Energy Proceedings
Vol 40, 2024
ISSN 2004-2965

# A Case Study on Well Structure Optimization Based on Improving the Heat Extraction Efficiency of Geothermal Wells

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**ABSTRACT**

The extraction of geothermal energy from hot dry rock resources has gradually received widespread attention. How to efficiently extract geothermal energy has become a key technology to be developed. In this study, based on 5 existing vertical geothermal wells with a depth of about 4000 meters in a basin in northwest China, numerical simulation of the well structure optimization has been carried out to improve the heat extraction performance. Research has found that, compared with a single vertical well, the outlet temperature of the heat-extraction fluid from a 3-branch L-shape horizontal well has increased by 74.65°C, with the corresponding heat extraction rate being increased by 2.2MW. The outlet temperature of the connecting well cluster (4 L-shape wells connected to a common vertical production well) is 8.66°C higher than that of the vertical well, with the total heat extraction rate being 0.11MW higher than that of the five vertical wells. One important finding in this case is that, the outlet pressure of this connecting well cluster is about 4 bars higher than its inlet pressure, indicating that there is an obvious thermal siphon effect. This implies that using the proposed connecting well cluster can greatly reduce the pump power required for system operation and hence greatly reduce the operating costs. The results obtained from this study is of theoretical-guiding significance for hot-dry-rock geothermal energy exploitation.

**Keywords:** well structure optimization, Closed-loop heat extraction, 3-branch L-shape horizontal well, connecting well cluster, thermal siphon effect

## 1. INTRODUCTION

In September 2020, China clearly proposed the "dual carbon" goals of "carbon peaking" in 2030 and "carbon neutrality" in 2060. Geothermal energy is an important clean energy source, and the development of geothermal energy can help achieve the "dual carbon" goal [1]. In recent years, the extraction and utilization of geothermal energy has gradually received widespread attention, and how to efficiently extract geothermal energy has become an urgent problem to be solved.

Liu et al. [2] established a closed system model and studied the effects of cement thermal conductivity, cement thickness, injection temperature, fluid rate, fluid heat capacity, heat exchanger height and diameter on the system heat extraction rate. Daneshipour et al. [3] used nanofluids as circulating fluid and concluded that using copper oxide water could extract more heat than alumina water, but the corresponding pressure loss and required pumping power were large. Wang et al. [4] found that groundwater flow can accelerate the stability of heat transfer processes. To further improve the heat extraction rate, domestic and foreign scholars have optimized the structure of a single vertical geothermal well. Kujawa et al. [5] established a bottom connected double pipe geothermal heat exchanger model and evaluated the possibility and applicability of obtaining geothermal energy from the existing production well Jacho'wka K-2 with a depth of 2870m. Ma et al. [6] established a U-shaped geothermal well heat extraction model based on abandoned oil wells and analyzed the variation of temperature field with time and space. Wei et al. [7] analyzed the effects of two different working fluids, water and thermal oil, on the thermal extraction rate of U-shaped geothermal wells with long horizontal section. Shi et al. [8] compared the heat extraction performance of three borehole heat exchangers (single U-tube, double U-tube and spiral tube).

At present, there is relatively little research based on practical engineering, especially on well clusters, and the guiding significance for practical engineering is relatively

# This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

weak. This study is based on the existing 5 vertical geothermal wells with a depth of 4000m in a basin in northwest China, studying the impact of mass flow rate on heat extraction performance, and optimizing the well structure to improve the heat extraction rate.

## 2. MODELS

### *2.1 Model description*

Fig. 1 shows the schematic diagram of the wellhead distribution of five existing wells in a basin in northwest China, and the five wells are all vertical wells with a depth of 4000m. The 2-D schematic diagram of their closed-loop heat extraction model is shown in Fig. 2. The working fluid flows downward from the annular space, exchanging heat with the formation, and then it returns to the wellhead through a circular inner pipe.

