



OPEN Horizontal well-assisted depressurization method for geothermal exploitation from fractured granite reservoir at Yangbajing geothermal field

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Utilizing the geological information obtained from the ZK4001 borehole of Yangbajing geothermal field, a horizontal well system with depressurization method was proposed to achieve heat production from fractured granite reservoir. Numerical simulations under the assumed geological and operational conditions were conducted to investigate the geothermal exploitation performance, the power generation potential and its dependent factors. Assessment indicates that within a reservoir spanning depths of 950–1350 m and maintaining an average temperature of 248 °C, at a production pressure of 2.5 MPa, the production temperature remains stable at 230 °C with a steam saturation of 0.28 for 12.5 years, subsequently experiencing a decline. Over a lifespan of 20.6 years, the fundamental horizontal well system achieves an electric power of 32.28–23.12 MW, exhibits a reservoir impedance of 0.072–0.096 MPa/(kg/s), requires a pump power of 1.14–1.83 MW, and demonstrates an energy efficiency of 28.87–12.65, suggesting favorable geothermal exploitation performance under the modeled conditions. The estimated reduction in greenhouse gas emissions amounts to 1.63–5.63 Mt. Sensitivity analysis indicates that, for the geothermal exploitation by the depressurization method, the production pressure has a significant impact on geothermal exploitation performance. Enhancing the permeability of the reservoir can effectively decrease flow impedance, minimize internal energy consumption, and result in improved energy efficiency. Moreover, adjusting the injection flow rate within a specific range can enhance the system's energy efficiency.

Keywords Yangbajing geothermal field, Horizontal well, Depressurization method, Fractured granite reservoir, Geothermal exploitation

Background

As a clean and renewable energy source, the study on the development and utilization of geothermal energy has received attention all over the world in recent years^{1,2}. Geothermal energy stems from the decay of long-period radioactive elements and high-temperature molten magma deep within the Earth's interior^{3–6}. The Earth serves as an immense thermal reservoir, with its internally stored heat exceeding that of oil and gas by approximately 50,000 times^{3,4}. Theoretical estimations suggest that the heat reserves within the top 10 km of the Earth's crust amount to roughly 1.3×10^{27} J⁷. Comparing this to the global energy consumption rate in 2012, which was approximately 6.0×10^{20} J/year⁸, these geothermal reserves could theoretically sustain global energy needs for approximately 217 million years.

Geothermal systems can be categorized into two main types based on their exploitation methods: traditional geothermal (hydrothermal) systems and enhanced geothermal systems (EGSs)⁹. Traditional geothermal power systems have undergone a century of development, rendering their power generation technology highly

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mature. Conversely, EGS technology has seen over four decades of advancement across several nations^{10–14}, yet commercial EGS power plants remain scarce owing to their high cost and inherent complexity. Nonetheless, four decades of rigorous technical testing and refinements have affirmed the viability of the EGS concept, demonstrating that thermal energy sourced from deep underground can indeed be harnessed. Notably, the Soultz EGS plant exemplifies this, having achieved a production capacity of 25 kg/s, and currently offering uninterrupted hydrothermal power generation⁹.

Most existing heat extraction schemes assume that the bottomhole production pressure is higher than the saturated vapor pressure according to the reservoir temperature, which makes the water in both the reservoir and well liquid, and avoids boiling liquid water at the bottomhole of the production well¹⁵. This is mainly because dissolved minerals in geothermal water may precipitate during gas-liquid two-phase flow, potentially increasing flow impedance or even blocking the wellbore¹⁵. As a result, most existing geothermal exploitation schemes aim to avoid phase change near the production well by maintaining single-phase liquid conditions. Consequently, in traditional geothermal systems, the produced high-temperature liquid water is typically used to generate electricity through heat exchange with a low-boiling-point organic working fluid or by surface flash evaporation to drive a turbine¹⁶.

However, fluid flow and heat transfer in deep underground rocks at high temperature and pressure are often accompanied by phase change and two-phase flow phenomena¹⁷. In many hydrothermal fields, mixtures of liquid water and steam are naturally produced at the wellhead^{17,18}. These processes are governed by complex thermo-hydraulic-mechanical-chemical (THMC) coupling effects, which significantly influence reservoir behavior and system performance. Despite the associated challenges, phase change during geothermal exploitation also provides an opportunity to enhance energy recovery by utilizing the large latent heat of vaporization.

Depressurization-based extraction methods have been widely used and deeply studied in methane hydrate production^{19–25}. The depressurization method can decompose methane gas from solid hydrate and extract it by changing the phase equilibrium condition²⁶. In geothermal exploitation, through reducing the pressure of the production well, the liquid water can absorb heat from the reservoir and undergo phase change from liquid to gas, carrying a large amount of latent heat of vaporization. It comes out that the depressurization method has the more potential of efficient geothermal exploitation. At the same time, depressurization-induced vaporization alters fluid composition, flow patterns, and pumping power requirements, and may also introduce challenges such as mineral crystallization and scaling. These effects may pose challenges to long-term reservoir performance and operational stability if not properly managed.

In this study, a depressurization-based geothermal exploitation method using horizontal wells is proposed to enhance energy extraction from high-temperature geothermal reservoirs. The primary objective is to evaluate the thermo-hydraulic behavior, power generation potential, and system efficiency of the proposed depressurization-enhanced EGS system. To isolate the fundamental performance characteristics of the proposed depressurization-based EGS system, the effects of mineral precipitation and scaling in geothermal water are neglected in this work. For the depressurization-based EGS system, the steam saturation of the produced fluid should be evaluated in addition to the conventional evaluation indexes such as output temperature, electric power, flow impedance and power generation efficiency. This will not only affect the installed capacity of geothermal power plant, but also the lifespan of the reservoir. In addition to the sensitivity analysis of the influencing factors of the system, besides the conventional key parameters such as reservoir naturally occurring parameters (i.e. reservoir temperature and reservoir permeability) and human-controlled parameters (i.e. the injection flow rate and the injection fluid temperature), it is also necessary to study the production pressure, which is very key to the depressurization method. This study evaluates the economic viability and environmental impact of the proposed depressurization-enhanced EGS system using conventional performance metrics. While the proposed depressurization method shows significant potential for enhancing geothermal energy extraction, its practical application may be constrained by scaling-related and hydraulic challenges, which warrant further investigation in future studies incorporating thermo-hydro-chemical coupling.

Characteristics of the research field

Yangbajing geothermal field is situated in Dangxiong County, approximately 90 km northwest of Lhasa, Tibet Autonomous Region, China. Located in the central Qinghai-Tibet Plateau at elevation of 4290–4500 m (Fig. 1a). It is the first high-temperature hydrothermal convective geothermal field in China. Previous studies^{15,27,28} have extensively documented its geologic structure, hydrology, and geothermal characteristics. As illustrated in Fig. 1b, well ZK4001²⁹ reveals a deep fractured granite reservoir at 950–1336 m depth, composed of mylonitized granite, granitic mylonite, and fractured granite. The reservoir exhibits an average temperature of 248°C peaking at 251 °C. It is covered by impermeable granite, altered fractured granite, and biotite-granite²⁹. The 950–1336 m interval is the target of this study. References²⁹ and³⁰ expand the depth range of this section to 950–1350 m. For the convenience of calculation, the depth of this section is unified as 950–1350 m, characterized by an average temperature of 248°C. The corresponding pressure range of 8.01–11.57 MPa was determined based on established pressure P (MPa) and depth h (m) correlations¹⁵.

Since the first experimental unit was built in Yangbajing in 1975, the total installed capacity has reached 24,180 kW so far, which is the largest installed capacity of geothermal power station in China³¹. The operation is stable and safe, as of June 2018, the cumulative power generation of Yangbajing geothermal power plant is 3.4 billion kWh³¹. In the 1990s, the electricity generation of Yangbajing geothermal field accounted for 60% of the electricity in Lhasa, solving the problem of serious power shortage^{18,31}. At the same time, as a pioneer in domestic geothermal power generation, reinjection and anti-scaling technology, it has provided supporting data and technical support for geothermal development. The existing generating units in Yangbajing area are mainly 1000 kW experimental unit and 3000 kW generator units, of which seven 3000 kW units are double flash

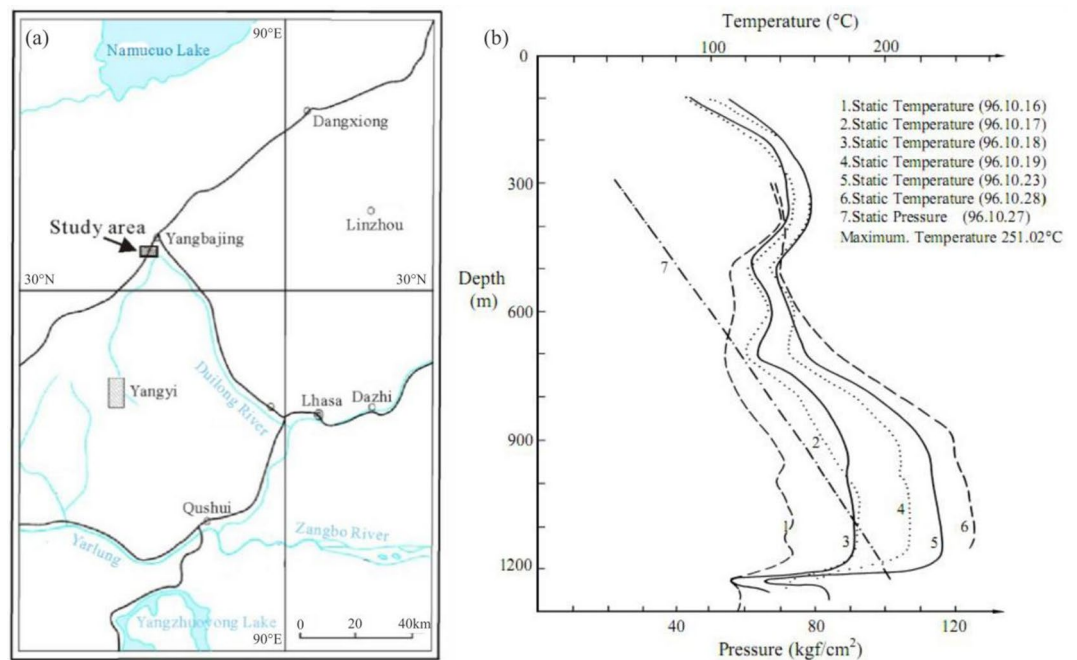


Fig. 1. Location (a), temperature and pressure logs from well ZK4001 (b) of Yangbajing geothermal field²⁹ in Lhasa, China ($1 \text{ kgf/cm}^2 = 0.1 \text{ MPa}$).

geothermal power generation system^{31,32}. Due to less auxiliary equipment, the plant electricity consumption rate is low (currently controlled at about 17%), and the power generation efficiency of the double flash system is high. In this work, a double flash system (Fig. 2) is also used to generate electricity from high temperature fluid produced by depressurization method.

