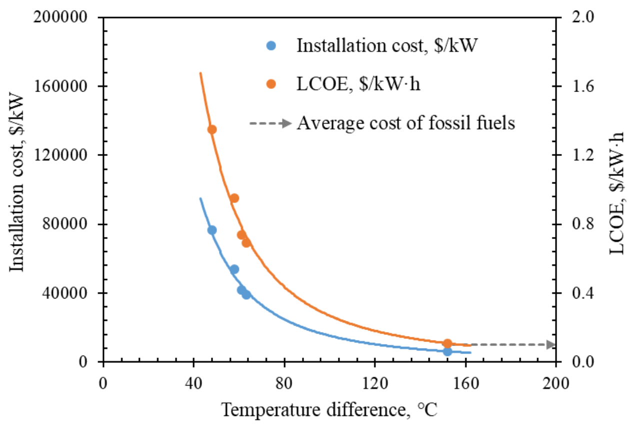

Fig. 13. The installation cost and LCOE of TEG at different temperature differences.

IV. Conclusions

According to the field test results, the following conclusions may be drawn:

(1) We have designed and manufactured two TEG devices with 10 and 20 layers respectively.

(2) At a temperature difference of 60 °C and a flow rate of 3 m^3/h on both hot and cold sides, the 10- and the 20-layer TEG devices could generate about 88.8 and 167.8 W respectively.

(3) The efficiency of the 10- and 20-layer TEG devices may increase, stay constant, or even decrease with the increase in the flow rates on the hot and cold sides.

(4) The TEG devices could achieve relatively high power output and high efficiency at the same time in an optimal flow rate range of 2-3 m^3/h on both the hot and cold sides.

(5) The performance of the TEG devices under the field test conditions was better than that in the laboratory experiments.

(6) The cost of the TEG devices decreases with the increase in the temperature difference between the hot and cold sides.

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