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Numerical Study of an Expandable Multi-layer Thermoelectric Generator System

Xiaoming TIAN[1], Changwei LIU[2] and Kewen LI[2]

[1]Delft University of Technology

[2]Stanford University

txm.arbeit@gmail.com

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ABSTRACT

A thermoelectric generator (TEG) system using thin plate framework (TPF) is considered for power generation. As we know, many geothermal and waste heat resources are at low or intermediate temperatures. Such low temperature geothermal energy can be captured effectively by TEG, with no need to apply the traditional high-cost and frequent-maintenance-required technologies, such as Organic Rankine Cycle (ORC) technology and so on. TEG technology is also useful to be applied in distributed power generation. However, most heat exchanger frameworks for TEG are not friendly to mass production, so the high cost spent on heat exchanger system reduces its competitiveness and hinders the large-scale application of thermoelectric technology. In this study, a power generation system is applied to make the best use of thin plate framework (TPF) and thermoelectric generator (TEG) techniques, which aim to reduce the cost, obtain higher heat-to-electricity efficiency and increase the space utilization ratio. Numerical model has been developed to calculate the power output at different inlet temperatures and different temperature differences of hot- and cold-water inlets. The temperature differences used in this study ranges from 30 ℃ to 90 ℃. Based on the analysis of a 1 kW power generation system, the optimization was conducted to give the best temperature difference of hot- and cold-water inlet, the initial temperature of hot water, and the value of water flow rate. The TPF-TEG stack combination patterns are investigated based on the characteristics of outlet temperature. In addition, preliminary economic appraisal was conducted based on modeling results, and it indicates that this multi-layer TEG system has a good application potential in many geothermal sites and distributed waste heat sources.

1. INTRODUCTION

Geothermal power generation currently needs higher installation cost and longer development period relative to other renewable energies, like wind and solar energy (Li et al, 2015). As a result, geothermal energy projects in many countries have been reliant on government incentives to compete against natural gas and other renewable generations (Montague, 2016). One possible solution for this problem is the application of thermoelectric generator (TEG) for electricity generation. A TEG module comprises of p-type and n-type semiconductor thermoelectric legs fastened between two hot/cold ceramic plates (Goldsmid and Nolas, 2001; Maneewan and Chinadaruksa, 2009; Demir and Dincer, 2017). A voltage is induced based on the Seebeck effect when there is the temperature gradient across the legs. The effect of the TEG dimensions and flow characteristics on the conversion efficiency has been examined for a stack with counter-flow configuration (Yu and Zhao, 2007; Suter et al, 2012; Wang et al, 2014; Liu et al, 2014). However, there are two aspects which impede the application of thermoelectric generators in geothermal fields; one is the relatively low material efficiency, and the other is the high cost of the thermoelectric power generation system, especially the heat exchanger parts. Most recently conducted researches have or are focused on the materials, and the achievements are promising, but the system design still lags far behind. Most heat exchanger frameworks for TEG are not friendly to mass production, so the high cost spent on heat exchanger system reduces its competitiveness and hinders the large-scale application of thermoelectric technologies.

This study applied a type of TPF-TEG stack that combines the thermoelectric generator (TEG) with the thin plate framework (TPF). The space utilization rate of TPF-TEG is high, and the cost per watt of TPF-TEG is 3-5 times cheaper than other existing models. The numerical model describing the TPF-TEG stack has been developed. Several parameters known to affect the TPF-TEG stack's performance were conducted using the proposed numerical model. These parameters are temperature difference of hot- and cold-water inlet, the initial temperature of hot water, and water flow rate, respectively. The TPF-TEG stack combination patterns are also investigated based on the characteristics of outlet temperature. The economic appraisal about the power generated using TPF-TEG stacks was conducted and compared with some geothermal ORC power generation scenarios.

2. CONFIGURATION OF THERMOELECTRIC STACK

The TPF-TEG stack configuration is shown in Figure 1. In this study, hot water is injected into the stack as geothermal working fluid. The TEG chip layers are set in between the hot- and cold-water channels.