The diagram defines the system boundary for the performance evaluation in this study, in which electric power output and internal energy consumption are assessed at the corresponding components of the plant.

Research objectives

The primary objectives of this study are to establish a conceptual model for the exploitation of high-temperature geothermal energy in Yangbajing geothermal field by depressurization method based on a horizontal well system. By leveraging geothermal geological data from the region, we aim to quantify the system's power generation capacity and efficiency, as well as identify key factors influencing its energy performance. The findings will offer a theoretical foundation and technical guidance to advance the sustainable exploitation of the high-temperature reservoir at Yangbajing geothermal field.

Production methodology and well configuration

Fractured reservoir stimulation and design

Horizontal well technology, as a new technology attracting much attention in the field of oil and gas and geothermal development, has always been the focus of geological resource development research in recent years³³. Focusing on improving productivity and efficiency and reducing costs in the geothermal development process, researchers have put forward many technical schemes for horizontal well geothermal exploitation, and the numerical results show that the horizontal well has good productivity and efficiency^{15,34,35}. Based on the previous work, this paper proposes to use the depressurization method of three horizontal wells to exploit a high-temperature reservoir. One horizontal well is located at the bottom, and the low-temperature fluid enters the fractured reservoir through the well to extract heat, while two production wells are located at the upper part of the reservoir. The hot water heated by the reservoir rock is extracted from the production well and enters the two-stage flash power plant on the ground for power generation. Figure 3 shows the arrangement of the horizontal wells. For injection wells, install injection pumps on the ground to keep the injection mass flow constant. For production wells, there are suction pumps on the ground to pump water out and keep the bottomhole pressure unchanged. Many previous experiments and numerical studies have proved that this geothermal exploitation method can reduce reservoir impedance and water flow loss³³. Water losses can be ignored as an approximate estimation so that the injection rate and production rate are equal: $q_{inj} = q_{pro} = q$.

For Yangbajing geothermal system, the target geothermal exploitation reservoir is situated at 950–1350 m depth, characterized by an average temperature of 248°C. At this temperature, the equilibrium vapor pressure of water reaches 3.84 MPa³⁶. Geothermal power generation from hydrothermal reservoirs typically employs two principal approaches: flash steam conversion and binary cycle technology¹⁶. Yangbajing geothermal power station uses two-stage flash method to generate electricity. For a typical two-stage flash power generation

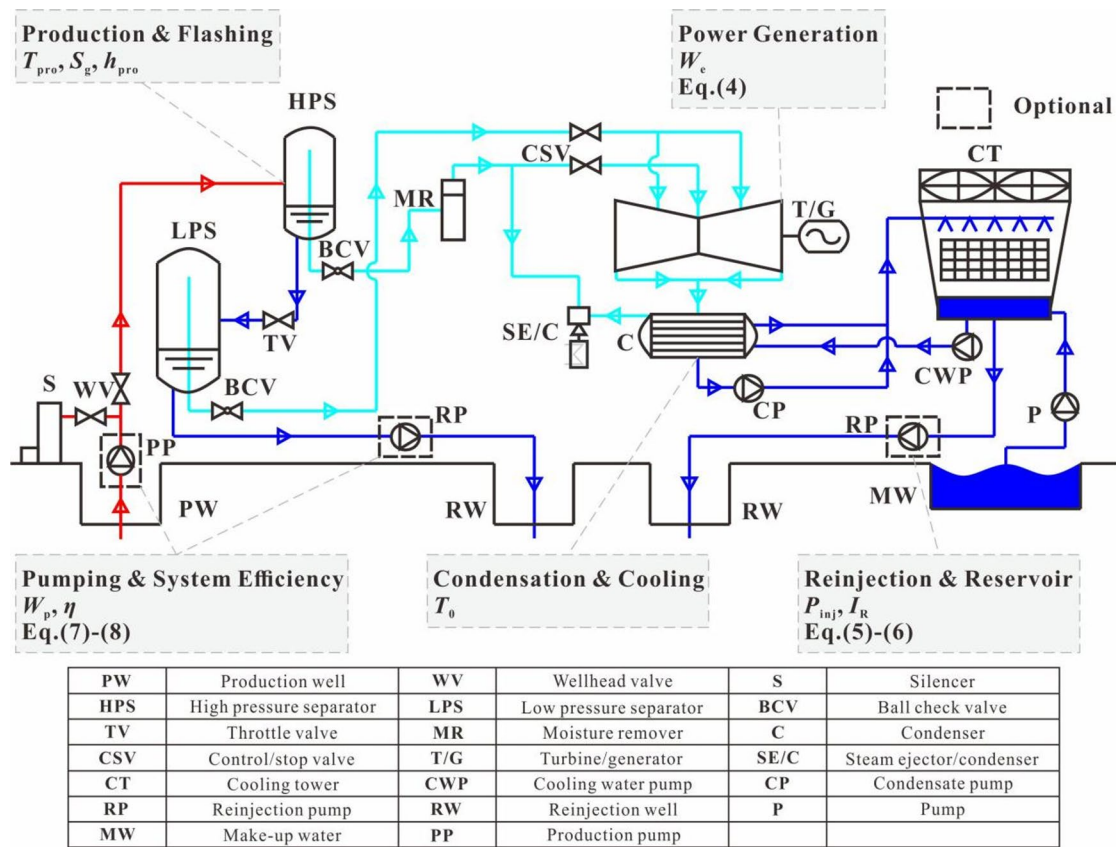


Fig. 2. Simplified schematic for a double-flash plant³².

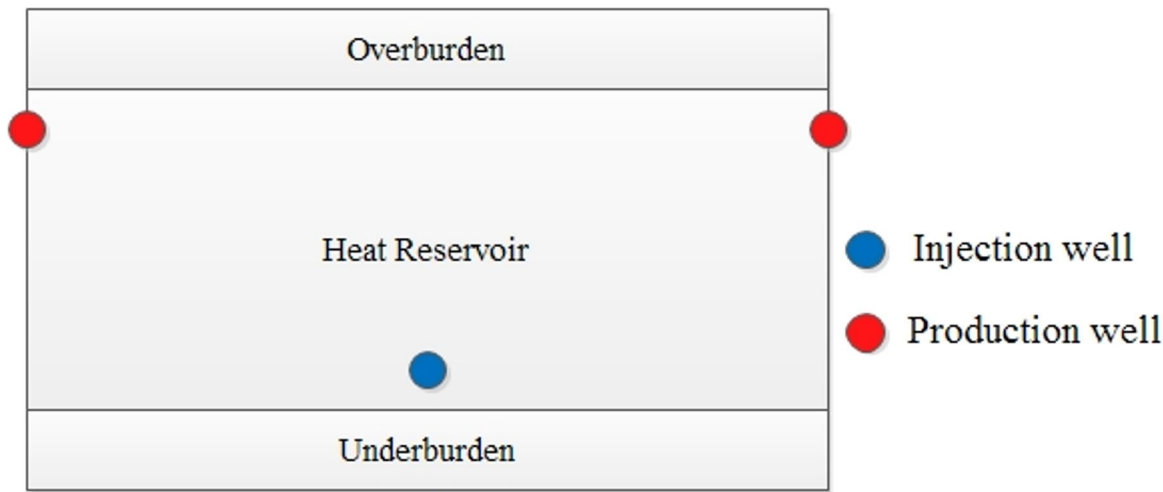


Fig. 3. Conceptual model of high temperature fractured granite reservoir exploited by three horizontal wells.

system, the primary steam production rate is usually 3.5%~8.8%, while the secondary gas production rate is 3.1%~6.8%¹⁶. It can be seen that the flash steam production rate on the ground surface is still very low, and most of the heat energy has not been effectively utilized. Based on this, this work innovatively proposes to use the depressurization method to extract geothermal steam in the reservoir and send it to the ground for power generation. The pressure-depth relationship follows a linear distribution: $P = -0.0089z - 0.4444$ (MPa)²⁹. The intermediate depth of the injection perforated interval is $z = -1325$ m, and the production perforated interval is $z = -975$ m. The corresponding initial pressure of the injection well is $P_{w0} = 11.35$ MPa. To prevent excessive injection pressure from damaging the reservoir and causing shutdowns, P_{inj} must be maintained lower than $P_{max} = 1.2P_{w0} = 13.62$ MPa³³. The circulating rate is determined by adjusting the injection rate to calculate the

injection pressure, and the injection rate not exceeding the maximum injection pressure is determined as the optimal production rate³³. The initial pressure corresponding to the depth of the production well is 8.23 MPa, and the saturated steam pressure corresponding to the reservoir temperature is 3.84 MPa. In this paper, the production well's bottomhole flowing pressure is reduced to 2.50 MPa during operation, resulting in a pressure drawdown (ΔP) of 5.73 MPa. Under this pressure, the hot water in the reservoir well will flash into steam, and the wet steam will be produced from the production well, which will enter the surface power station for power generation.