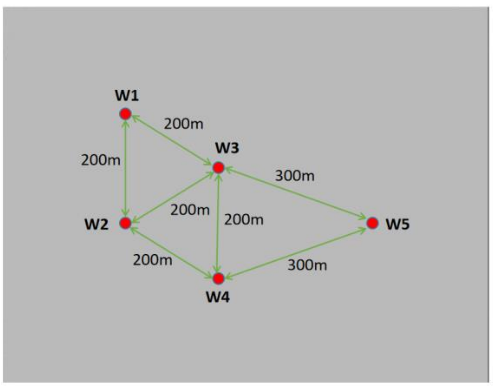


Fig. 1. Schematic diagram of wellhead distribution

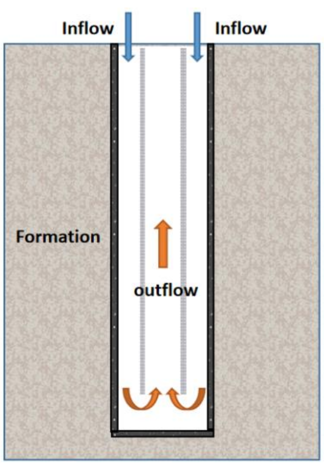


Fig. 2. Closed-loop heat extraction model

In order to improve the heat extraction performance of existing geothermal wells, the well structure is optimized and two new geothermal well models are constructed. The schematic diagrams of the two models are shown in Fig. 3.

Model 1: A 3-branch L-shaped horizontal well (hereinafter referred to as a horizontal well), with a length of 2000m for each branch and 4000m for vertical section.

Model 2: A connecting well cluster, with 4 L-shape injection wells connecting to a common vertical production well (hereinafter referred to as connecting well cluster).

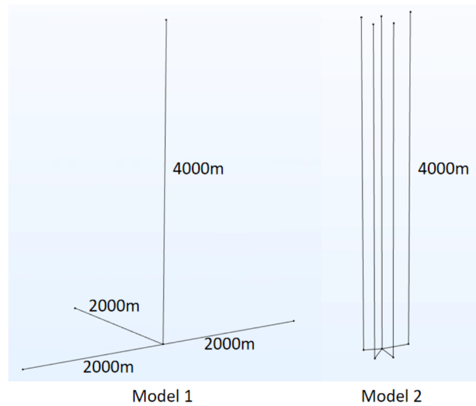


Fig. 3. Schematic diagram of two new geothermal well models

In this study, the inlet temperature is set to 60°C. The surface of the formation takes constant temperature boundary conditions, and the temperature is set at 0 °C, the formation temperature profile is shown in Fig. 4. The adiabatic boundary condition is selected for the outer boundary of the whole calculation domain. The formation properties used in the simulation are shown in Table 1. The parameters of the coaxial heat exchangers used in Model 1 are shown in Table 2, and the parameters of the pipes in Model 2 are based on the outer pipe in Table 2. The operation time of all models in this study is 120 days.

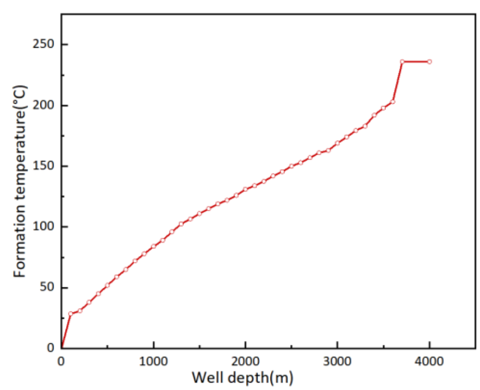


Fig. 4. Formation temperature profile

Table. 1. Properties of the formation [9]

| Density ($kg \cdot m^{-3}$) | Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$) | Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) |
|---|---|---|
| 2820 | 1170 | 2.8 |

Table. 2. Main parameters of the coaxial heat exchangers used in the simulation [9]

| Name | Size (mm) | Length (m) | Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) | Density ($kg \cdot m^{-3}$) | Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$) |
|---|---|---|---|---|---|
| Inner pipe | ⌀110×10 | 3998 | 0.02 | 950 | 2300 |
| Outer pipe | ⌀177.8×9.19 | 4000 | 40 | 7850 | 498 |

### *2.2 Model validation*

Here, a single vertical well model was validated with on-site test data in Hebei. Fig. 5 shows the fitting curve between the measured outlet temperature and the simulated outlet temperature. The comparison between simulated and measured values is shown in Table 3, and the relative error after 47 hours is 2.9%. Therefore, the vertical well model is relatively reliable.

Since the models of horizontal well and connecting well cluster agree with vertical well in the same modeling method and solution method, it is assumed that all the models used in this study are reliable.