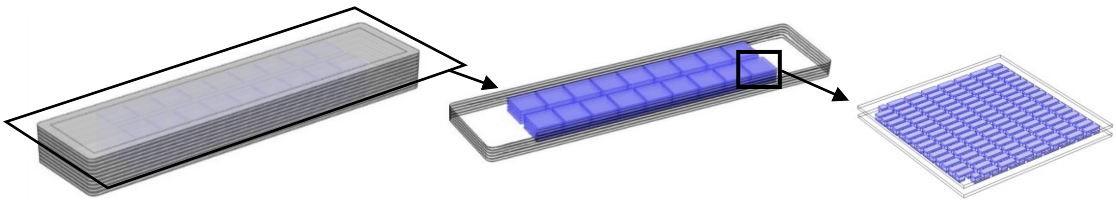


Figure 1: The TPF-TEG stack configuration

The plate heat exchanger is modified to make room for TEG chip arrays and provide hot/cold water channels. Some steel plates are set in between TEG chip arrays and water channels. A bottom cold-water channel layer, middle TEG chips array layer, and upper hot-water channel layer are combined into a TPF-TEG unit. Each TPF-TEG unit is separated by a steel plate. Each TEG array contains 18 TEG chips and is monolayer set in between two steel plates. The length, width and thickness of the TEG chip are 40 mm, 40 mm and 3 mm, respectively. The heat of hot water can be provided by geothermal resources. All the TEG chips are connected in series as power source and there is an external load in circuit. Hot- and cold-water flow in the channels in between the TPF plate and TEG plate, and in a parallel-flow configuration. Water is injected into the inlet on one side of the plate, then out through the outlet on the other side of the plate. The hot water, which is supplied by the thermostatic water bath circulator, simulates the geothermal or hot water and provided heat for the generators.

For a thermoelectric power generation system, the heat exchangers always account for a large part of the total cost. Therefore, improving the heat transfer efficiency and cutting down the cost at the same time is always a main objective for a project of thermoelectric power generation. Comparisons of different types of heat exchangers were conducted with previous study at the same experimental condition (Chen et al., 2017). Their study indicates that the proposed model (TPF) ratio of fluid channel volume to apparent size is higher than others, so its space utilization rate is higher. In addition, the heat exchanger cost per watt was calculated based on the real manufacture cost in experimental stage, while the proposed model (TPF) is 3-5 times cheaper than other models. The structure of our proposed model is more suitable for mass production, so its cost advantage will be more obvious in the commercial stage.

3. MODEL DESCRIPTION

The TEG arrays are set in between the cold- and hot-water channels in order to obtain temperature gradient in the TEG chips. Each cold-water or hot-water box is separated into two channels by a steel plate, except for the water channels at the first and the last unit of the whole stack. The assumptions made for this heat transfer model include: 1) there are thermal insulations at all outer boundaries, 2) TEG arrays are in directly contact with steel plate, 3) water flow pattern is laminar flow, 4) the roughness of water channel wall mainly caused by the steel plate texture is not considered, 5) the flow rates of both cold and hot water channel branches from the manifold are identical, and 6) the velocity of the water is uniform in the water channel. Stationary condition was considered in this modeling. This model utilized a thin plate framework of 550mm×130mm. Modeling was conducted using the finite element software COMSOL Multiphysics.

3.1 Governing Equations

A three-dimensional model was applied to describe the whole heat transfer system. Heat exchange takes place between fluid part (water) and solid part (steel plates and TEG arrays) simultaneously (Tao, 1988). The stationary governing equation corresponds to the convection-diffusion equation for steady-state heat transfer process, which contains additional contributions of heat flux (Fourier's law of heat conduction) and no heat source (Bird et al., 2007). The heat flux describes the heat transfer from the hot water to the steel plate, from the steel plate to the TEG chips, etc. Therefore, the equation is expressed as follow:

$$\rho C_p \vec{u} \cdot \nabla T + \nabla \vec{q} = 0 \tag{1}$$

where ρ is the density (kg/m^3), C_p is the specific heat capacity at constant pressure (J/(kg·K)), T is the absolute temperature (K), $\vec{u}$ is the velocity vector (m/s) and $\vec{q}$ is the heat flux by conduction (W/m^2), which can be described by using Fourier's three dimensional diffusion law.

$$\vec{q} = -k \nabla \mathrm{T} \tag{2}$$

where k is thermal conductivity (W/(m·K)). The thermal properties of water, TEG chip, and the steel plate used in the numerical simulation are provided in the material library in COMSOL Multiphysics.