Well design

Previous research on the oil, gas, and geothermal field has confirmed that the uniform distribution of 8 grooves along the circumference of the horizontal wells is simple and technologically feasible. Relevant information and description can refer to previous studies³³. For injection wells, due to symmetry, there are four grooves in the simulation domain, which are replaced by two grids. Each grid represents the injection flow in two grooves. For production wells, the production flow of four grooves in half of the domain is regarded as a grid, and a grid is used to replace the groove of the production well.

Model description

Domain, grid and parameters

This study employs the TOUGH2-EOS1 numerical simulator to solve the mathematical models for geothermal heat flow and mass transfer. Specific introductions and governing equations can be found in the user manual³⁷. As previously mentioned, due to symmetry, the study area is $500 \text{ m} \times 500 \text{ m}$. It is assumed that the changes of the seepage field and temperature field along the well length can be ignored, and only 10 m is needed for research. The water flow and heat energy production within the entire 500 m thickness range is 50 times of the simulated domain. The computational domain measures $500 \text{ m} \times 10 \text{ m}$, bounded by 100 m thick caprock and bedrock layers. According to the previous research and analysis, the thickness is large enough for the thermal recovery in the simulated reservoir³⁸. The fractured reservoir spans a vertical depth range of -1350 m to -950 m, resulting in a total simulated thickness of 600 m. Assuming impermeable cap and bottom rocks, the domain is discretized along the vertical (z) direction into 10 gridblocks, each with a length of 10 m. To capture rapid variations in heat transfer and fluid flow near the wells, the subdomains adjacent to the top ($-1350 \text{ m} \leq z \leq -1300 \text{ m}$) and bottom ($-1000 \text{ m} \leq z \leq -950 \text{ m}$) of the reservoir are refined with gridblocks of 5 m thickness. The remaining vertical subdomains are discretized using 15 m gridblocks. Similarly, in the horizontal (x) direction, regions near the injector ($0 \leq x \leq 50 \text{ m}$) and producer ($450 \text{ m} \leq x \leq 500 \text{ m}$) are discretized with 5 m gridblocks to account for localized flow and thermal gradients. In the remaining horizontal (x) subdomains, the gridblocks have a uniform length of 10 m. This discretization results in a total of 60 gridblocks along the vertical (z) direction and 60 gridblocks along the horizontal (x) direction, yielding a 2-D grid with 3,600 elements (as illustrated in Fig. 4b).

For reservoirs exhibiting uniform fracture distribution and high connectivity, the equivalent porous medium (EPM) approach can be employed to model the 3-D fracture network³³. In this study, the EPM method is adopted to simulate the fractured reservoir of the Yangbajing geothermal field.

Reservoir permeability is a key parameter governing fluid circulation and heat extraction in fractured geothermal systems. Previous studies indicate that effective permeabilities in the range of 10–100 mD (approximately 10^{-14} – 10^{-13} m^2) are generally required for commercially viable EGS development, whereas lower values may lead to insufficient injectivity and increased flow impedance^{33,39,40}. Significantly higher permeabilities are uncommon in naturally fractured high-temperature geothermal reservoirs³. For the Yangbajing geothermal field, available geological data and previous numerical studies suggest that the reservoir permeability falls within this effective range^{15,33}. Accordingly, a reference-case intrinsic permeability of $50 \times 10^{-15} \text{ m}^2$ is adopted for both

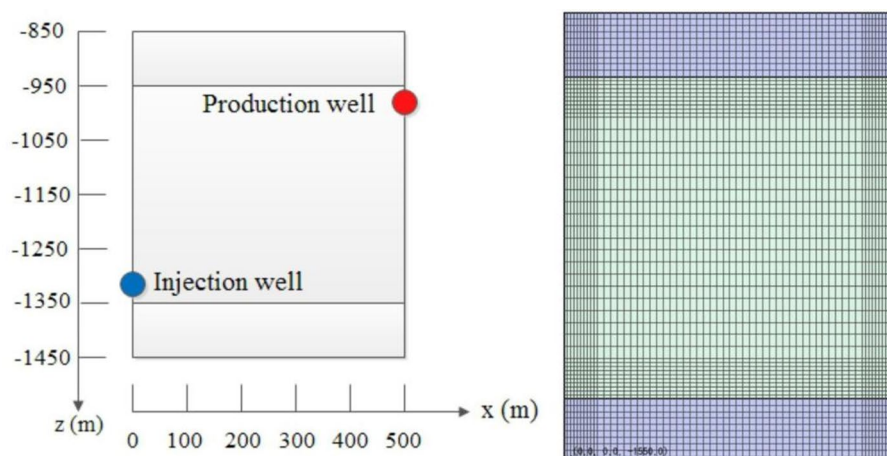


Fig. 4. Schematic diagram of the fractured reservoir geometry and corresponding computational grid.

the horizontal and vertical directions in this study, representing a moderate and realistic value for fractured geothermal reservoirs.

Given the gradual boiling of hot water during geothermal production, Corey's Curves are utilized to characterize the relative permeability of the liquid and gas phases.

$$k_{rl} = s^4 \quad (1)$$

$$k_{rg} = (1 - s)^2 (1 - s^2) \quad (2)$$

$$s = \frac{s_l - s_{lr}}{1 - s_{lr} - s_{gr}} \quad (3)$$

where s_l is the liquid saturation, and s_{lr} and s_{gr} are the relative permeability model parameter; in this work, $s_{lr}=0.30$, $s_{gr}=0.05$ ³⁷.

Other reservoir properties and operational parameters used in the simulations are summarized in Table 1 and are selected based on available field data and commonly adopted values in previous geothermal modeling studies^{15,33,37}.

Boundary and initial conditions

Owing to the symmetry, both lateral boundaries in Fig. 4 are treated as impermeable to fluid flow and adiabatic to heat transfer. Because the cap rock and base rock are impermeable, the thicknesses of the cap rock and base rock are great enough, the topmost and bottom-most boundaries are also no-flow for mass and heat. So, all the boundaries in Fig. 4 are no-flow for mass and heat. The initial reservoir temperature is 248 °C, and the initial pressure is $P=-0.0089h-0.4444$ (MPa).

Results and discussion

The reference case

As presented in Table 1, the reference scenario sets the fluid production rate of the simulated domain q at 2 kg/s, with an injection temperature of 60 °C. For the fractured reservoirs, only when the reservoir permeability lies between 10 and 100 mD, can they have good exploitation value³³. Therefore, in this study, the reference - case reservoir permeability is set at $50 \times 10^{-15} \text{ m}^2$. The primary focus of this investigation is to evaluate the heat production performance and efficiency over a 30 - year span. The performance evaluation in this study is conducted within the system boundary defined by the double-flash geothermal power plant shown in Fig. 2.

Production temperature and steam saturation

Figure 5 depicts the evolution of production temperature T_{pro} and steam saturation S_g over a 30 - year period. Numerical studies reveal that the heat production process can be divided into three stages based on the variation patterns of T_{pro} and S_g . The first stage is a stable stage, which lasts about 12.5 years. During this stage, with the production pressure held constant at 2.50 MPa, the corresponding saturation temperature is around 230 °C. Given that the initial reservoir temperature is 248 °C, T_{pro} stabilizes at about 230 °C and remains unchanged. A

Parameter	Value
Rock thermal conductivity	2.50 W/(m.K)
Rock specific heat	1000 J/(kg.K)
Rock density	2650 kg/m ³
Reservoir height	400 m
Reservoir length (simulated domain)	500 m
Reservoir width (simulated domain)	10 m
Thickness of cap rock	100 m
Thickness of base rock	100 m
Permeability of cap rock	0 m ²
Permeability of base rock	0 m ²
Reservoir porosity	10%
Horizontal intrinsic permeability $k_x=k_y$ (reference case)	$50 \times 10^{-15} \text{ m}^2$
Vertical intrinsic permeability k_z (reference case)	$50 \times 10^{-15} \text{ m}^2$
Water production rate q (simulated domain)	2.0 kg/s
Bottomhole production pressure P_0	2.50 MPa
Productivity index PI	$5.0 \times 10^{-12} \text{ m}^3$
Injection specific enthalpy h_{inj}	260.66 kJ/kg (about 60 °C)
Initial temperature T_R	248 °C
Initial pressure	$P=-0.0089h-0.4444$ (MPa)

Table 1. The 950–1350 m reservoir properties and conditions at well ZK4001^{15,33,37}.