Table. 3. Comparison between measured and simulated values

| Region | Value |
|---|---|
| Well depth (m) | 1400 |
| Flow rate ($m^3 \cdot h^{-1}$) | 46 |
| Measured outlet temperature (°C) | 18 |
| Simulated outlet temperature (°C) | 17.47 |

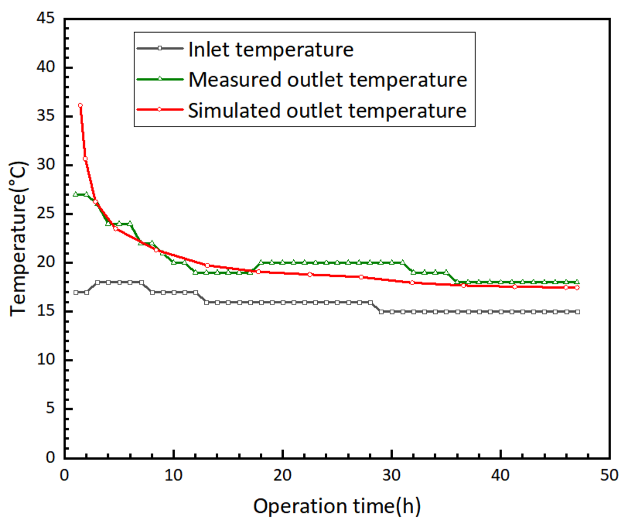


Fig. 5. Fitting curve between measured outlet temperature and simulated outlet temperature

## 3. SIMULATION RESULTS

Fig. 6 shows the variation of outlet temperature and heat extraction rate with mass flow rate for a single vertical well. It can be seen that the outlet temperature gradually descends with the increase of mass flow rate, but the magnitude becomes smaller. The heat extraction rate rises with the increase of mass flow rate. Taking into account the outlet temperature and heat extraction rate of the working fluid, the optimization of the well structure in this study will be carried out with a mass flow rate of 7kg/s. After 120 days of operation, the outlet temperature of a single vertical well is 90.99 °C, and the heat extraction rate is 0.91MW.

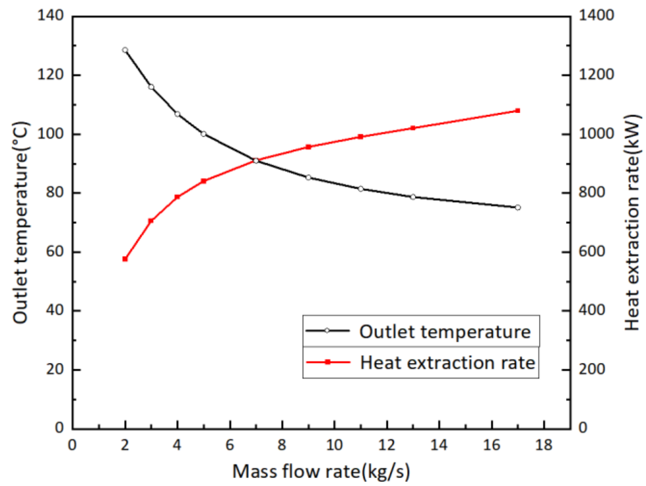


Fig. 6. Outlet temperature and heat extraction rate variations of vertical well with mass flow rate

As can be seen from Fig. 7, the outlet temperature of the horizontal well has increased by 74.65 °C compared to a single vertical well, and the heat extraction rate has increased by 2.2MW. This is because compared to a vertical well, the total length of a horizontal well is longer, then the heat exchange area and time between the working fluid and the formation is increased. As a result, the working fluid fully exchanges heat with the formation, and the heat extraction rate is increased.

The total length of a horizontal well is 10000m, with a linear meter heat extraction rate of 0.31kW/m, while the total length of a vertical well is 4000m, with a linear meter heat extraction rate of 0.23kW/m. This indicates that the heat extraction rate does not increase in multiple with the length of the well, and constructing horizontal sections in the underground high-temperature area can improve the heat extraction performance of geothermal wells.

