

# Optimisation of displacement selections and structures for the Geothermal Aided Power Generation plant

Yin Zhou

China Institute of FTZ Supply Chain

Jiyun Qin (✉ [qin.jiyun@foxmail.com](mailto:qin.jiyun@foxmail.com))

Shanghai Maritime University

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## Research

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**Optimisation of displacement selections and structures for  
the Geothermal Aided Power Generation plant**

Yin Zhou, Jiyun Qin\*

China Institute of FTZ Supply Chain, Shanghai Maritime University, Pudong

Shanghai 201306 China

Corresponding author: [qin.jiyun@foxmail.com](mailto:qin.jiyun@foxmail.com)

## **Abstract**

Geothermal Aided Power Generation (GAPG) technology is a method of integrating geothermal energy into a regenerative Rankine cycle (RRC) power plant. In such a power system, the geothermal energy is used to preheat the feedwater to boiler of the power plant. Therefore, the extraction steam of RRC power plant is displaced by the geothermal energy. Then, the displaced extraction steam is expended further in steam turbine to produce power. In a GAPG plant, a heat exchanger system is used to facilitate the heat exchange between the geothermal fluid and the feedwater. As power from geothermal energy comes from displaced extraction steam, different displacement selections for extraction steam would lead to different technical performance of the GAPG plant. When the geothermal fluid flows up from the geothermal well and quench to a lower temperature in the heat exchanger system, the silica scaling occurs in the heat exchanger system. As silica scaling can be controlled by adjusting geothermal fluid temperature, different displacement selections would have different influences on the silica scaling process in the heat exchanger system. There are two kinds of structures for the heat exchanger system of the GAPG plant, which are series structure and parallel structure. The different structures also lead to different performance of the GAPG plant. In present paper, a 300 MW GAPG plant is used as a case study to optimise displacement selections and structures of the GAPG plant. The results show that there is no silica scaling in the heat exchanger system for the displacement selection of geothermal energy to displace extraction to all high-pressure feedwater heaters. For this displacement selection, the power output of the Parallel GAPG plant is higher than the

Series GAPG plant.

***Key words:*** geothermal hybrid power system; Geothermal Aided Power Generation; silica scaling; structures of the GAPG; displacement selection.

## 1. Introduction

With rapid economic development, the consumption of electricity has supplied an increasing share of the world's total consumption of energy [1]. Coal is the most widely used fuel to produce electricity [2]. However, with the increasing awareness of the negative environment impacts from carbon dioxide, which is an emission from coal fired power plants, the used of other kinds of energy resources to produce electricity has become more attractive [3]. Renewable resources, such as geothermal energy, solar energy and wind energy, are receiving growing attention for production of electricity purpose [3]. However, some of the renewable energy resources such as solar and wind energy have the disadvantage of being intermittent nature. Compared with other renewable energy such as solar and wind energy, geothermal energy has the advantage of being non-intermittent.

For the low to medium temperature geothermal resources in the range of 90 °C to 300 °C, from the thermodynamic points of view, the efficiency of these kinds of geothermal power plants are capped by the temperature of geothermal fluid entering geothermal power plants [4]. On the other hand, fossil fuel power plant is presently the backbone of the electricity production, which has a better efficiency as the combustion temperature is much higher [5]. Therefore, a hybrid power plant, integrating geothermal energy into fossil fired power plants, is a practical way to efficiently use geothermal energy and reduce emission from electricity production [6].

The concept of hybrid geothermal power plant was first presented in the late 1970s by DiPippo [7]. It was pointed that there are three kinds of hybrid power system [8, 9].

The first choice is integrating geothermal fluid into boiler for superheating, the second choice is using geothermal fluid to preheating feedwater to boiler, and the third choice is compound these two choices. Comparing these three choices, DiPippo found that the second choice have advantages of easy control than other two choices. In present study, the second choice is termed as geothermal aided power generation (GAPG) technology.

The GAPG technology is a method of integrating geothermal energy into a conventional regenerative Rankine cycle (RRC) power plant technology [6]. In such a technology, geothermal energy carried by geothermal fluid is used to displace extraction steam from steam turbine by preheating feedwater to boiler. Therefore, the displaced extraction steam is then can be expended further in steam turbine. The GAPG plant can be operated both for power boosting and fuel saving purpose by adjusting the mass flow rate of feedwater entering the boiler [10].

For a GAPG technology, the efficiency of geothermal to power efficiency is no longer capped by the temperature of the geothermal fluid. A thermodynamic analysis shows that the GAPG technology has an overall improvement in the utilisation of low to medium temperature geothermal resources [11, 12]. Kestin et al. found that, for geothermal fluid at 200°C, a GAPG plant can theoretically produce 4% more electricity than a fossil fired power plant and 60% more work than a geothermal alone power plant [13]. Buchta analysed a GAPG plant modified from a 200 MW power plant, and geothermal energy is used to displace extraction steam to low pressure feedwater heaters, it was found that even for the geothermal fluid temperature at 90°C, the geothermal to power efficiency can achieve to about 10% [14, 15]. For a 500MW power

plant, GAPG technology can increase the electricity production up to 19% [16]. However, it was found that the thermodynamic of GAPG plant over other kinds of geothermal alone power plant is dependent on the distance between geothermal well and RRC power plant [17]. Except thermodynamic advantages, it was also pointed that GAPG plant have advantage of lower cost of electricity than other kinds of geothermal alone power plant [18, 19].

Besides geothermal resources, solar thermal energy can also be used for preheating purpose, this kind of renewable preheating power system is termed as Solar Aided Power Generation (SAPG) technology [20]. Previous studies found that this kind of SAPG power system still have thermodynamic and economic advantages over solar alone power plants [21-26]. However, due to the intermittent nature of solar resources, a storage system is needed for the SAPG system [27-29]. Compared with SAPG plant, GAPG plant can be operated without thermal storage system, which means lower capital cost.

In a GAPG plant, power from geothermal comes from displaced extraction steam. Therefore, displacement of extraction steam at different stages leads to different technical benefit [6]. This means that geothermal to power efficiencies of the GAPG plant might be dependent on the displacement selections. Previous studies pointed that there are two kinds of structures for the GAPG plant, which were series structure and parallel structure [11, 12]. It was found that series structure has advantages of easy to control. However, the comparison of two structures for a given displacement selections is lack of study.

On the other side, GAPG plant faces problem of silica scaling in heat exchanger system, which would have negative effect on geothermal to power efficiency of the GAPG plant [30]. In the GAPG technology, with the geothermal fluid pumped from geothermal reservoir for preheating purpose, the temperature of geothermal fluid would be dropped. Then, the dissolved silicon dioxide would be precipitated from the geothermal fluid, and the silica scaling occurs in the heat exchanger system of the GAPG plant. The precipitation rate of silicon dioxide is mainly dependent on the geothermal fluid temperature and silica concentration. Therefore, displacement selections might have impact on silica scaling process in the heat exchanger system.

In present study, the silica scaling process in heat exchanger system with different displacement selections has been simulated for optimising displacement selections. Also, the technical performance of the parallel and series structures for the GAPG plant for the optimal displacement selections have been compared. In particulate, a GAPG plant, modified from 300 MW subcritical RRC power plant, is used as case study to optimise the displacement selections and structures of the GAPG plant.

## **2. Geothermal Aided Power Generation**

In a regenerative Rankine cycle (RRC) power plant (shown in Fig. 1), some parts of steam are extracted from steam turbine to preheat feedwater of power plant, the bled steam is terms as extraction steam (points A to H in Fig. 1). By doing this, the overall efficiency of the RRC power plant can be increased but it would lead to a decrease in the total power output per kilogram of the steam flow through the boiler.

The GAPG plant is based on the RRC power plant. In such a plant, the geothermal

energy carried by the geothermal fluid enters a heat exchange system for feedwater preheating purpose. The extraction steam replaced by the geothermal energy, terms as saved steam, could be expanded further in the lower stages of the steam turbine to generate power. After the feedwater of the RRC power plant is preheated by the geothermal fluid, the geothermal fluid is sent back to the geothermal wells. In order to integrate geothermal energy into power plant, there are two kinds of GAPG plant: parallel and series GAPG plant.