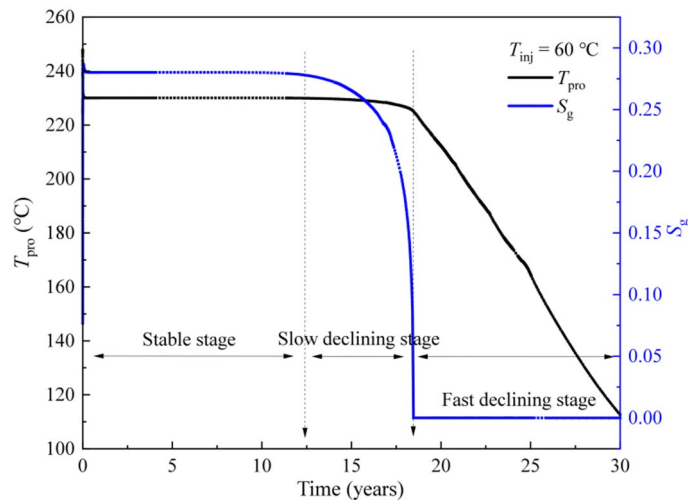


Fig. 5. Evolution of T_{pro} and S_g during the 30 years period.

mixture of steam and liquid is produced at the bottom of the well with S_g maintained at about 0.28. The second stage is a slow declining stage, which lasts from 12.5 to 18.4 years. In this stage, T_{pro} slowly decreases from 230 °C to 225.1 °C, while the corresponding S_g gradually decreases from 0.28 to 0. At this stage, the system still produces a mixture of steam and liquid, but S_g rapidly decreases to 0 due to the gradual decrease of temperature. The third stage is a rapid declining stage, which lasts from 18.4 to 30 years. In this stage, T_{pro} decreases from 225.1 °C to 112.6 °C, and S_g is 0, indicating that only liquid water is produced at the production well in this stage. The results indicate that, under the reference conditions, the production temperature drops to 112.6 °C at the end of the extraction period, reduced by about 54.6%. Garnish et al. have asserted that T_{pro} decline over the entire production lifespan should be less than 10%⁴¹. According to this standard, under the reference condition, geothermal exploitation can last until the 20.6th year, after which T_{pro} drops to below 207 °C. The reservoir should stop exploitation to protect the renewable performance of underground geothermal resources. The simultaneous production of liquid water and steam in the production well significantly affects the flow characteristics of the reservoir-well system. For example, it may cause mineral precipitation, thus increasing the flow resistance at the bottom of the production well, or even blocking the pipeline and causing shutdown¹⁵. Therefore, in addition to the theoretical numerical simulation research carried out in this paper, a large number of geothermal water flash experiments need to be carried out to validate the practical viability of exploiting thermal energy Yangbajing geothermal field through the depressurization method¹⁵.

Production enthalpy and electric power

The total production rate (Q) of the three-horizontal-well system is 100 times the fluid production rate (q) of the simulated domain, namely $Q = 100q$. The production specific enthalpy h_{pro} is calculated with $h_{\text{pro}} = h(T_{\text{pro}}, P_{\text{pro}})$, in which T_{pro} represents the production temperature and P_{pro} denotes the production pressure. In the reference case, the injection temperature is 60 °C, and the corresponding injection specific enthalpy $h_{\text{inj}} = 260.66$ kJ/kg. Yangbajing geothermal power station operates as a two-stage flash evaporation system, with an average condensation temperature $T_0 = 9$ °C = 282.15 K¹⁵. Assuming a utilization efficiency of 0.45 for the maximum available work converted to electric power³⁵, and neglecting the water loss during the flashing process, we assume that all the liquid water is flashed into steam and enters the steam engine. Based on the principles of thermodynamics, water with a flow rate of $Q = 100q$ can generate electric power W_e , as described by Eq. (4)³³:

$$W_e = 0.45Q(h_{\text{pro}} - h_{\text{inj}})\left(1 - \frac{T_0}{T_{\text{pro}}}\right) = 45q(h_{\text{pro}} - h_{\text{inj}})\left(1 - \frac{T_0}{T_{\text{pro}}}\right) \quad (4)$$

The electric power W_e corresponds to the output of the turbine-generator unit in the double-flash system illustrated in Fig. 2.

Figure 6 illustrates the evolution of h_{pro} and W_e during the 30 years period. The patterns of h_{pro} and W_e variation closely resemble those of T_{pro} . During the stable stage, h_{pro} and W_e remain at constant values of 1075.53 kJ/kg and 32.28 MW, respectively. This stability can be attributed to the fact that T_{inj} , h_{inj} , T_{pro} , and P_{pro} all remain essentially constant. After 12.5 years, the system transitions into the declining stage, with the slow declining and rapid declining stages constituting a continuous process. As T_{pro} and S_g gradually decrease, h_{pro} decreases from 1075.53 kJ/kg to 474.06 kJ/kg, while W_e decreases from 32.28 MW to 5.16 MW during the declining stage. The patterns of h_{pro} and W_e variation are consistent with the previous research, which indicates that the variation pattern of power generation of the depressurization method is consistent with that of the conventional method. For the geothermal power system, a reference commercial target is to obtain an electricity production power of 3.5 MW at a water production rate of 50 kg/s⁴². In this paper, the electric power of 32.28–5.16 MW is

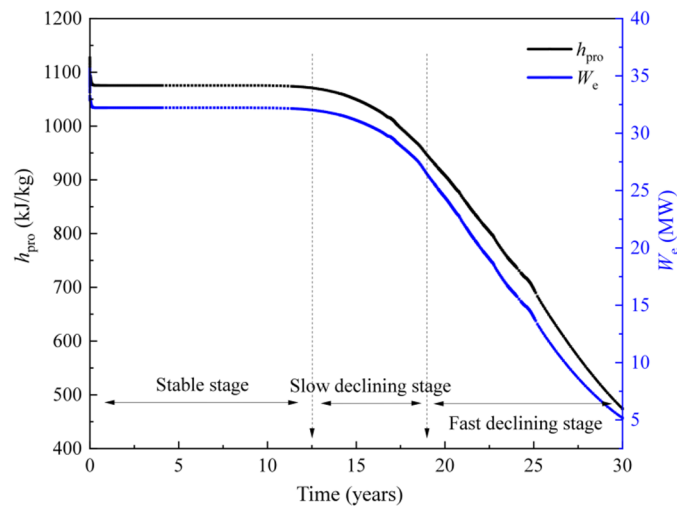


Fig. 6. Evolution of H_{pro} and W_e during the 30 years period.

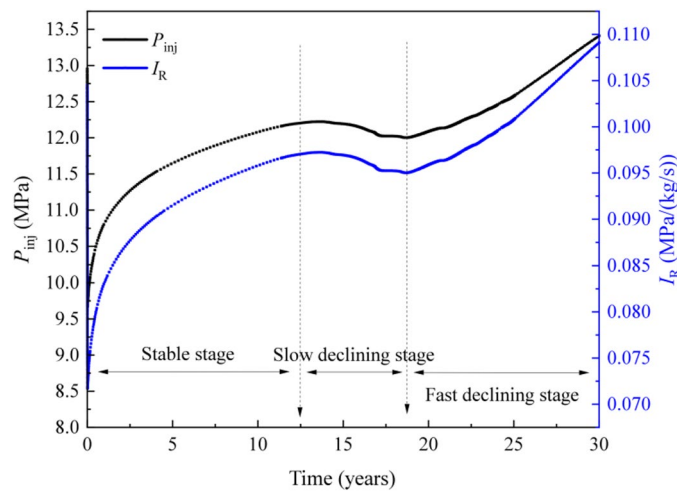


Fig. 7. Evolution of P_{inj} and I_R during the 30 years period.

obtained with the production rate of 100 kg/s, which shows that the power generation per unit flow can meet the commercial production demand.

Injection pressure and reservoir impedance

The flow impedance I_R signifies the power consumption per unit production rate required to penetrate the fractured reservoir, and it is mathematically defined as Eq. (5)³³. In this work, the production pressure $P_{\text{pro}} = P_0 = 2.50$ MPa, and the water production rate $q_0 = 50q = 100$ kg/s.

$$I_R = (P_{\text{inj}} - P_{\text{pro}})/q_0 \quad (5)$$

Figure 7 shows the variations in P_{inj} and I_R over a 30 - year duration. In the stable stage (0–12.5 years), saturated wet steam is produced, P_{inj} increases from 9.67 to 12.20 MPa, and I_R rises from 0.072 to 0.097 MPa/(kg/s). The reservoir impedance can be calculated as Eq. (6), where L is the length of the seepage path, k is the permeability of the seepage zone, A is the cross-sectional area of the seepage zone, and μ/ρ is the ratio of the viscosity to the density of the fluid in the reservoir. In the stable stage, the ratio gradually increases with the decrease of reservoir temperature. Therefore, according to Eq. (6), the reservoir impedance and injection pressure increase gradually. In the slow declining stage (12.5–18.4 years), the saturation of the produced steam decreases gradually. According to Eq. (6), this is because the ratio μ/ρ in the reservoir decreases as S_g decreases from 0.28 to 0. This reduces I_R from 0.097 to 0.095 MPa/(kg/s), while the corresponding P_{inj} gradually decreases from 12.20 to 12.01 MPa. In the rapid declining stage (18.4–30 years), the system produces liquid water and the reservoir temperature gradually decreases. Therefore, I_R rises from 0.095 to 0.109 MPa/(kg/s), and the corresponding P_{inj} increases from 12.01 to 13.41 MPa. Garnish et al. have put forward the proposition that the reservoir impedance

should remain below 0.1 MPa/(kg/s) throughout the production period⁴¹. On the other hand, Evans proposed that the reservoir impedance should be less than 0.2 MPa/(kg/s)⁴². In this study, the flow impedance of the reservoir during 30 years of exploitation falls within the range of 0.072 ~ 0.109 MPa/(kg/s), thereby fulfilling the criteria for commercial exploitation. Therefore, for Yangbajing geothermal field, the reservoir impedance of the depressurization method for high-temperature geothermal exploitation meets the requirements of commercial development⁴¹.

$$I_R = \frac{\mu L}{k \rho A} \quad (6)$$

Pump power and energy efficiency

The energy efficiency of the system is characterized as the quotient of the total energy generated to the internal energy consumption³³. The internal energy consumption predominantly encompasses the energy consumed by the injection pumps and the production pumps. Ignoring the friction of the pipeline and internal fluid³³, the efficiency of the pump is set as 80%⁴³. According to reference³³, the total energy consumed by the injection pump and production pump is defined as Eq. (7) :

$$W_p = \frac{100q(P_{inj} - P_{pro}) - 100\rho qg(h_1 - h_2)}{\rho\eta_p} \quad (7)$$

Here, h_1 denotes the depth of the injection well and h_2 represents the depth of the production well. In this study, $h_1 = 1325$ m, $h_2 = 975$ m. Consequently, the system energy efficiency η can be computed as Eq. (8)³³:

$$\eta = \frac{W_e}{W_p} = \frac{0.45\rho\eta_p(h_{pro} - h_{inj})(1 - T_0/T_{pro})}{(P_{inj} - P_{pro}) - \rho g(h_1 - h_2)} \quad (8)$$

Therefore, the energy efficiency η represents the overall performance of the integrated geothermal power system shown in Fig. 2, accounting for both power generation and internal energy consumption.