3.2 Boundary Conditions

As mentioned in the assumptions, all outer boundaries of the TPF-TEG stack are heat-insulated which means the heat fluxes at those boundaries are zero. The temperatures at the inlet of hot and cold water are constant, and are given by:

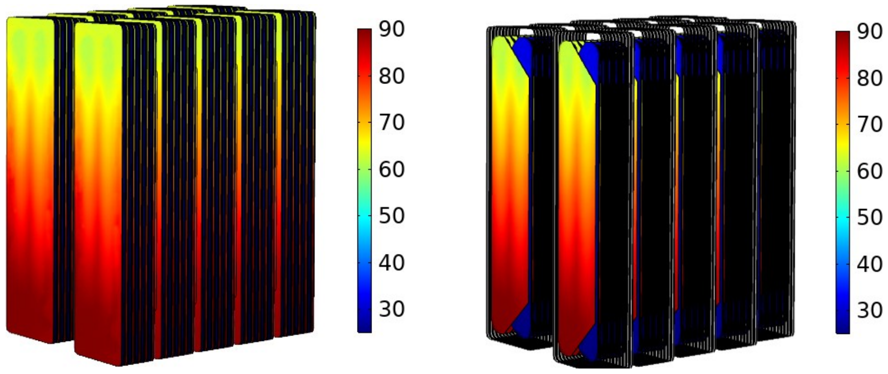
$$-\vec{n} \cdot \vec{q}|_{\Gamma_{outer}} = 0,\ \mathrm{T}|_{\Gamma_{hot\_in}} = \mathrm{T}_{hot\_w}\ ,\ \mathrm{T}|_{\Gamma_{cold\_in}} = \mathrm{T}_{cold\_w} \tag{3}$$

where $\vec{n}$ is the normal vector, Γ_{outer} represents the outer boundaries of the TPF-TEG stack, Γ_{hot_in} and Γ_{cold_in} represent the boundaries at inlet of hot and cold water, T_{hot_w} and T_{cold_w} represent the initial temperatures of injected hot and cold water, respectively.

4. MODELING RESULTS

4.1 Temperature Distribution of TPF

The temperature distribution of TPF-TEG model is shown in Figure 2.



(a) Temperature distribution of steel plates (b) Temperature distribution of water

Figure 2: The temperature distribution of TPF-TEG model

A TPF-TEG stack contains several TPF-TEG units. The number of TPF-TEG unit is changeable. Figure 2 shows the temperature distribution of 10 TPF-TEG stacks with 100 TPF-TEG units in total. In this model, T_{hot} and T_{cold} are 90 °C and 25 °C, respectively, and the hot- and cold-water flow rate are 0.15 m^3/h. The unit of the color legend is degrees Celsius (°C). The inlets of hot and cold water are in the lower left and upper left corner of the figure, respectively. Two high temperature strips in Figure 2 indicates the place where the TEG chips transfer the heat from hot water to cold water.

4.2 Comparison and Optimization

In this study, the TPF-TEG stack was applied to generate electric power using geothermal water resources. Large amount of water is assumed to be recycled in a closed geothermal loop system. The hot and cold water from TPF-TEG outlets will be eventually re-injected into geothermal wells. This means when calculating the heat-to-electricity efficiency, the heat transferred from hot water to cold water needs to be subtracted from the calculation, which is

$$\eta = \frac{P}{mC_p\Delta T_{hot} - mC_p\Delta T_{cold}} \quad (4)$$

where η is the heat-to-electricity efficiency (%), P is the useful electric power output (W), m is the water mass flow (kg/s), C_p is the heat capacity of water (J/(kg·K)), ΔT_{hot} is the temperature difference between the hot water inlet and outlet, and ΔT_{cold} is the temperature difference between the cold water inlet and outlet.