Figure 2 shows the schematic diagram of parallel GAPG plant feedwater heater system. As shown in Fig. 2, in a parallel GAPG plant each FWHs of an RRC power plant (FWH1 to FWH3 in Fig. 2) has one heat exchanger named geothermal preheater to transfer of the geothermal heat to the feedwater. Each geothermal preheater is parallel with the displaced FWH. The FWHs that is displaced by geothermal fluid is depended on the geothermal fluid temperature. If the temperature of geothermal fluid can be used to displace FWH1 in Fig. 2, the geothermal fluid enters geothermal preheater from point s1. After the geothermal fluid enters geothermal preheaters (geothermal preheater 1 to 3 in Fig. 2), the extraction steam at points A to C are replaced by geothermal energy. The valve A to H would be adjusted according to the geothermal fluid flow rate to make sure the feedwater temperature at exit of the FWH (points w1 to w8 in Fig. 2) keep unchanged. The valve  $V_{fA}$  to  $V_{fC}$  and  $V_{sA}$  to  $V_{sC}$  would also be adjusted to control the flow rate of feedwater across FWHs and geothermal preheaters. If the temperature of geothermal fluid can be used to displace FWH5 in Fig. 2, the geothermal fluid enters geothermal preheater from point s5 and FWH5 to FWH8 are displaced.

Figure 3 shows the schematic diagram of GAPG plant series operation. As shown in Fig. 3, in a series GAPG plant, there is only two heat exchangers to be used to preheat feedwater of power plant. The geothermal preheater 1 is used to displace FWH1 to FWH3 (high pressure FWHs) and the geothermal preheater 2 is used to displace FWH5 to FWH8 (low pressure FWHs). After the geothermal fluid enters geothermal preheater from point s1 in Fig. 3, the feedwater is preheated by geothermal fluid, the feedwater temperature at point ws1 increase with the geothermal fluid flow rate increasement, and the extraction steam at point C would be adjusted. After the feedwater temperature at point ws1 achieve  $T_{w3}$ , the extraction steam at point C are fully replaced. If the geothermal energy is sufficient enough, the extraction steam at point B and A would be replaced until all the extraction steam at point A, B and C are replaced. If the geothermal fluid is used to displace FWH4 to FWH8, the geothermal fluid enters geothermal preheater from point s3.

As shown by previous, the parallel and series GAPG plant have different structures. The different between two kinds of GAPG plant are shown as:

- In the parallel GAPG plant, the FWHs are simultaneous displaced by geothermal energy; and in the series GAPG plant, the FWHs are displaced by geothermal energy from lower pressure FWHs to higher pressure FWHs.
- The number of geothermal preheaters in the series GAPG plant is fewer than the parallel GAPG plant. The system structure of the series GAPG plant is simple than the parallel GAPG plant.

In a GAPG plant system, in order to maximise the technical benefit from

geothermal energy, the geothermal fluid should be used to displace extraction steam of the RRC power plant stage by stage, and the temperature of geothermal fluid drops from each stage to other stage of extraction steam. However, when the temperature of geothermal fluid drops, the dissolved silicon dioxide in geothermal fluid would precipitate from the fluid, which the precipitation rate of silicon dioxide is as a function of geothermal fluid temperature and silica concentration [31]. In a GAPG plant, there are different displacement selections of using geothermal fluid to displace different stages of extraction steam. Different displacement selections lead to different geothermal inlet and outlet temperature. Therefore, with various silica concentration of geothermal fluid, different displacement selections can help to reduce silica scaling in heat exchanger system of the GAPG plant.

### **3. Methodology**

A simulation model has been developed for calculating the performance of the GAPG plant. The simulation model consists of two parts. The first part is used to simulate the technical performance of the GAPG plant, and the second part is used to evaluate the silica scaling process in heat exchanger system with different displacement selections.

#### **3.1 Modelling of the GAPG plant**

In a GAPG plant, the geothermal energy is used to preheat feedwater by integrating geothermal energy into the FWH system of the RRC power plant. Therefore, the simulation of the GAPG plant is actually modelling the energy and mass balance flows in the FWH system. In the SAPG plant, Matrix Method is an often-used approach to

simulate the FWH system after solar integration [32]. In this paper, the Matrix Method is used to calculate the mass flow rate of the extraction steam after geothermal energy integration can be calculated. Then, the power output of steam turbine can be calculated by using new calculated mass flow rate.

For a GAPG plant modified from a power plant with 8 FWHs (1 deaerator, 3 high pressure FWHs and 4 low pressure FWHs), and geothermal energy is used to displace extraction steam to all high pressure FWHs, the Matrix for FWH system can be expressed as:

$$\begin{pmatrix} q_1 & \dots & 0 \\ r_2 & q_2 & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_3 & r_3 & q_3 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ r_4 & r_4 & r_4 & q_4 & \ddots & \ddots & \ddots & \ddots & \vdots \\ \tau_5 & \tau_5 & \tau_5 & \tau_5 & q_5 & \ddots & \ddots & \ddots & \vdots \\ \tau_6 & \tau_6 & \tau_6 & \tau_6 & r_6 & q_6 & \ddots & \ddots & \vdots \\ \tau_7 & \tau_7 & \tau_7 & \tau_7 & r_7 & r_7 & q_7 & \ddots & \vdots \\ \tau_8 & \tau_8 & \tau_8 & \tau_8 & r_8 & r_8 & r_8 & q_8 & \vdots \end{pmatrix} \begin{pmatrix} y_A \\ y_B \\ y_C \\ y_D \\ y_E \\ y_F \\ y_G \\ y_H \end{pmatrix} + \begin{pmatrix} \dot{Q}_{Geo,1}/\dot{m}_0 \\ \dot{Q}_{Geo,2}/\dot{m}_0 \\ \dot{Q}_{Geo,3}/\dot{m}_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \\ \tau_7 \\ \tau_8 \end{pmatrix}, \quad (1)$$

where,  $q_i$  (kJ/kg) is the specific enthalpy decrease of the extraction steam in the  $i^{\text{th}}$  FWH;  $\tau_i$  (kJ/kg) is the specific enthalpy increase of the FW in the  $i^{\text{th}}$  FWH;  $r_i$  (kJ/kg) is the specific enthalpy decrease of the drained steam from the  $(i-1)^{\text{th}}$  FWH in the  $i^{\text{th}}$  FWH; and  $y_i$  is the mass flow rate of the each stages of extraction steam.  $\dot{Q}_{Geo,i}$  (kJ/s) is the geothermal energy displacing the extraction steam of  $i^{\text{th}}$  FWH; and  $\dot{m}_0$  (kg/s) is the mass flow rate of steam outlet boiler. The  $\dot{Q}_{Geo}$  is equal to  $\sum \dot{Q}_{Geo,i}$ . The mass flow rates of each extraction steam required with various geothermal energy input could be calculated by solving Eq. (1). Then, the power output of steam turbine can be calculated by using new calculated mass flow rate.

In a GAPG plant, when geothermal energy is used to increase power output of

RRC power plant, the increased power output can be termed as geothermal power output. Therefore, the power efficiency for the whole GAPG plant can be given as:

$$\eta_{Geo} = \frac{\Delta W_e}{Q_{Geo} + Q_{Boiler}}, \quad (2)$$

where  $\Delta W_e$  is the power output of the steam turbine after geothermal integration; and  $Q_{Geo}$  is the geothermal energy input.

### 3.2 Prediction of the silica deposition

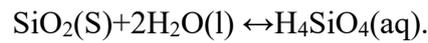
In a GAPG plant, when the geothermal fluid flow up the geothermal well and quench to a lower temperature, the silicon dioxide becomes supersaturated [33]. Polymerization occurs when silica is in a supersaturated concentration, and polymerization continues until the silica scaling [34]. The silica scaling occurs in geothermal wells (both production wells and injection wells), pipes of well field and heat exchanger system of the GAPG plant.