The water density ρ in the reservoir - well system varies with changes in temperature and pressure. In this study, the average density is employed for the calculation in Eqs. (7) and (8). Over the 30-year geothermal exploitation period, the maximum density recorded is 990 kg/m³, and the minimum density is 803 kg/m³. Consequently, an average density of 896.5 kg/m³ is utilized for the calculations in this work³³. Figure 8 illustrates the variations in W_p and η over the 30 years period. During the stable stage (0–12.5 years), as P_{inj} gradually increases, W_p gradually increases from 1.14 to 1.85 MW. Meanwhile, W_e remains constant. As a result, the corresponding η decreases from 28.87 to 17.32. In the slow declining stage (12.5–18.4 years), P_{inj} decreases gradually, W_p decreases from 1.85 to 1.79 MW. As W_e decreases gradually, the corresponding η continues to decrease from 17.32 to 15.42. In the rapid declining stage (18.4–30 years), W_p increases from 1.79 to 2.19 MW, η continues to decrease from 15.42 to 2.36. During the designed 30-year production period, η is maintained in the range of 28.87–2.36, which is far greater than 1, indicating that the exploitation of Yangbajing high-temperature reservoir by the depressurization method has a favorable economic performance³³.

Economic analysis and environmental benefit

The total cost of a geothermal project typically comprises three primary components: drilling costs (C_d), surface installation costs (C_s), operation and maintenance costs (C_o). For the multilateral horizontal well system, drilling costs can be calculated using the methodology outlined in Reference⁴⁴.

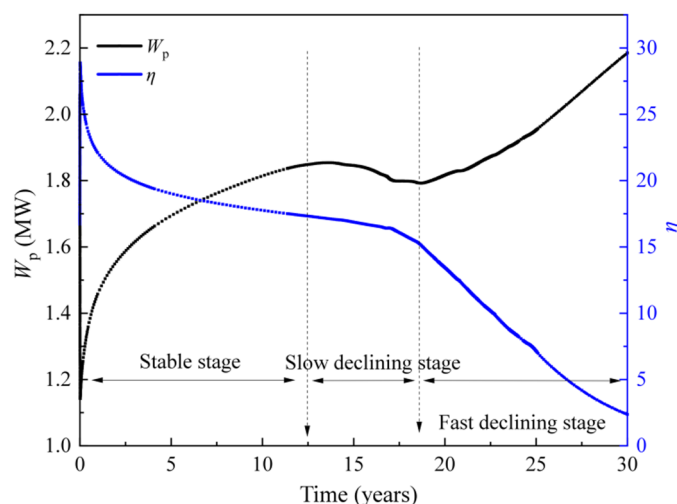


Fig. 8. Evolution of W_p and η during the 30 years period.

$$C_d = H_v \times P_v + H_h \times P_h \quad (9).$$

where $H_v = 1325 + 2 \times 975 = 3275$ m, $H_h = 3 \times 500 = 1500$ m, P_v is \$ 1100 and P_h is \$ 3300⁴⁵, the total drilling costs C_d were \$ 8.5525 million.

The investment costs for surface installation exhibit a linear relationship with the size of the power plant. Conversely, the unit capital cost is expected to decline exponentially with increasing plant capacity^{1,46}. Modeling results indicate that W_e varies within the range of 23.12–33.59 MW over the reservoir lifespan of 20.60 years. Given this variability and the economic trade-offs, a power plant capacity of 32.0 MW was deemed reasonable for the proposed EGS project.

Equation (10) defines the unit cost (C_{surf} in \$/kW) for surface equipment as a function of installed power capacity ($\dot{W}$, in MW)¹

$$C_{surf} = 2000 \cdot \exp(-0.0045 \cdot (\dot{W} - 5)) \quad (10)$$

The unit capital cost for the proposed EGS power plant was calculated as 1771.18 \$/kW, based on its design capacity of 30 MW. Consequently, the total cost for surface installation was estimated at approximately \$ 56.6778 million.

Equation (11) defines the unit O&M cost ($C_{O\&M}$ in \$/MWh) as a function of the installed power capacity ($\dot{W}$, in MW)¹.

$$C_{O\&M} = 20 \cdot \exp(-0.0025 \cdot (\dot{W} - 5)) \quad (11)$$

Based on the design capacity of 30 MW for the proposed EGS power plant, the unit capital cost here was calculated as 18.69 \$/kW. The cost for operation and maintenance was estimated at \$ 0.5982 million.

According to the above calculations, the total estimated cost for the proposed multilateral horizontal well system of the EGS project is approximately \$ 65.8285 million.

The total energy consumed by the pumps (γ_p) can be calculated from Eqs. (12),

$$\gamma_p = \int_0^t W_p dt \quad (12)$$

Assuming 8,000 operational hours per year for maintenance considerations, the actual total energy production over the 20.6-year project lifespan was calculated as 287.73 GWh. For the base case scenario, the cumulative electricity generation after 20.6 years was estimated at 5,107.47 GWh. Subtracting the system's self-consumption, the total net power generation was determined to be 4,819.74 GWh. The levelized cost of energy (LCOE) was estimated by dividing the total project costs (\$65.8285 million, as previously calculated) by the total net power generation, yielding a value of \$0.0137/kWh. This is significantly lower than the 2022 industrial electricity price in the Tibet Autonomous Region (\$0.09/kWh). Based on the LCOE and net generation, the projected profit from net power generation over 20.6 years is approximately \$367.95 million.

The average greenhouse gas (GHG) emission intensity of the geothermal power plant was estimated at 122 g/kWh^{35,47}, significantly lower than that of fossil fuel-based power generation, which ranges from 460 to 1290 g/kWh^{1,35}, translates to a GHG emission reduction potential of 338–1168 g/kWh for geothermal power plants. For the proposed EGS power plant, the cumulative GHG emissions avoided over its 20.6-year operational lifespan are projected to be 1.63–5.63 Mt. Under the 2018 Beijing carbon emission trading pilot prices of 8.46–9.23 \$/t^{1,48}, the estimated revenue from the sale of saved GHG emissions (carbon credits) would be \$ 13.78–51.96 million.

Spatial distribution of temperature

Figure 9 depicts the temporal evolution of the spatial temperature distribution over the 30-year span. Since the geothermal exploitation begins, an approximate annular low-temperature region is formed around the injection well. Moreover, the temperature in this area exhibits a gradual increase from the injection well towards the outer regions. As the heat production goes on, the region gradually expands to the production well, indicating the gradual extraction of thermal energy. During the stable stage, the production temperature basically remains unchanged because the cold front has not yet reached the production well. After entering the declining stage, the cold front reaches the production well, causing the production temperature to decrease gradually until the end of the production. The evolution pattern of the temperature field throughout the entire exploitation period is basically the same as that of the Yangbajing geothermal field exploited by horizontal wells previously studied. This shows that the temperature spatial distribution evolution of high-temperature geothermal in Yangbajing geothermal field by depressurization method is approximately the same as that of the general extraction scheme²⁸.

Spatial distribution of pressure

Figure 10 illustrates the evolution of the pressure spacial distribution over the 30-year span. During the production process, a high-pressure annular area is formed around the injection well, with the pressure exhibiting a gradual decline from the inner region towards the outer periphery. Since the production pressure is maintained at a fixed value of 2.50 MPa, the pressure around the production well remains unchanged throughout the production period. As heat production proceeds, the high-pressure region around the injection well expands towards the production well, signifying the gradual extraction of thermal energy from the reservoir. In the stable stage, the reservoir pressure exhibits a gradual increase. Upon entering the slow declining stage, the reservoir pressure decreases slightly, which is caused by the gradual decrease of the saturation of the wet steam. In the final rapid-declining stage, the reservoir pressure undergoes a continued increase, ultimately reaching its maximum value at the end of exploitation.