Figure 3 demonstrates the variation of the maximum power output (P) and electricity output (Q) as the functions of water volumetric flow rate and the initial hot water temperature. The computational results of this figure are based on the 10 TPF-TEG units by injecting 1 m^3 hot water. Using such a fixed hot water volume like 1 m^3, it is easier to estimate how many kW of electricity can be generated by using per unit volume (for example, 1 m^3 in this study) of hot water with a specific temperature difference, which is a common engineering question of interest. The initial temperatures of hot water are 90 °C, 80 °C, 70 °C and 60 °C, respectively. The initial temperature of cold water is 25 °C and has the same volumetric flow rate of hot water.

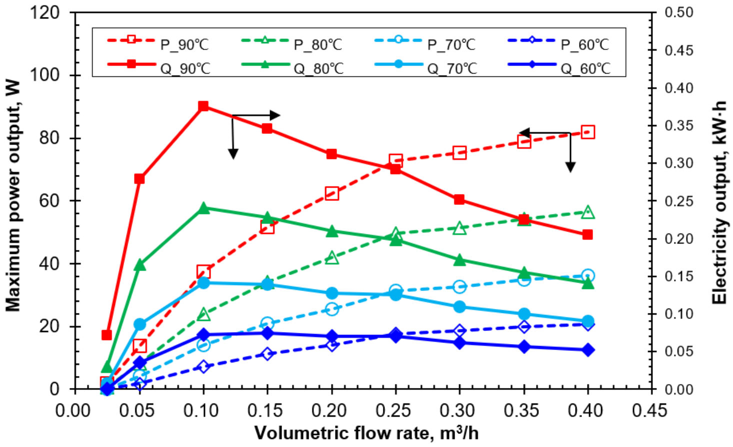


Figure 3: The variations of maximum power output and electricity output on different initial hot water temperature

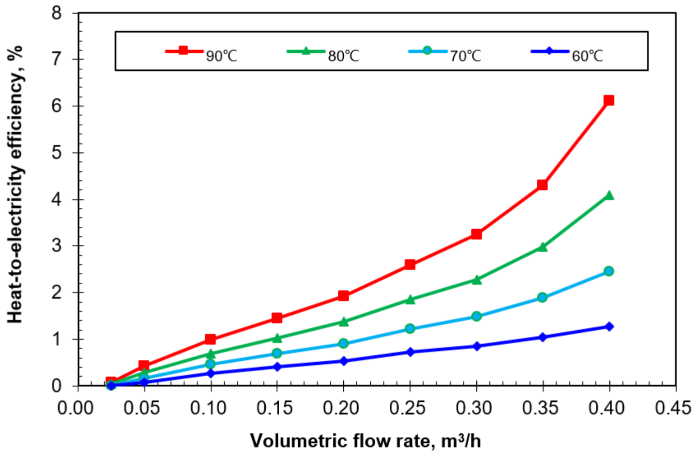


Figure 4: The variations of heat-to-electricity efficiency on different initial hot water temperature

It can be clearly seen from Figure 3 that the maximum power output (dashed lines) increases as the water flow rate increases. This is because the high water flow rate is helpful to establish large temperature difference between the two ceramics of TEG chips. The electricity output (solid line) increases at the beginning and then decreases as the water flow rate increases. This indicates that there is an optimal water flow rate of 0.1 m^3/h, which leads to the highest electricity output. The reason is that the TPF-TEG stack with high water flow rate has less time to generate electricity if the total amount of hot water is fixed at 1 m^3, even though it has larger power output. For the higher initial hot water temperature, both maximum power output and electricity output are larger than those of lower initial hot water temperature. Based on Equation (7), the heat-to-electricity efficiency of the different scenarios can be calculated. Figure 4 shows that the heat-to-electricity efficiency increases with the increase of water flow rate and the initial hot water temperature. It can be explained that both the high water flow rate and the higher initial hot water temperature can help to establish large temperature difference.

5. ECONOMIC APPRAISAL

The economic appraisal of the power generation using TPF-TEG stacks was conducted and compared with some geothermal ORC power generation scenarios. The duration of payback period of the capital cost and the cumulative net cash flow for 50 years operation have been investigated by using economic appraisal. This economic appraisal is conducted based on the current fiscal and taxation system and price system of China, and the current status of geothermal energy development.