In geothermal fluid, the rates of silica deposition and polymerization is determined by the PH and salt concentration of geothermal fluid, the residence time and temperature of geothermal fluid [34]. The rate of silica deposition can be controlled by adjusting PH through the addition acid or by adding salt [34]. However, adding salt might still have a negative effect on the pipes of power system and environment of geothermal wells. In present paper, it is assumed that the solubility of silicon dioxide is only controlled by the temperature of the geothermal fluid and the silica scaling occurs in the heat exchanger system of the GAPG system.

In order to optimise the displacement selections of the GAPG plant with different silica concentration, the net precipitation rate of silicon dioxide should be calculated.

The approaches taken to calculate the silica precipitation and deposition rate of silicon dioxide are quite complex and poorly understood [35]. A simplified approach using experimental data from Brown and Bacon is used in present paper to calculate the deposition rate of silicon dioxide.

The precipitation rate of silicon dioxide is mainly determined by the kinetics of amorphous silica in the geothermal fluid. For geothermal fluid at temperatures ranging from 0-300°C, the kinetics of amorphous silica precipitation have been determined by the study of Rimstidt and Barnes [36]. The reversible reaction of silicon dioxide is shown as:



For this reversible reaction,  $\text{H}_4\text{SiO}_4(\text{aq})$  is the precipitation of silicon dioxide.

The net precipitation rate can be expressed as [31]:

$$r'_{\text{SiO}_2} = -k_+ \left(1 - \frac{Q}{K}\right) \frac{\text{mol}}{\text{L.S}}, \quad (3)$$

where the  $k_+$  is the forward rate constant,  $K$  is the equilibrium constant and  $Q$  is the activity quotient. The  $Q/K$  is the degree of saturation ( $S$ ).

$Q$  is then calculated by

$$Q = \frac{a_{\text{H}_4\text{SiO}_4}}{(a_{\text{SiO}_2})(a_{\text{H}_2\text{O}})^2}, \quad (4)$$

where,  $a_i$  is the activity of species  $i$ . In the mathematical model,  $a_i$  is calculated as the silica concentration. As  $\text{SiO}_2$  and  $\text{H}_2\text{O}$  are present as a solid and a liquid, then  $a_{\text{SiO}_2}$  and  $a_{\text{H}_2\text{O}}$  can be calculated as “1”.

Rimistidt and Barnes provide a method to calculate  $k_+$  and  $K$  as a function of the geothermal fluid temperature [36]. The forward rate constant  $k_+$  and the equilibrium

constant are given by:

$$\log K = a_1 + b_1 T + c_1 / T, \quad (5)$$

$$\log k_+ = (a_1 + a_2) + b_1 T + (c_1 + c_2) / T. \quad (6)$$

Rimistidt and Barnes provide the  $a_1$ ,  $a_2$ ,  $b_1$ ,  $c_1$ ,  $c_2$  which is shown in Table 1.

From Eq.3 to Eq.6, the net precipitation rate of silica with various geothermal fluid temperature and silica concentration can be expressed as follows:

$$r'_{\text{SiO}_2} = 10^{(a_1 + a_2) + b_1 T + \frac{c_1 + c_2}{T}} \left( 1 - \frac{a_{\text{H}_4\text{SiO}_4}}{10^{a_1 + b_1 T + \frac{c_1}{T}}} \right) \frac{\text{mol}}{\text{L.S}}. \quad (7)$$

By using Eq. 6, silica scaling process in heat exchanger system of the GAPG plant can be simulated.

#### 4. Case study

In present study, a GAPG plant, modified from a 300 MW subcritical RRC power plant, are used as case study, which is shown in Fig. 1. The key parameters of the 300 MW power plant is given in Table 2. As can be seen in Fig. 1, 300MW subcritical RRC power plant have seven feedwater heaters and one deaerator. Three different displacement scenarios have been evaluated in present study, which is given in Table 3.

In the Scenario 1, the geothermal energy is used to displace extraction steam to all high-pressure feedwater heaters (FWH 1 to FWH 3 in Fig. 1). In the Scenario 2, the geothermal fluid is used to displace extraction steam to all low-pressure feedwater heaters (FWH5 to FWH8 in Fig. 2). In the Scenario 3, the geothermal fluid is used to displace extraction steam all feedwater heaters.

In present study, the geothermal fluid temperature is assumed to be about 10 °C higher than the feedwater temperature for heat transfer purpose. In geothermal

reservoirs, solid is present as quartz, and the concentration of silica in the reservoir ranges from 500 to 700 mg/kg SiO<sub>2</sub>, which is dependent on the temperature of geothermal reservoir [37]. Therefore, the concentration of silica is assumed at 550, 600, 650, and 700mg/kg, respectively.

## 5. Results and discussion

Fig. 4 presents the precipitation rate of amorphous silicon dioxide as a function of geothermal fluid temperature and silicon dioxide concentration. As shown in Fig. 4, as the temperature decreases, the silicon dioxide begin to precipitate from geothermal fluid. The precipitation rate increases rapidly to achieve a maximum precipitation rate. Following the achievement of maximum precipitation rate, the precipitation rate decreases slowly. When the temperatures below about 60 °C, the precipitation rate is small.

From Fig. 4, it can be seen that the silicon dioxide scaling temperature and the temperature of maximum precipitation rate are depended on the silicon dioxide concentration. When the silicon dioxide concentration is 700 mg/kg, the silicon dioxide begins to precipitate at about 162°C, and the maximum precipitation rate occurs at about 140°C. While, when the silicon dioxide concentration decreases to 550 mg/kg, these two temperatures decrease to about 136°C and 116°C. This trend provides a mechanism to decrease silica scaling in the heat exchanger system of the GAPG plants.

For the Scenario 1, the geothermal inlet temperature for 300 MW power plant is 280 °C, and the geothermal outlet temperature are 180 °C. However, from Fig. 4, it can be seen that when the silicon dioxide concentration of geothermal fluid ranges from

550ppm to 700ppm, the silicon dioxide begins to precipitate from geothermal fluid from about 140 °C to 160 °C. This means that, for the Scenario 1, silica scaling would not occur in the heat exchanger system. In other words, precipitation of silicon dioxide has no impact on the technical performance of the GAPG plant.

Fig. 5 presents the variations of precipitation rate in the heat exchangers system of the GAPG plant as a function of temperature and silicon dioxide concentration for the Scenario 2. For the Scenario 2, the geothermal inlet temperature is 155 °C, and the geothermal outlet temperature is 45 °C. As can be seen in Fig. 5, when the geothermal fluid with concentration of silica at 650 mg/kg and 700 mg/kg, silicon dioxide begins to precipitate from geothermal fluid when they entering the heat exchanger system of the GAPG plant. When the concentrations of silica are 550 mg/kg and 600 mg/kg, about 90% and 80% of heat exchanger system of the GAPG plant are susceptible to fouling by silicon dioxide. This means that the Scenario 2 is not suitable for the GAPG plant.

The variations of precipitation rate of silicon dioxide in the heat exchanger system for Scenario 3 is plotted in Fig. 6. For the Scenario 3, the geothermal inlet and outlet temperatures are 280 °C and for 45 °C. As can be seen in Fig. 6, when the temperature decreases to about 160 °C, the geothermal fluid becomes saturated. This means that about 50% of heat exchanger system is susceptible to fouling by silicon dioxide. This area is the heat exchanger system parallel with low pressure heat exchanger system. This means that geothermal fluid with concentration of silica at 550 mg/kg to 700 mg/kg is also not suit for the Scenario 3.

From Fig. 4 to Fig. 6, it can be concluded that geothermal energy used to displace

extraction steam to all high pressure FWHs is the best option for the GAPG plant, due to the low silica scaling during the preheating process. Therefore, the technical performance of the GAPG plant with two structures for scenario 1 has been compared.