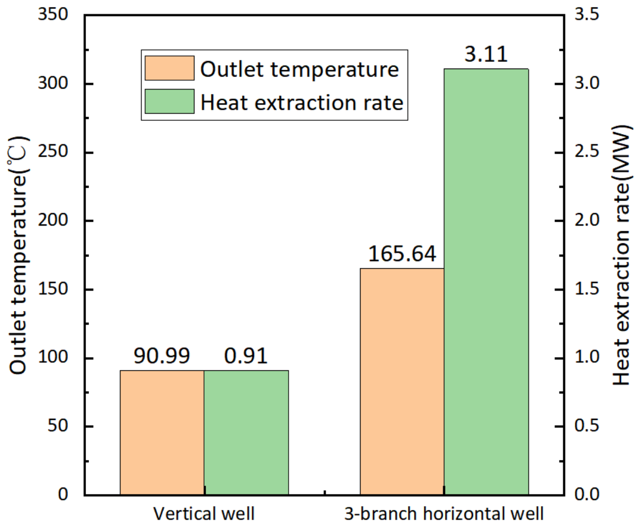


Fig. 7. Outlet temperature and heat extraction rate of vertical well and horizontal well at the end of 120 days

Fig. 8 demonstrates that the outlet temperature of the connecting well cluster is 8.66 °C higher than that of a vertical well, and the total heat extraction rate is 0.11MW higher than that of the five vertical wells. This indicates that although the connecting well cluster sacrificed one well as a production well, due to its connection at the bottom of the well, four horizontal sections were constructed in high-temperature formations, resulting in an increase in heat extraction rate compared to five vertical wells.

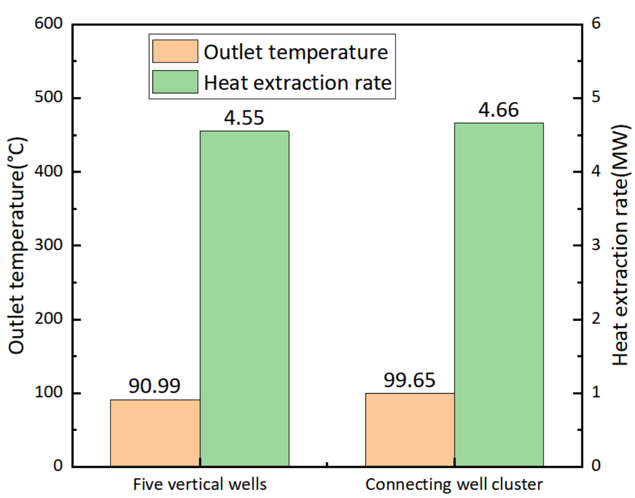


Fig. 8. Outlet temperature and heat extraction rate of vertical well and connecting well cluster at the end of 120 days

Especially, the simulation found that due to the energy loss of the working fluid flowing in the pipe, the outlet pressure of vertical well and horizontal well is lower than the inlet pressure. But the outlet pressure of the connecting well cluster is about 4 bar higher than the inlet pressure. This implies that there is a thermal siphon phenomenon in the connecting well cluster, which will greatly reduce the pump power required for system operation and then reduce operating costs.

## 4. CONCLUSIONS

In order to improve the heat extraction performance of geothermal wells, two new well models are constructed based on the five existing geothermal wells in the basin in northwest China. The simulation results of two new models and existing vertical wells are compared, and the main conclusions are as follows:

(1) The outlet temperature of the working fluid is inversely proportional to the mass flow rate, and the heat transfer rate is directly proportional to the mass flow rate. Taking the outlet temperature and heat extraction rate into account, a mass flow rate of 7kg/s is set for subsequent simulations in this study.

(2) After 120 days of operation, the outlet temperature of the vertical well is 90.99 °C, and the heat extraction rate is 0.91MW. The outlet temperature of the horizontal well has increased by 74.65 °C compared to the vertical well, and the heat extraction rate has increased by 2.2MW. The linear meter heat extraction rate of horizontal well is 0.31kW/m, while that of vertical wells is 0.23kW/m. This indicates that the heat extractionrate does not increase in multiple with the length of the well.

(3) The outlet temperature of the connecting well cluster is 8.66 °C higher than that of the vertical well, and the total heat extraction rate is 0.11MW higher than that of the five vertical wells. Specifically, the outlet pressure of the connecting well cluster is approximately 4 bar higher than the inlet pressure. This indicates that there is a thermal siphon phenomenon in the connecting well cluster, which will greatly reduce the pump power and then reduce operating costs.


## ACKNOWLEDGEMENT

This work was supported by the National Key Research and Development Program of the 13th Five-Year Plan of China (No. 2021YFB1507402).


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