5.1 The Economic Appraisal of Geothermal ORC Power Generation

Generally, the unit capital cost of power generation project will decrease as the installed capacity increases. Figure 5 shows the unit capital cost of ORC geothermal project as a function of installed capacity (Tocci 2017).

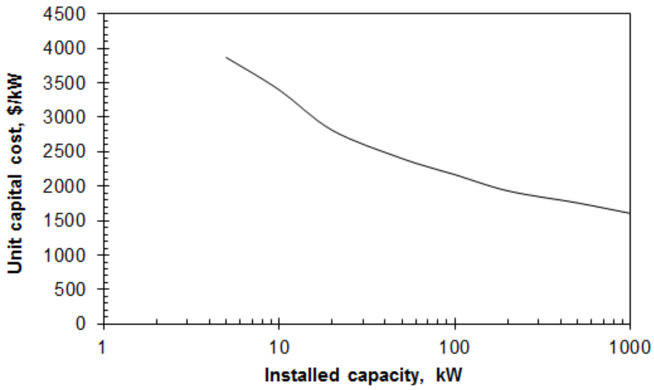


Figure 5: The unit capital cost of ORC geothermal project

Here we assume that the geothermal power generation is put into use only after all equipment and ground engineering are ready. The average electricity sale price of connecting to State Grid Corporation of China in Yangbajing geothermal project (2018) is $0.14 (¥0.93) per kW·h. The management expense is 1% of annual sales. The unit operating cost for generating electricity is 0.045$/kW (Zhang 2011). The total sales tax rate and additional duty rate is 18.7% of the annual sales. Corporate income tax rate is 25%. Therefore, for a period of 50 years operation, the cumulative net cash flow (NCF) curves are shown in Figure 6.

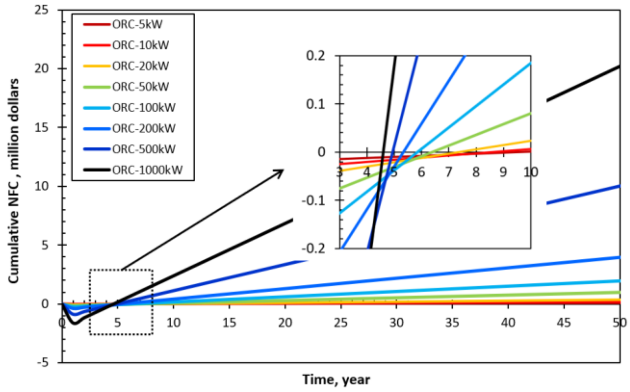


Figure 6: The cumulative NCF curves for different installed capacity of ORC geothermal power generation

If plot the payback time with the corresponding installed capacity of ORC geothermal power generation in a new figure, it gives:

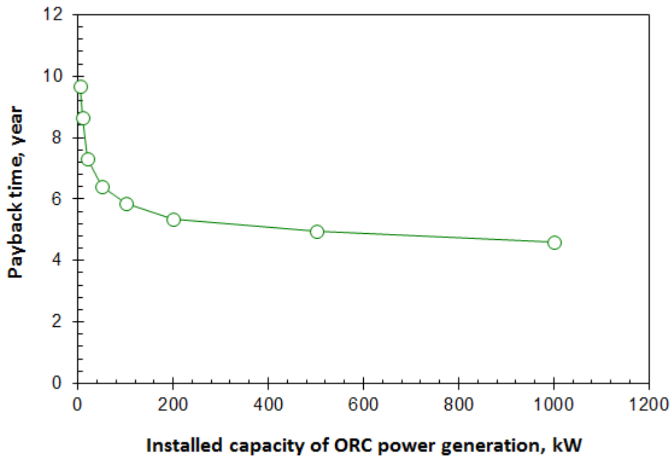


Figure 7: The payback time of capital cost for different installed capacity of ORC geothermal power generation

As it can be seen from Figure 6 and Figure 7, the value of installed capacity strongly affects the ORC power generation on payback time. The large value of installed capacity ORC power generation is helpful to pay back the capital cost and has the large final cumulative NCF. Figure 7 demonstrates that small installed capacity ORC power generation may take a long time to pay back the capital cost. Its economic benefits are small and limited. Therefore, we also conducted the economic appraisal of TPF-TEG power generation in order to find out the advantages and disadvantages of both technologies.