Figure 7 shows the Extra power output of steam turbine after different geothermal fluid flow rate integration. Fig. 7 shows that when the FWH1 to FWH3 are fully displaced by geothermal energy, the two kinds of GAPG plant have the same power output. When the extraction steam to FWH1 to FWH3 are fully displaced by the geothermal energy, the extra output of steam turbine is 38.9MW for both of the GAPG plants. However, when the extraction steam to FWH1 to FWH3 are partly displaced by the geothermal energy, the power output of the Parallel GAPG plant is higher than the Series GAPG plant. The reason is thought that in the Series GAPG plant, the lower pressure FWH is displaced firstly, this leads to the lower power output than the Parallel GAPG plant.

Figure 8 shows the power output percentage difference of two kinds of GAPG plant. As shown in Fig. 8, when 50kg/s geothermal fluid is integrated into two kinds of GAPG plant, the extra output of the Parallel GAPG plant is 29.3% higher than the Series GAPG plant. With the increasement of geothermal fluid, the power output difference percentage decrease with the amount of geothermal energy integration.

Figure 9 shows the power output difference of two kinds of the GAPG plant with difference geothermal fluid integration. The Fig. 9 indicates that when the flow rate of geothermal fluid integrated into two kinds GAPG plant from 50kg/s to 100kg/s, the output difference increases from 1.1MW to 2.1MW. After the geothermal fluid flow

rate is 100kg/s, with the increasement of geothermal fluid flow rate, the output difference of two kinds of GAPG plant decrease until to 0.

Table 4 shows the hybrid efficiencies of two kinds of GAPG plant with different geothermal energy integration. The hybrid efficiency is defined as the total output of the steam turbine divided by the boiler fuel consumption and geothermal integration. As shown by Table 4, with the same amount of geothermal thermal energy integration, the two kinds of GAPG plant have almost the same hybrid efficiencies.

## **6. Conclusions**

In a GAPG plant, geothermal fluid at different temperature can be used to displace extraction steam at different stages of feedwater heater. Different displacement selections lead to different technical performance. As the rate of silica deposition is mainly dependent on the temperature of geothermal fluid, adjusting displacement selections can be used to control silica scaling in heat exchanger system of the GAPG plant. Also, there are two structures for the GAPG plant, Parallel and Series structures, which leads to different technical performance for the GAPG plant. In present paper, the silica scaling in heat exchanger system of the GAPG plant with different displacement selections are simulated to optimise displacement selections. The technical performance for the optimal displacement selections with two structures has been compared. In order to achieve this aim, a GAPG plant, modified from a 300MW subcritical power plant, are used as case study. Three different displacement selections are used as scenarios for assessment. The first scenario is geothermal fluid used to displace extraction steam to all high-pressure feedwater heaters. The second and third

scenarios are geothermal fluid used to displace extraction steam to all low-pressure feedwater and all feedwater heaters, respectively. The results indicate that:

- For the Scenario 1, there is no silicon dioxide scaling occurred in the heat exchanger system of the GAPG plant. In other words, for scenario 1, there is no energy loss caused by silica scaling with different silicon dioxide concentration in geothermal fluid.
- In the Scenario 2, when the silica concentration is greater than 550 mg/kg, more than 80% of heat exchanger system are susceptible to fouling by silicon dioxide.
- For the Scenario 3, it was found that, when the concentration of silica ranges from 550 mg/kg to 700 mg/kg, silicon dioxide scaling occurs in the heat exchanger system parallel with low pressure heat exchanger system.
- Considering the silicon dioxide scaling in heat exchanger system of the GAPG plant, the Scenario 1 is the best displacement selections for the GAPG plant.
- When the geothermal energy is used to partly displace the extraction steam of power plant, the power output of the Parallel GAPG plant is higher than the Series GAPG plant. However, when the geothermal energy is used to fully displace the extraction steam of power plant, the two kinds of GAPG plant have the same power output. When the geothermal fluid flow rate is 100kg/s, there is a maximum power output difference which is 2.1MW.

## **Declarations**

- Availability of data and materials

The datasets generated and/or analysed during the current study are available in

the Zhou repository.

- Competing interests

The authors declare that they have no competing interests.

- Funding

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- Authors' contributions

Zhou provided the acquisition analysis of this work and drafted this paper. Qin designed this work and substantively revised it.

- Acknowledgements

Not applicable.

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# Figures

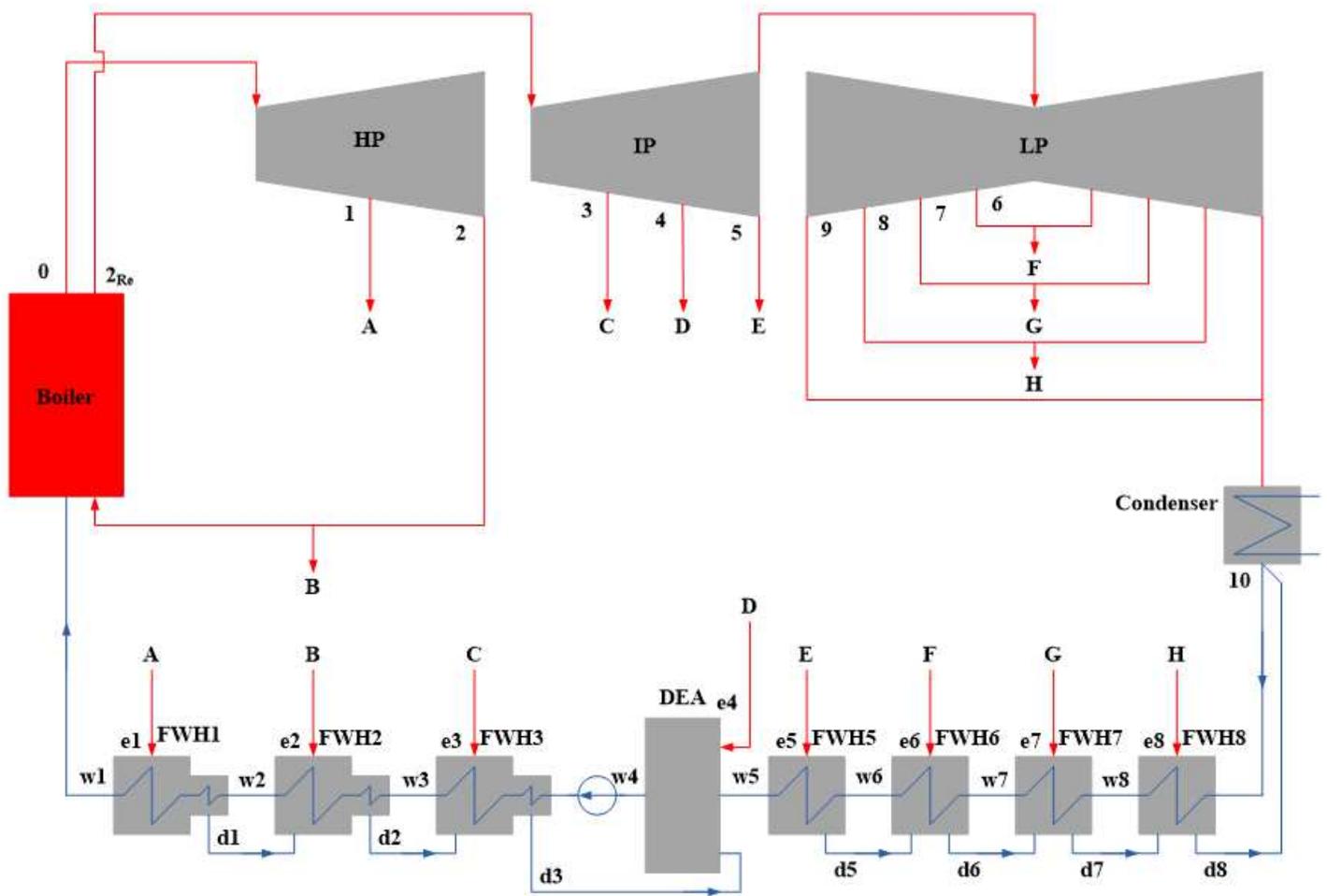


Figure 1

Schematic diagram of a typical 300 MW regenerative Rankine cycle power plant with seven feedwater heater (FWH) and one deaerator.