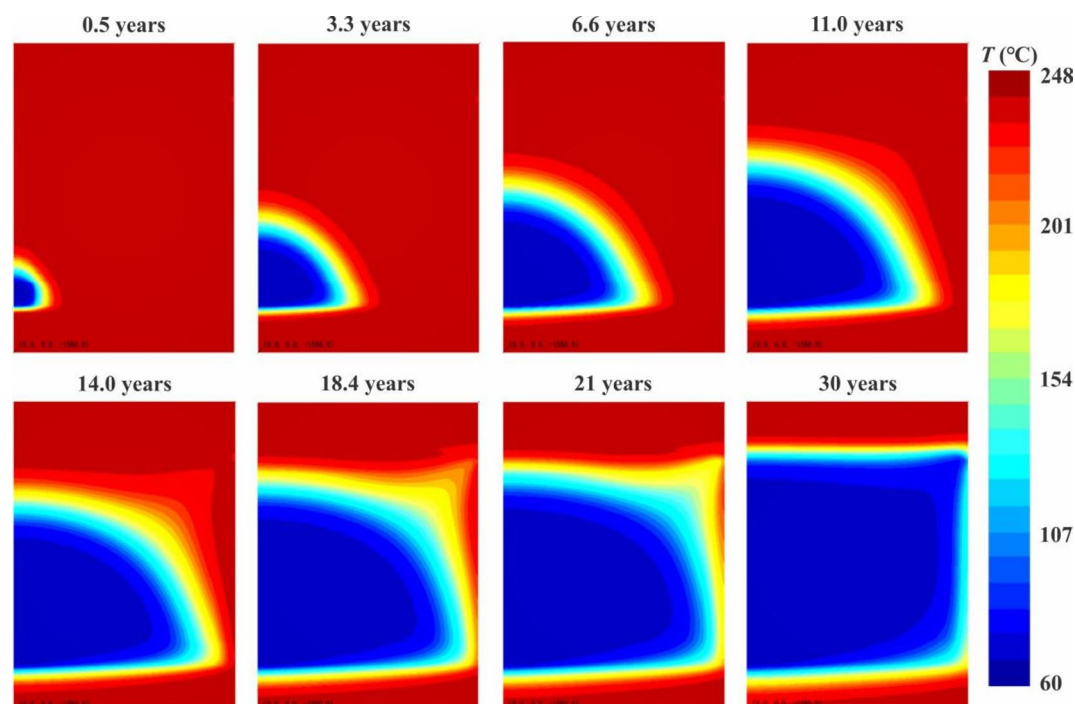


Fig. 9. Evolution of the spatial distribution of temperature (°C) during the 30 years period.

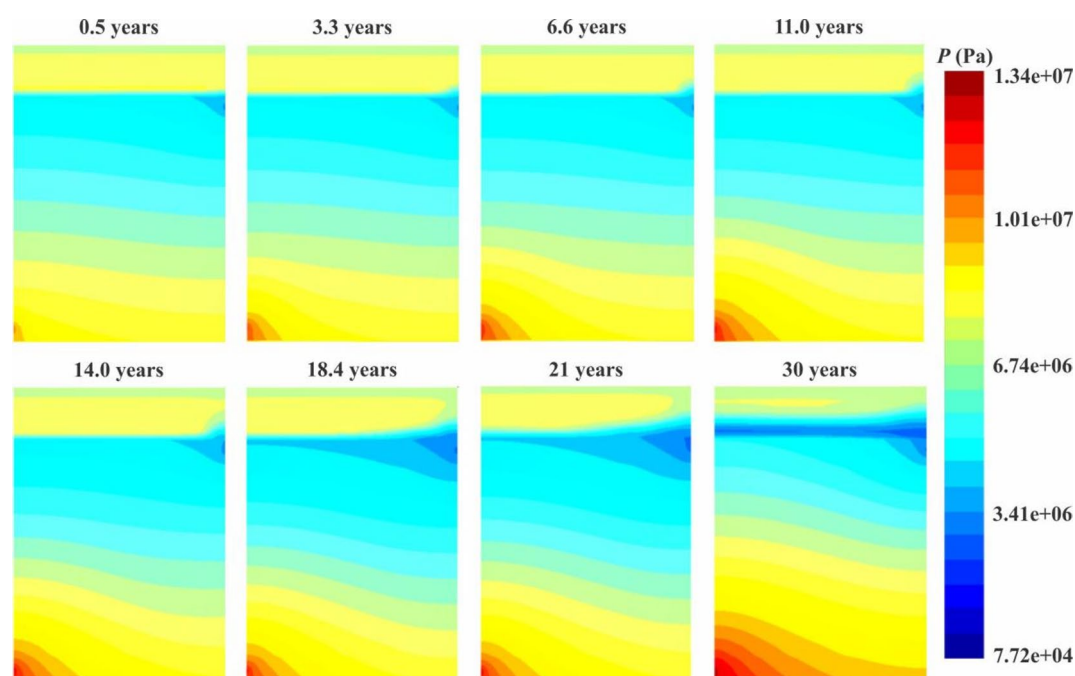


Fig. 10. Evolution of the spatial distribution of pressure (Pa) during the 30 years period.

Spatial distribution of steam saturation

Figure 11 shows the evolution of the steam saturation spacial distribution over the 30-year period. During the stable stage (0–12.5 years), a region with high steam saturation is formed around the production well, and the size and shape of this region are basically unchanged during this period. As previously stated, this phenomenon occurs because the temperature and pressure around the production well are basically unchanged. Consequently, the steam saturation is also maintained at about 0.28. After entering the slow declining stage (12.5–18.4 years), due to the slow decrease of reservoir pressure, the high steam saturation area formed near the production well gradually increases and forms a special shape. The steam saturation in this area gradually decreases, resulting in

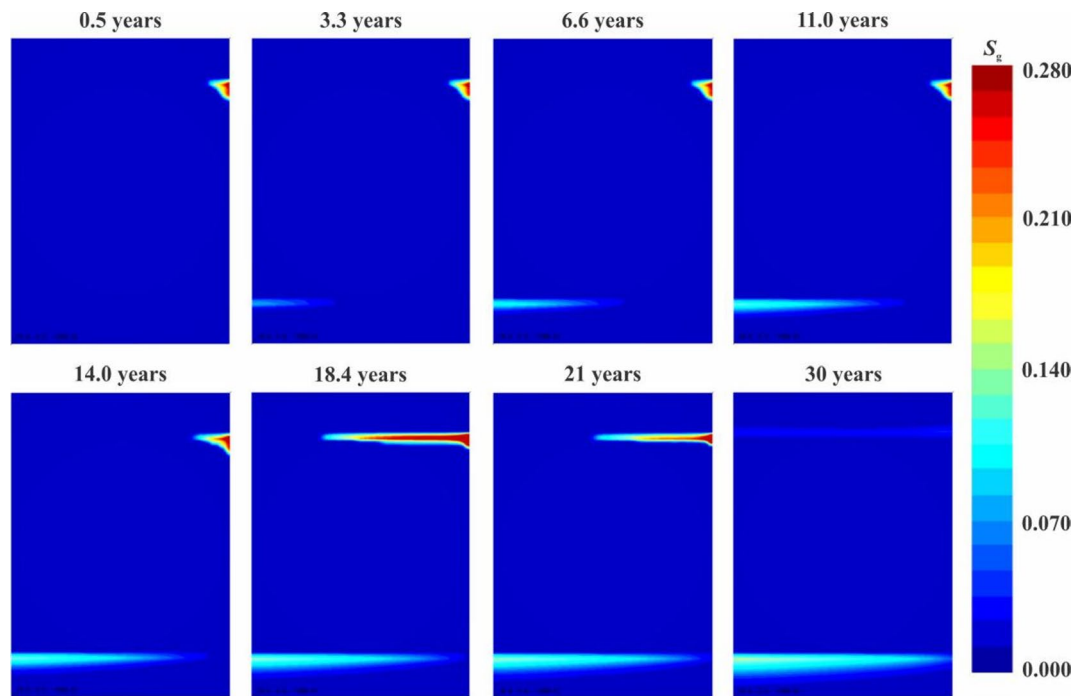


Fig. 11. Evolution of the spatial distribution of steam saturation during the 30 years period.

the gradual decrease of the produced steam saturation. In the final rapid declining stage (18.4–30 years), the area with high steam saturation shrinks rapidly, the saturation of produced steam drops to 0, and only liquid water is produced from the production well, which is due to the further reduction of production temperature.

Sensitivity analysis of electricity generation to various parameters

In this study, we investigate the sensitivity of electricity generation through horizontal wells employing the depressurization method to variations in the following parameters: production pressure, P_{pro} ; reservoir permeability, k ; reservoir temperature, T_R ; water production rate q ; and injection temperature, T_{inj} . Based on the reference case, sensitivity analyses are performed by altering one parameter at a time while holding others constant. Notably, this study does not account for nonlinear interactions among parameters during sensitivity analysis and assumes that the impact of parameter variations on production performance is strictly monotonic¹⁰. Based on the reference case (R), we analyzed the performance and efficiency characteristics of 5 distinct scenarios: (a) Reducing the production pressure (P_{pro}) to 2.00 MPa; (b) Increasing the reservoir permeability (k) to $80 \times 10^{-15} \text{ m}^2$; (c) Lowering the reservoir temperature (T_R) to 238 °C; (d) Decreasing the water production rate (q) to 1.60 kg/s; (e) Raising the injection temperature (T_{inj}) to 80 °C (i.e. increasing the specific enthalpy of injection, h_{inj} , from 260.66 to 343.95 kJ/kg). Figures 12, 13, 14, 15 and 16 illustrate the sensitivity of key performance metrics - steam saturation S_g , electric power W_e , water flow impedance I_R , pump power W_p , and energy efficiency η to variations in these parameters.