5.2 The Economic Appraisal of Geothermal TPF-TEG Power Generation

Before conducting the economic appraisal of TPF-TEG power generation, the combination pattern of TPF-TEG stack should be discussed. As we know, the outlet temperature of hot water sometimes is higher than the temperature of waste water or re-injected water. In this case, more TPF-TEG stacks should follow and be connected to the former stacks to harvest the heat from geothermal water as much as possible. To be more specific, several TPF-TEG stacks are connected in series as a group, i.e. the hot water outlet of the stack is directly connected to the hot water inlet of the next stack. Several groups are then connected in parallel, see Figure 8.

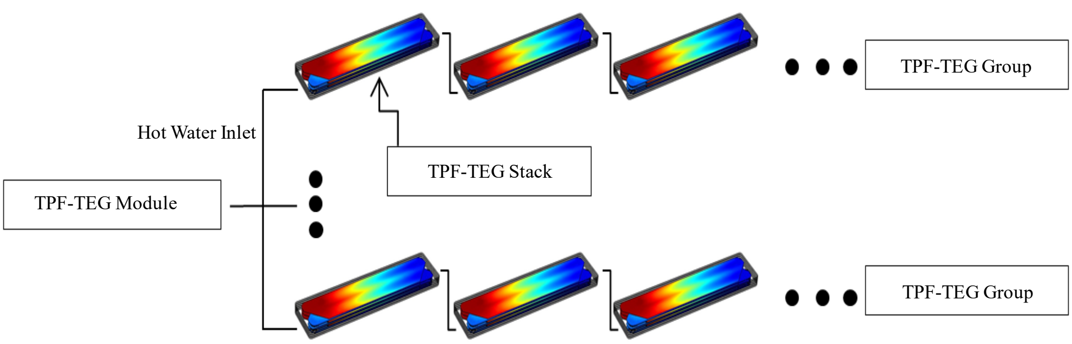


Figure 8: The combination pattern of TPF-TEG power generation

Figure 8 shows the combination patterns of TPF-TEG stack for power generation. The pipes of cold water are not shown in Figure 8. Also, the TEG chips can be connected electrically in different combination patterns. In this study, the TEG chips are connected electrically in series in the same group while they are connected in parallel in different groups. An example of 10 TPF-TEG stacks is also shown in Figure 2. In that figure, 5 TPF-TEG stacks are connected as a group, and two groups are then combined as a working module.

Some basic data are cited from the geothermal project in Soultz, France (Genter et al., 2010). The GPK2 well of Soultz geothermal project has the geothermal water flow rate of 20 L/s. The initial temperature of geothermal water is 162 °C and then the water is re-injected into GPK3 well at 50 °C. In order to achieve good basics for comparison, the proposed TPF-TEG power generation also has the same initial temperature of geothermal water 162 °C. The initial temperature of cold water is 25 °C. Some specific combination patterns of TPF-TEG stack were applied in order to control the final temperature of hot water outlet that is around 50 °C. The detailed calculation results for different combination patterns of TPF-TEG stack are shown in Table 1.

Table 1: The calculation results of different combination patterns of TPF-TEG stack

Water flow rate in group	$0.05\ m^3/h$	$0.1\ m^3/h$	$0.2\ m^3/h$	$0.3\ m^3/h$	$0.4\ m^3/h$
TPF-TEG stack number of a group	1	2	4	7	9
Temperature of hot water outlet (℃)	56.84	61.33	63.72	53.69	56.71
The power output of a group（W）	133.27	312.15	699.95	1078.83	1489.89
Group number	1440	720	360	240	180
Total TPF-TEG stack number	1440	1440	1440	1680	1620
Total power output of TPF-TEG power generation （kW）	191.91	224.75	251.98	258.92	268.18

Generally, the unit capital cost of TPF-TEG for thermoelectric power generation is about $4393.9/kW (¥26000/kW) based on the laboratory cost data. However, in this study, the mass production of TPF-TEG will greatly reduce the capital cost in half, i.e. $1969.7/kW (¥13000/kW). For both ORC and thermoelectric power generation, we mainly focus on the part of power plant in economic appraisal, because we assume both technologies are applied in the identical geothermal well so that the costs of drilling are the same.