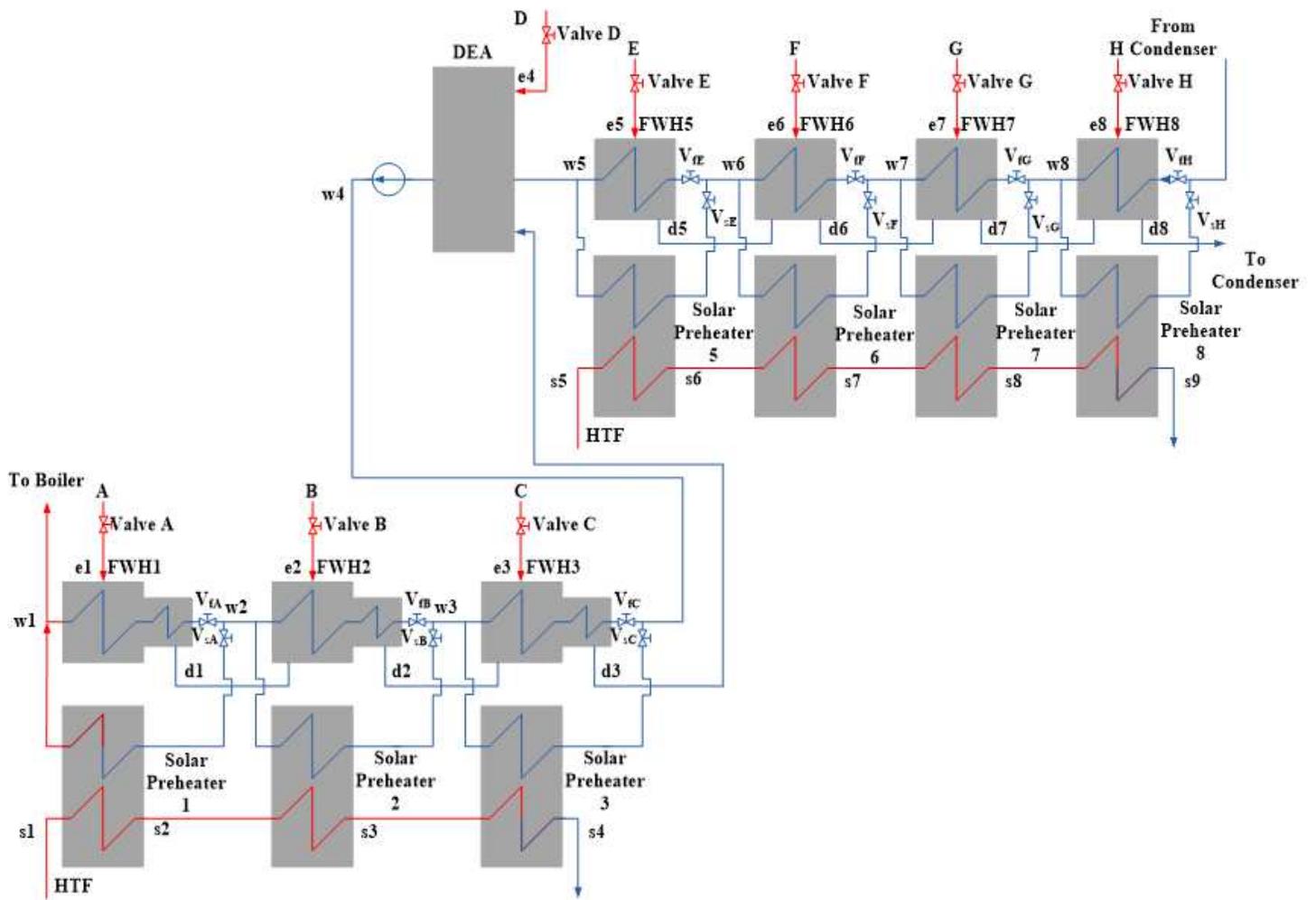


Figure 2

Schematic diagram of parallel GAPG plant feedwater heater system.

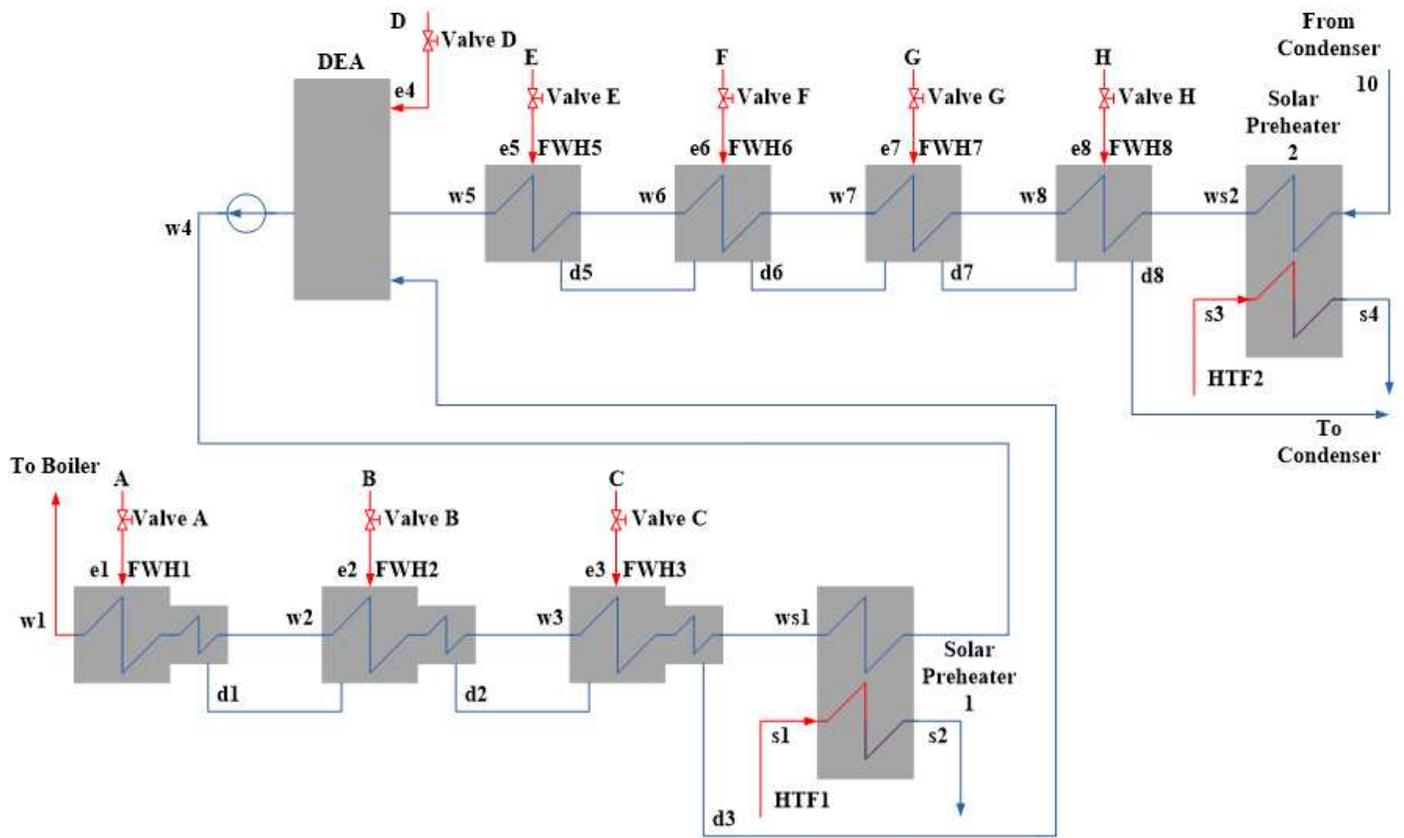


Figure 3

Schematic diagram of series GAPG plant feedwater heater system.