Sensitivity to P_{pro}

Figure 12a shows that reducing P_{pro} from 2.50 MPa to 2.00 MPa results in a decrease of the temperature of saturated steam from 230 °C to 221.3 °C. And the reservoir lifespan prolongs from 20.6 years to 21.4 years. Figure 13a shows that the reduction of P_{pro} results an increase of S_g from 0.28~0 to 0.31~0, while extending the stable stage from 0~12.5 years to 0~13.85 years, and extending the slow declining stage from 12.5~18.4 years to 13.85~19.92 years. Since the initial reservoir temperature T_R in Yangbajing geothermal field is 248 °C, when P_{pro} is reduced, the temperature of saturated steam corresponding to this pressure decreases. Therefore, the reservoir can heat more liquid water to vaporize, so as to improve the steam saturation, extend the time of steam production, and prolong the time of the stable stage and slow declining stage. Figure 14a shows that the reduction of P_{pro} results in a drop of W_e from 32.28–5.16 MW to 31.05–5.06 MW. This is because lower P_{pro} reduces the corresponding S_g and h_{pro} . Based on Eq. (4), this will decrease W_e . Figure 15a shows that the reduction of P_{pro} results an increase of I_R from 0.072~0.109 MPa/(kg/s) to 0.076~0.109 MPa/(kg/s). This is because reducing P_{pro} will reduce the saturation temperature in the reservoir, thereby reduce the temperature of the reservoir water flow, thus increase the water viscosity. Based on Eq. (6), this will significantly improve I_R . Figure 16a illustrates that reducing P_{pro} increases W_p from 1.14–2.19 MW to 1.27–2.19 MW. This is because the reduction of P_{pro} reduces I_R , based on Eq. (5), which will increase P_{inj} . Figure 17a demonstrates that reducing P_{pro} decreases η from 28.87~2.36 to 25.98~2.31. This is because lower P_{pro} decreases W_e , meanwhile increases W_p , based on Eq. (8), η is obviously decreased. Overall, P_{pro} is a key parameter influencing the production temperature and steam saturation. Within a specific operational range, reducing P_{pro} enhances S_g during the stable stage, prolongs

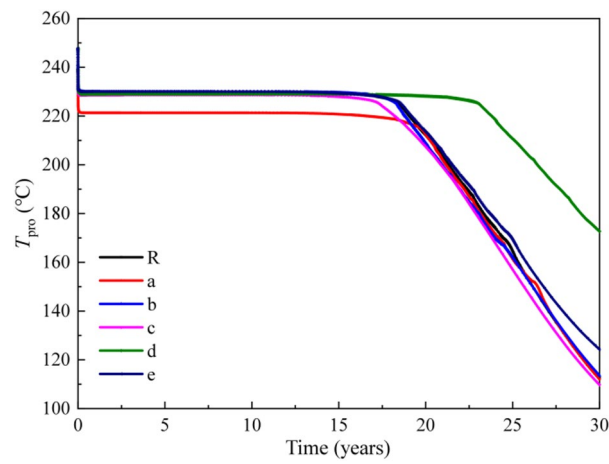


Fig. 12. Sensitivity of production temperature T_{pro} to various parameters.

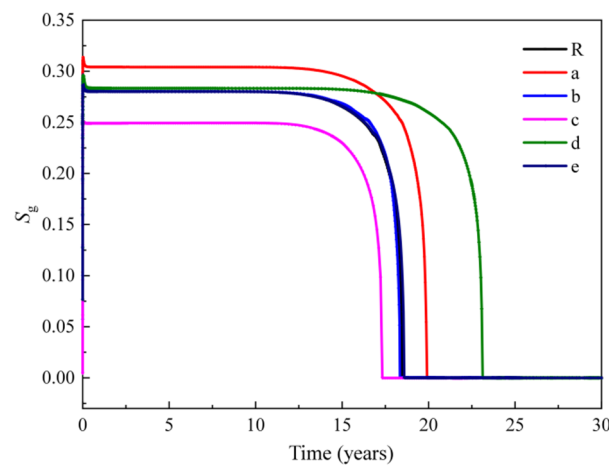


Fig. 13. Sensitivity of steam saturation S_g to various parameters.

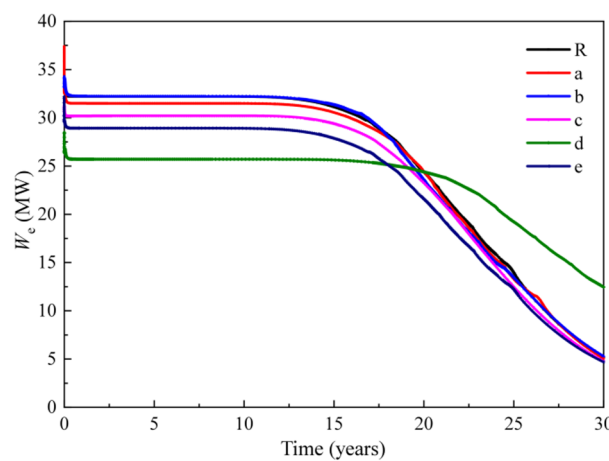


Fig. 14. Sensitivity of electric power W_e to various parameters.

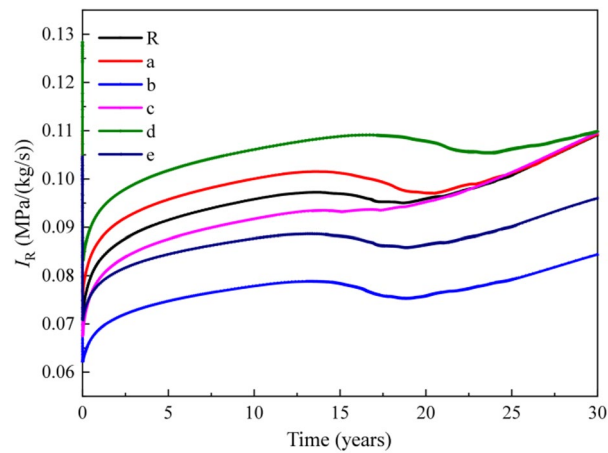


Fig. 15. Sensitivity of water flow impedance I_R to various parameters.

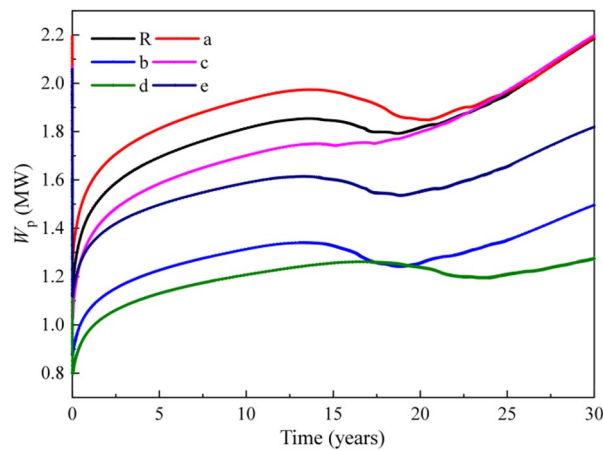


Fig. 16. Sensitivity of pump power W_p to various parameters.

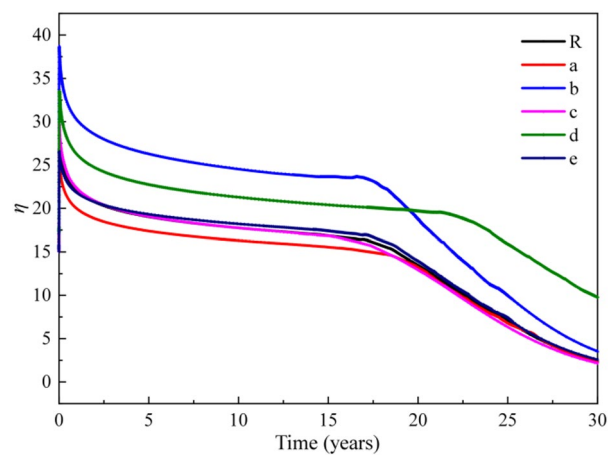


Fig. 17. Sensitivity of energy efficiency η to various parameters.

both the stable and slow declining stages, meanwhile decreases W_e and increases I_R and W_p . These combined effects ultimately reduce the energy efficiency η . Additionally, elevated steam saturation levels may exacerbate scaling and chemical deposition issues, potentially damaging generation equipment. Therefore, when selecting

the optimal production pressure, the field fluid composition and power plant configuration should be evaluated to balance performance and operational risks.

Sensitivity to k

Figures 12b, 13 and 14b demonstrate that increasing k from $50 \times 10^{-15} \text{ m}^2$ to $80 \times 10^{-15} \text{ m}^2$ has a slight impact on T_{pro} , S_{g} and W_{e} during both the stable and declining stages. This is because the steam saturation and production enthalpy are primarily governed by the production pressure and temperature, rather than reservoir permeability. As Eq. (4) indicates, modifying k alone does not alter the bottomhole production pressure or temperature, resulting in negligible changes to S_{g} and W_{e} . Figure 15b reveals that the increase in k reduces I_{R} from 0.072–0.109 MPa/(kg/s) to 0.062–0.084 MPa/(kg/s). This reduction occurs because higher reservoir permeability enhances flow conditions, thereby lowering the reservoir impedance according to Eq. (6). Figure 16b illustrates that increasing k reduces W_{p} from 1.14–2.19 MW to 0.88–1.50 MW. This reduction occurs because higher reservoir permeability lowers both the reservoir impedance and the injection pressure, thereby significantly decreasing the pump power as described by Eq. (7). Figure 17b demonstrates that the increase of k enhances η from 28.87–2.36 to 38.70–3.54. This improvement arises because the slight reduction in W_{e} is outweighed by the substantial decrease in W_{p} , leading to a net gain in η . Overall, k is a critical parameter affecting flow impedance and energy efficiency. Within a specific operational range, increasing k reduces I_{R} and W_{p} , while only marginally affecting S_{g} and W_{e} , thereby significantly improving the energy efficiency η .