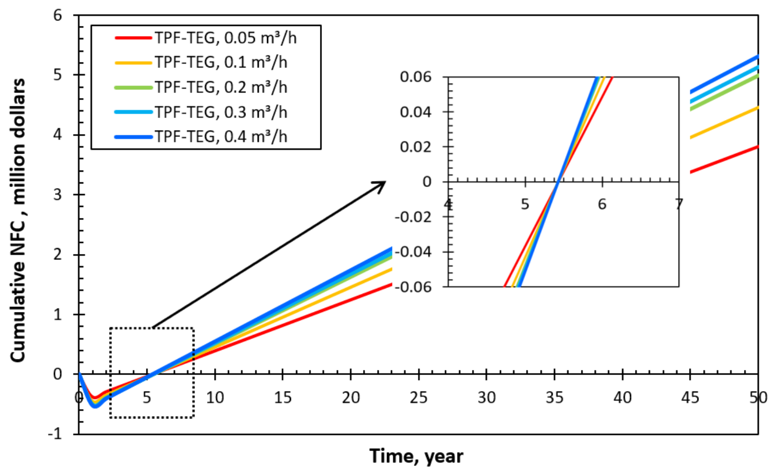


Figure 9: The cumulative NCF curves for different injected water flow rates of TPF-TEG geothermal power generation

As it can be seen from Figure 9, the value of cumulative NCF of TPF-TEG power generation is smaller than that of ORC power generation. However, the payback time (about 5.4 years) is smaller than most of ORC projects. The reason is that ORC technology has much higher heat-to-electricity efficiency while TPF-TEG technology has relatively smaller upfront capital cost.

The above indicates that ORC and TPF-TEG technology can be combined into the same geothermal power generation project. For example, since the construction cycle for geothermal plant is very long, there is gap between power plant construction and geothermal well drilling. Consequently, lots of heat cannot be used during this period and the project may need to wait 1 to 3 years for installing the power generation system and plant construction. However, the TPF-TEG technology can be chosen at the early stage of the geothermal power generation project in order to pay back capital cost faster and obtain some profit to support the further operation. At the middle and late period of the project, ORC technology can be applied to get higher heat-to-electricity efficiency for more cumulative NCF. Considering that TPF-TEG technology has less mechanical failure and is more suitable for low temperature geothermal water resource, it can continuously be used to harvest the residual heat of ORC even in the middle and late period of the geothermal project and therefore be applied through the whole project period.

Furthermore, compared with ORC technology, TPF-TEG technology can be applied to distributed heat source which just could support kilowatt level power generation, because it will be very expensive to build a power generation plant for just ten-kilowatt capacity using ORC technology. It can be used and located close to the load they serve so that it does not need to transmit the electricity to very long distances. It can also be installed close to the heat source like geothermal wellhead, because it is a flexible technology and modular. When conducting a geothermal project, TPF-TEG technology is easy to be applied to generate electricity throughout the whole geothermal project from when the first geothermal well is drilled, and does not need to wait until the drilling of the rest of the geothermal wells, the centralized power plant and ground engineering are ready。

6. CONCLUSIONS

The following conclusions are drawn based on the analysis of experiments and the proposed model in this study:

1. A thermoelectric generator (TEG) system using thin plate framework (TPF) is considered for geothermal and waste heat power generation. The specially-designed TPF-TEG has high space utilization rate, and its cost per watt is 3-5 times cheaper than other existing models. Furthermore, the numerical model describing the TPF-TEG physical model has been proposed.

2. The electric power output increases with temperature difference, inlet temperature of hot water, and water flow rate. There is an optimal value of 0.1 m^3/h of water flow rate at specific conditions, which leads to the maximum total electricity output. The increase of water flow rate and the initial hot water temperature can also improve the heat-to-electricity efficiency of the TPF-TEG power generation.

3. The TPF-TEG power generation system is good at shortening the payback time because of its low capital cost. Also, TPF-TEG technology can be applied in distributed generation, because it is a flexible technology and modularization. When conducting a geothermal project, TPF-TEG technology is easy to be applied to generate electricity throughout the whole geothermal project, especially during the early stage.

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