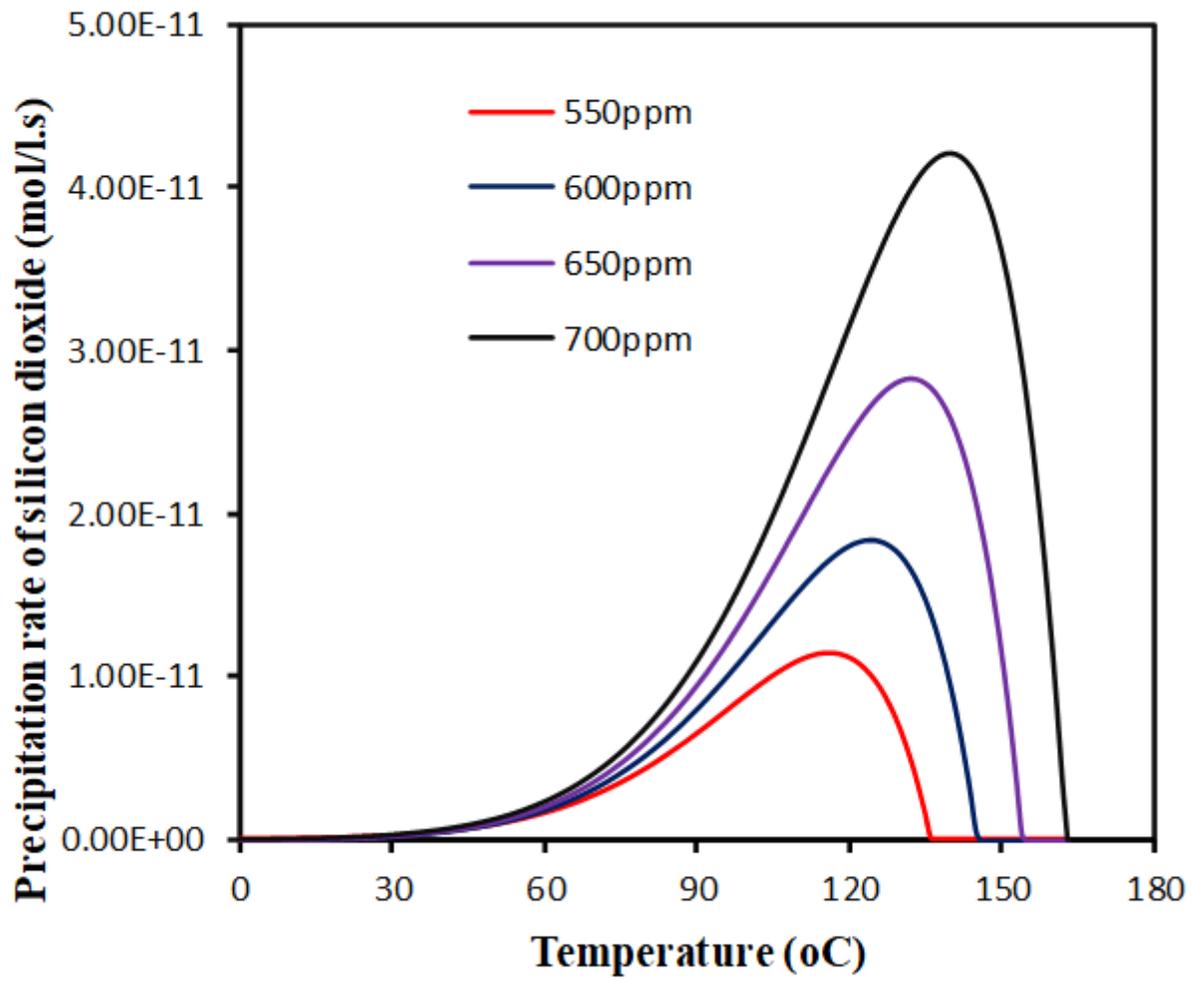


Figure 4

Precipitation rate of silicon dioxide as a function of geothermal fluid temperature and silicon dioxide concentration.

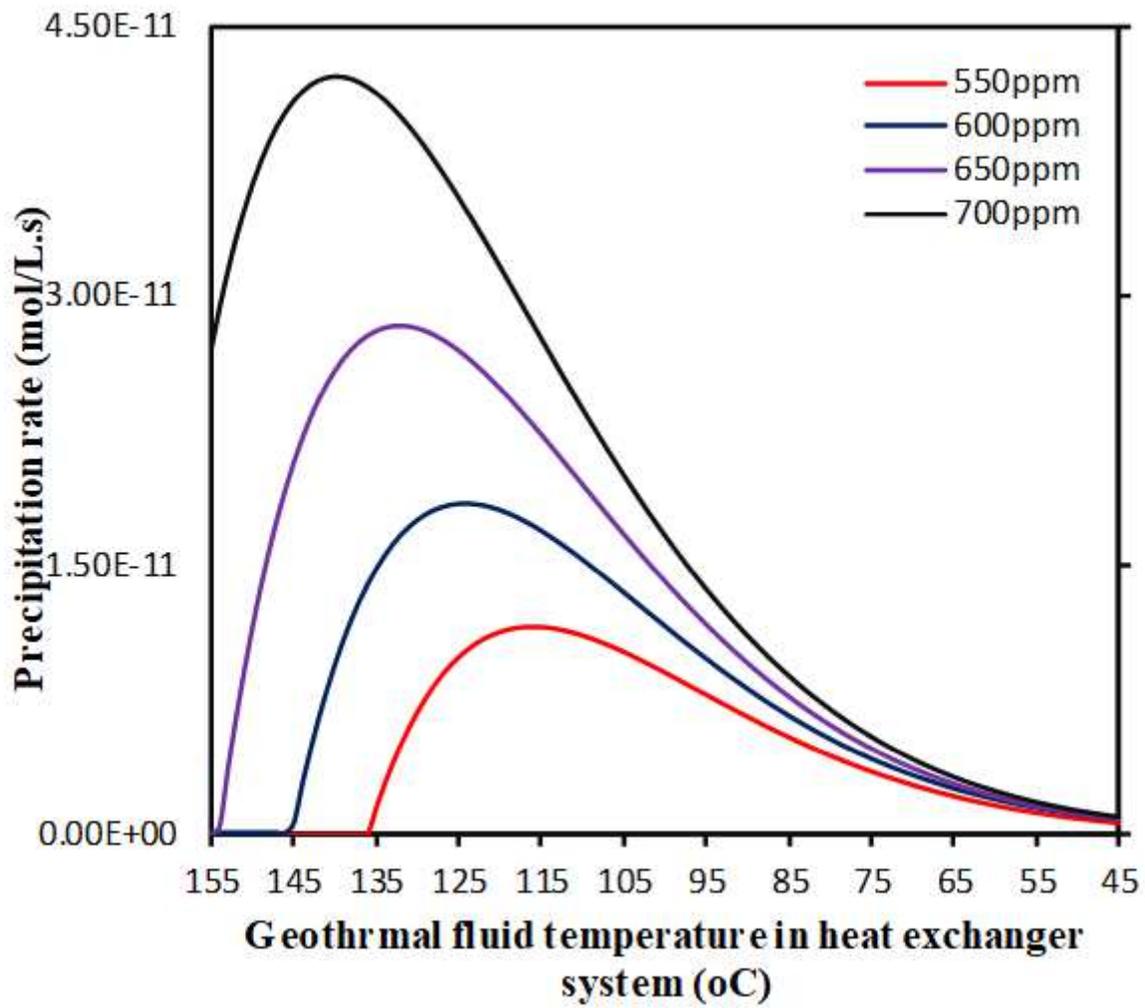


Figure 5

Precipitation rate as a function of temperature in the heat exchanger system for Scenario 2, the GAPG plant is modified from a 300 MW subcritical power plant.