Sensitivity to T_{R}

Figure 12c shows that decreasing T_{R} from 248 °C to 238 °C results in a drop of the temperature of saturated steam from 230 °C to 228.7 °C, and a decrease of reservoir lifespan from 20.6 years to 20.2 years. Figure 13c illustrates that reducing T_{R} decreases S_{g} from 0.28–0 to 0.25–0, shortens the stable stage from 0–12.5 years to 0–11.17 years, and reduces the slow declining stage from 12.5–18.4 years to 11.17–17.33 years. This occurs because the initial reservoir temperature directly reflects the available thermal energy in situ. Lower reservoir temperatures will reduce the grade of energy used to heat the water flow, thereby reducing the steam saturation and shortening the duration of both the stable and slow declining stages. Figure 14c shows that the decrement of T_{R} results in a drop of W_{e} from 32.28–5.16 MW to 30.21–4.76 MW. This is because the lower T_{R} significantly reduces T_{pro} and h_{pro} , which will significantly reduce W_{e} according to Eq. (4). Figure 15c shows that the decrement of T_{R} results in a drop of I_{R} from 0.072–0.109 MPa/(kg/s) to 0.068–0.109 MPa/(kg/s). This is because lower reservoir temperature reduces the saturation temperature of wet steam in the reservoir. For wet steam containing liquid water and vapor, the viscosity of wet steam changes a little but the density increases a lot in the studied temperature range, resulting in a large decrease in the ratio of μ/ρ . According to Eq. (6), this will significantly reduce the water flow impedance I_{R} . Figure 16c demonstrates that reducing T_{R} lowers W_{p} from 1.14–2.19 MW to 1.02–2.19 MW. This occurs because lower I_{R} significantly reduces P_{inj} , which will significantly reduce W_{p} according to Eq. (7). Figure 17c reveals that the same reduction in T_{R} decreases η from 28.87–2.36 to 28.87–2.17. This decline arises because lower T_{R} significantly reduces W_{e} and W_{p} , with the combined effect leading to a net decrease in η . Overall, T_{R} is a critical parameter affecting steam saturation and electric power. Within a specific operational range, decreasing T_{R} reduces S_{g} during the stable stage, shortens the duration of the stable and slow declining stage, and lowers W_{e} , I_{R} , and W_{p} , thereby significantly reducing η .

Sensitivity to q

Figure 12d shows that decreasing q from 2.0 kg/s to 1.60 kg/s results in a drop of the temperature of saturated steam from 230 °C to 229 °C, and a dramatic increase of reservoir lifespan from 20.6 years to 25.6 years. Figure 13d shows that decrease of q results in a slight effect on S_{g} , but extends the stable stage from 0–12.5 years to 0–17.87 years, and extends the slow declining stage from 12.5–18.4 years to 17.87–23.13 years. This occurs because the lower q reduces the heat extraction rate, allowing the same in-situ thermal energy to sustain heat extraction over a longer period. Consequently, this significantly extends the duration of the stable and slow declining stage. Figure 14d illustrates that reducing q decreases W_{e} from 32.28–5.16 MW to 26.80–12.46 MW, i.e. W_{e} is significantly reduced in the stable and slow declining stage but increased in the rapid declining stage. According to Eq. (4), in the stable stage, lower q will significantly reduce W_{e} . However, in the fast declining stage, lower q can obtain higher T_{pro} , then W_{e} is significantly improved. Figure 15d demonstrates that reducing q increases I_{R} from 0.072–0.109 MPa/(kg/s) to 0.083–0.110 MPa/(kg/s). According to Eq. (6), lower q significantly reduces the cross-sectional area A of the fluid channel, which significantly elevates I_{R} when other parameters remain constant. Figure 16d illustrates that the decrement of q decreases W_{p} from 1.14–2.19 MW to 0.80–1.27 MW. Based on Eq. (7), a lower q will significantly reduce W_{p} . Figure 17d reveals that reducing q enhances η from 28.87–2.36 to 33.51–9.77. According to Eq. (8), η is significantly improved when W_{e} and W_{p} are reduced, consistent with previous studies²⁸. Although lower q can significantly improve η , it reduces W_{e} , which is not conducive to commercial power generation. Overall, q is a key parameter affecting electric power and flow impedance. Within a specific operational range, reducing q extends the duration of the stable and slow declining stage, lowers W_{e} and W_{p} , increases I_{R} , and significantly reduces the energy efficiency η .

Sensitivity to T_{inj}

Figures 12e and 13e show that increasing T_{inj} from 60 °C to 80 °C has a slight effect on T_{pro} and S_{g} , and has prolonged the reservoir lifespan from 20.6 years to 20.8 years slightly. This is because only increasing T_{inj} has no effect on the bottomhole production pressure P_{pro} and production temperature T_{pro} , so it has little effect on the vaporization process. Figure 14e shows that the increment of T_{inj} causes a drop of W_{e} from 32.28–5.16 MW to 32.19–4.69 MW. This is because the increment of T_{inj} will increase the h_{inj} , this will finally decrease W_{e} according to Eq. (4). Figure 15e shows that the increment of T_{inj} results in a drop of I_{R} from 0.072–0.109 MPa/(kg/s) to

0.071–0.096 MPa/(kg/s). This occurs because the higher T_{inj} increases the average water flow temperature in the reservoir, thereby decreasing the overall μ/ρ . According to Eq. (6), this reduction in μ/ρ significantly lowers I_R . Figure 16e demonstrates that increasing T_{inj} decreases W_p from 1.14–2.19 MW to 1.12–1.82 MW. This reduction arises because lower I_R reduces P_{inj} , which in turn reduces W_p according to Eq. (7). Figure 17e reveals that the increment of T_{inj} raises η from 28.87–2.36 to 26.53–2.58. According to Eq. (8), increasing T_{inj} reduces W_e and W_p , but the combined effect is to slightly improve η , consistent with prior studies³³. Overall, T_{inj} is a critical parameter affecting electric power and flow impedance. Within a specific operational range, increasing T_{inj} has a modest impact on S_g , reduces W_e , W_p , and I_R , and meanwhile increase the energy efficiency η .

Conclusions

Based on the geological data of ZK4001 borehole of Yangbajing geothermal field, a conceptual model for the geothermal exploitation of fractured reservoir by depressurization method through the horizontal well system is established. Based on the developed model, we numerically investigated the heat production performance, calculated the power generation capacity, and analyzed the primary factors influencing energy efficiency. The key conclusions are as follows:

- (1) Heat production process can be divided into three stages. During the stable stage (0–12.5 years), a mixture of steam and liquid water is produced with a production temperature of 230 °C and a steam saturation of 0.28. In the slow declining stage (12.5–18.4 years), the production temperature decreased to 225.1 °C, and the steam saturation decreased to 0 gradually. In the rapid declining stage (18.4–30.0 years), the system produces liquid water with the production temperature decreasing gradually.
- (2) In the reference case, through three horizontal wells with depressurization method during the 30 years, the electric power is within 32.28–5.16 MW, the water flow impedance is within 0.072–0.109 MPa/(kg/s), the pump power is within 1.14–2.19 MW, and the energy efficiency is within 28.87–2.36, showing favorable electricity generation performance.
- (3) The installed power capacity of the proposed EGS configuration is 30 MW. Over the 20.6-year reservoir lifespan, the designed power plant is projected to generate approximately 4819.74 GWh of electricity, with total costs estimated at \$65.83 million. The LCOE is estimated to be 0.0137\$/kWh, significantly lower than the 2022 industrial electricity price of 0.09\$/kWh in the Tibet Autonomous Region. The profit of net power generation is \$367.95 million. The proposed EGS power plant is expected to reduce green house gas emissions by 1.63–5.63 Mt over 20.6 years, yielding estimated profits from carbon credits of \$13.78–51.96 million under the assumptions adopted in this study.
- (4) In the stable stage, a region of high steam saturation is formed around the production well, and the size and shape of this region are basically unchanged. In the slow declining stage, the affected region expands gradually and the internal steam saturation decreases gradually. In the rapid declining stage, the high steam saturation region decreases gradually and finally disappears.
- (5) Production pressure is a key parameter affecting production temperature and steam saturation. Therefore, the choice of production pressure should prioritize the reservoir's fluid composition and power plant pattern.
- (6) Reservoir permeability is a critical parameter affecting flow impedance and energy efficiency. Higher reservoir permeability effectively reduces flow impedance, minimizes internal energy consumption, and enhances the system's energy efficiency.
- (7) Initial reservoir temperature is a key parameter affecting steam saturation and electric power. A lower reservoir temperature leads to lower power generation and diminished energy efficiency.
- (8) Injection rate is a critical parameter affecting electric power and flow impedance. A lower injection rate reduces power generation but extends the reservoir lifespan and decreases flow impedance. Optimizing the injection flow rate within a specified range can enhance the system's energy efficiency.
- (9) Injection temperature is a key parameter affecting electric power and flow impedance. A higher injection temperature typically reduces power generation and diminishes the system's energy efficiency.

Fluid flow and heat transfer in deep underground rocks at high temperature and pressure are often accompanied by two-phase flow caused by boiling. Meanwhile, the two-phase flow process is affected by the coupled thermal-hydraulic-mechanical-chemical interactions. In this study, the numerical model mainly considers thermal-hydraulic processes, while mechanical deformation, fracture evolution, and chemical effects are not explicitly included. The present simulation results are therefore specific to the modeled conditions and parameter settings and should not be directly extrapolated to other geothermal reservoirs without further validation. These numerical experiments provide a detailed characterization of dynamic evolution, offering valuable insights into the integrated processes of fluid flow, heat transfer, geothermal exploitation, and power generation in a horizontal-well geothermal system operated via depressurization method.

Data availability

The data that support the findings of this study are available from the corresponding author, H.Z. ZHAI, upon reasonable request.

Received: 21 August 2025; Accepted: 30 December 2025

Published online: 03 February 2026

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Author contributions

Y. Z., L. D., N. W., X. S., and H. Z. wrote the main manuscript text. Y. S., E. O., L. H., Q. L., and H. Z. prepared the Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17. All authors reviewed the manuscript.

Funding

This work was supported by Laoshan Laboratory and the Taishan Scholar Special Experts Project (No. ts201712079), the Key Field Program of Ordinary Universities in Guangdong Province (2022ZDZX4023), the Chinese Academy of Sciences (CAS) Scholarship, and the Open Fund (OGE202302-12) of the Key Laboratory of Oil & Gas Equipment, Ministry of Education (Southwest Petroleum University).

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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