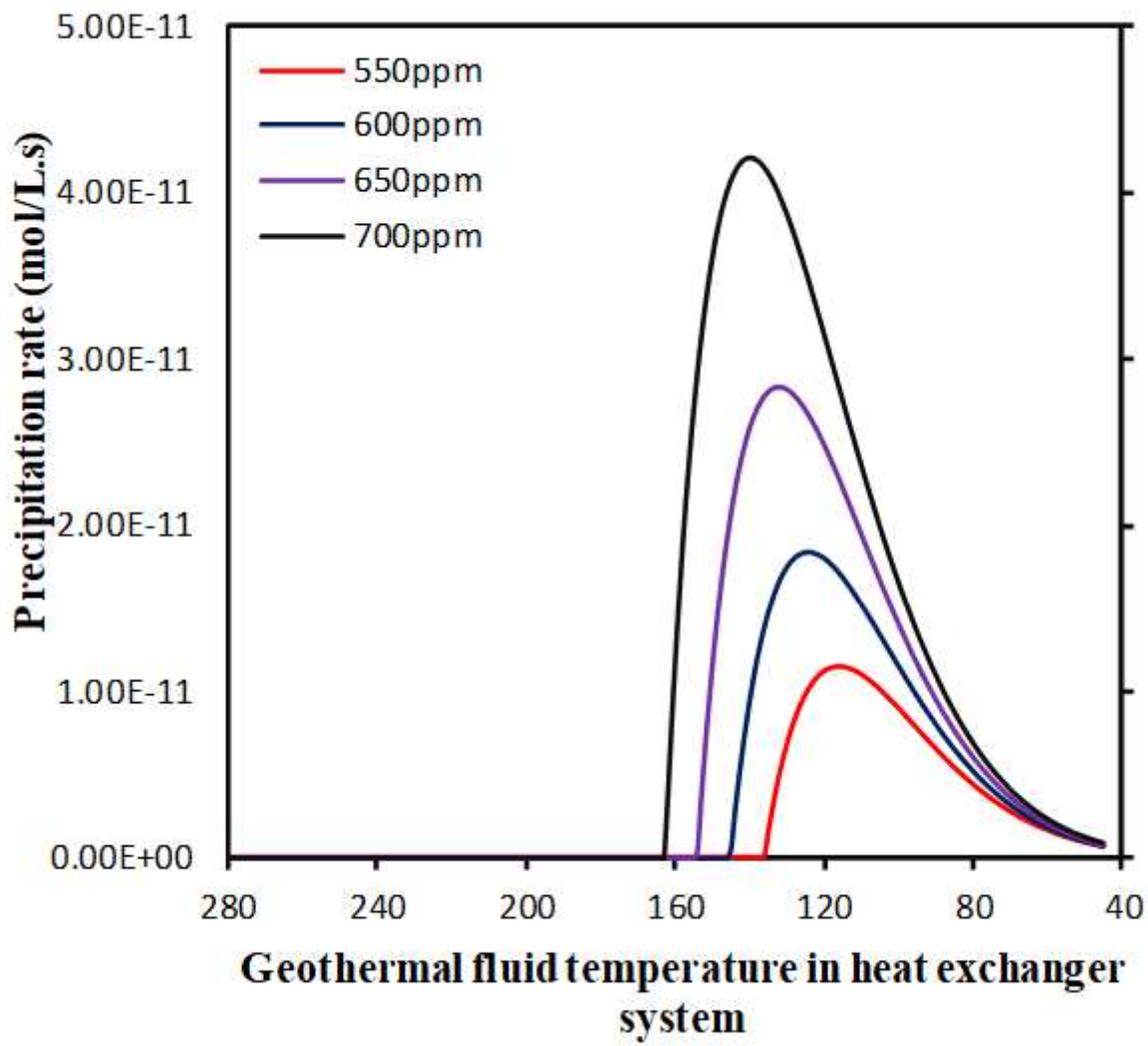


Figure 6

Precipitation rate as a function of temperature in the heat exchanger system for Scenario 3.

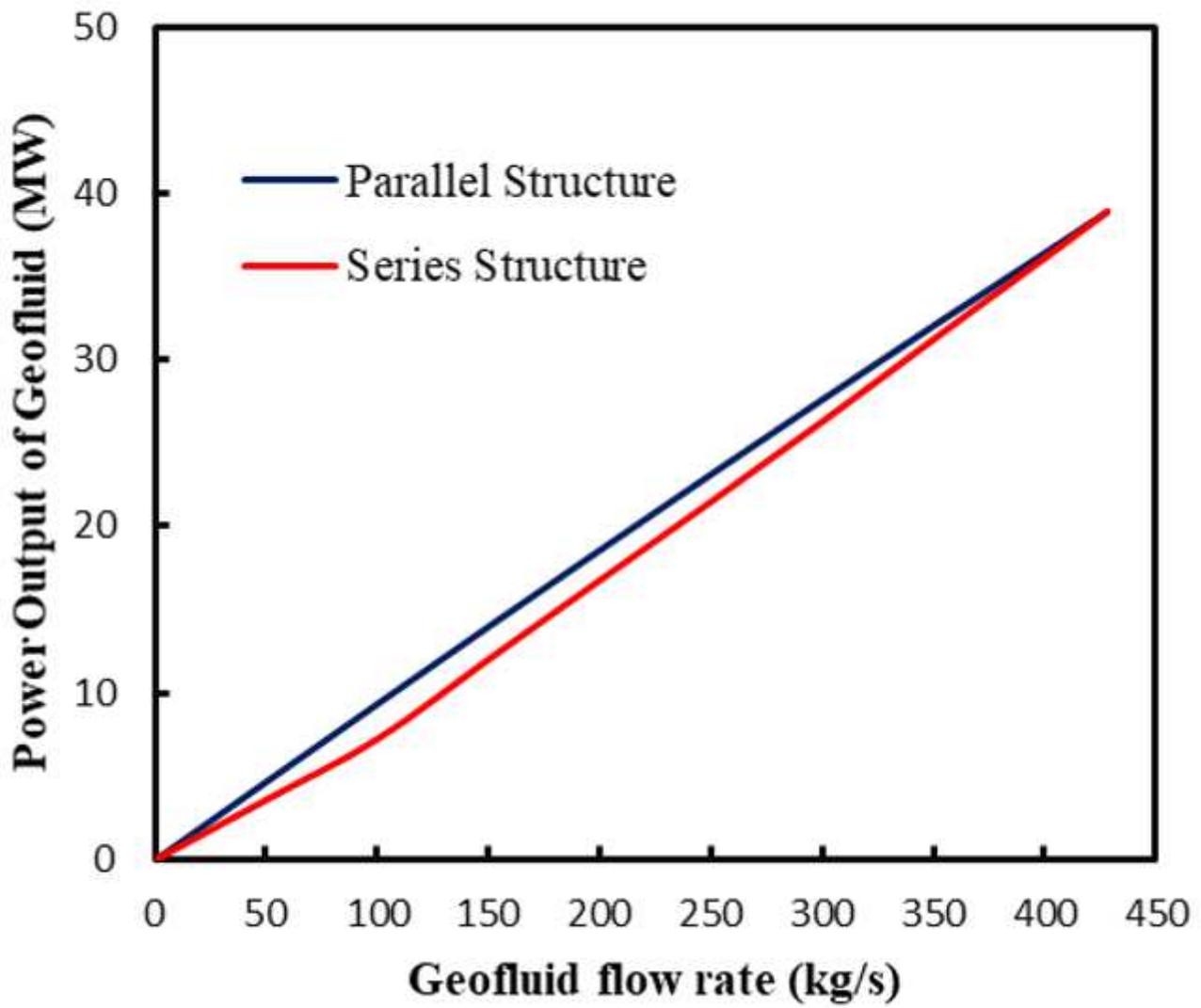


Figure 7

Power output of geothermal energy of two kinds of GAPG plant with different geothermal fluid integration.

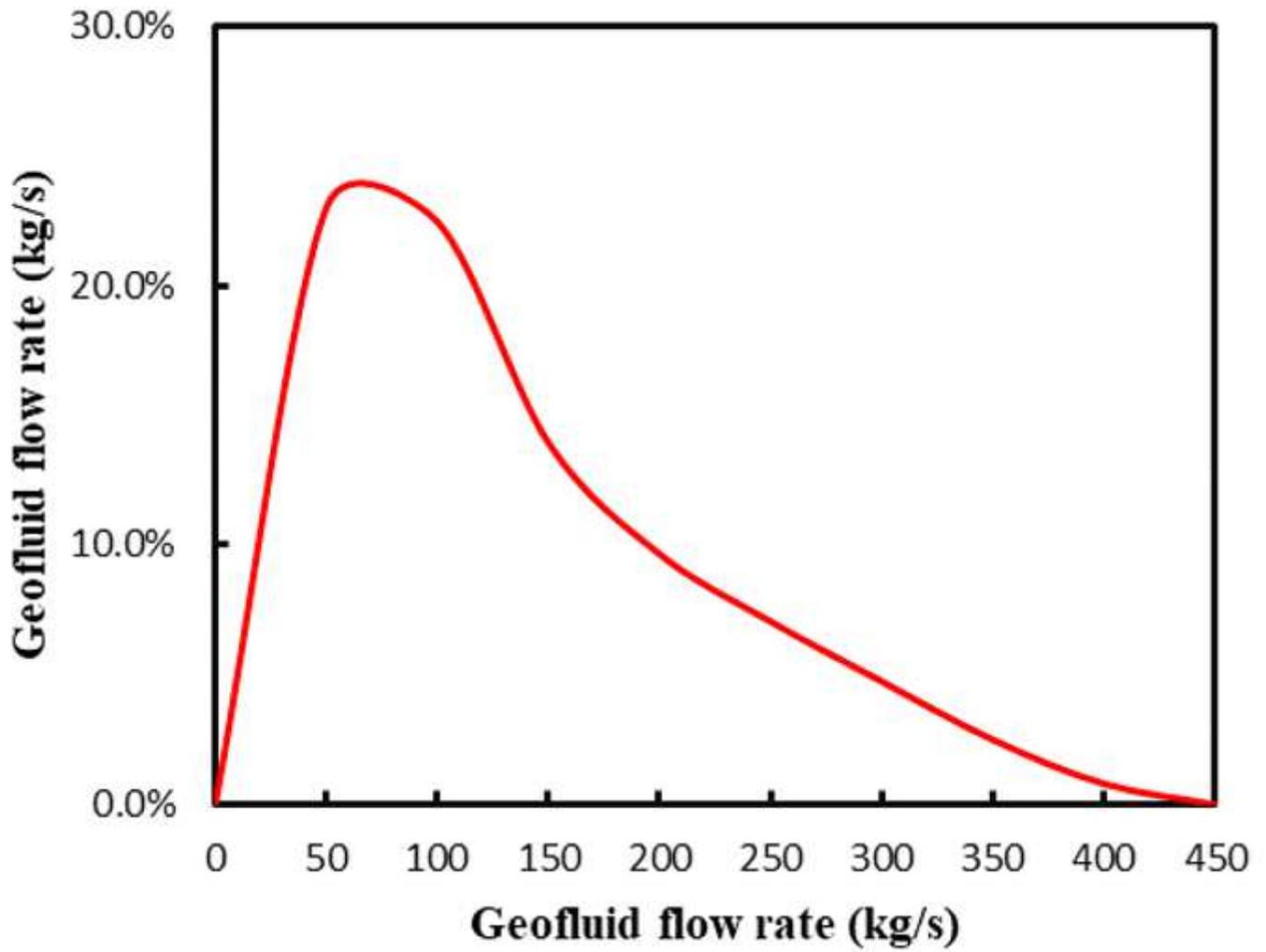


Figure 8

Comparison of two kinds of GAPG plant output with same amount of geothermal integration.

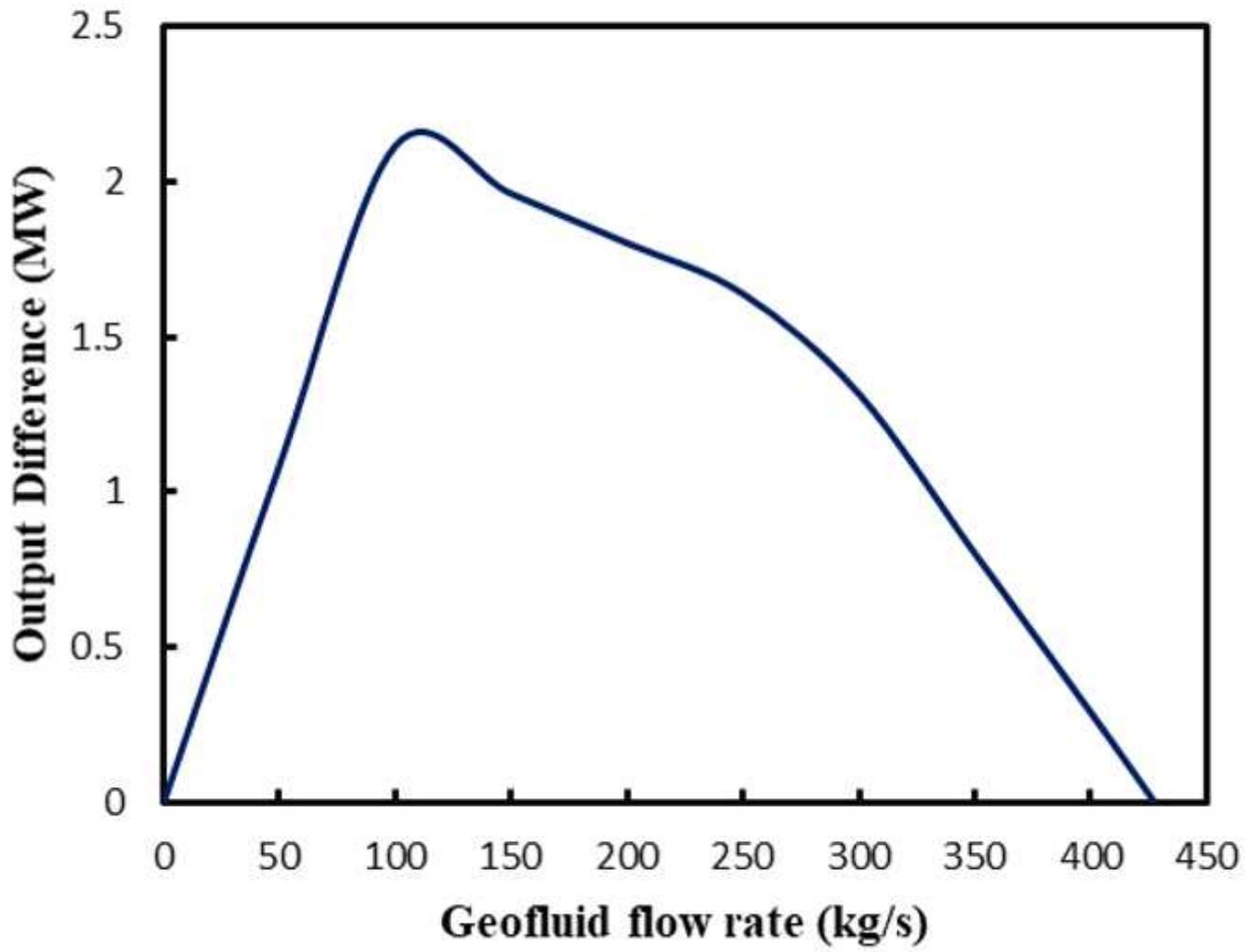


Figure 9

Power output difference between two kinds of GAPG plant with same amount of geothermal integration.