INTRODUCTION

Exploration, development, and utilization of renewable energy are new challenges for all countries. Geothermal energy, as a renewable energy source, has been paid more and more attention. Geothermal resources can be divided into high (>150°C), medium (90‐150°C), and low temperature (<90°C) according to their attributes and even supercritical geothermal system (T > 374°C, P > 221 bar), and into deep (>4 km, power generation), intermediate (0.1‐4 km, direct heating), and shallow (<0.1 km, direct cooling) according to their depth and purpose. Also, the geothermal resources can be divided into hot dry rock and hydrothermal type according to their way of extracting heat. The hot dry rock (HDR) is a kind of deep geothermal resource (granite, metamorphic, tight sandstone), which the temperature is over 200°C and
the reservoir is generally 3-10 km underground. As a new renewable energy source, dry hot rock has many advantages, which include stability (unaffected by season and climate), low cost (low cost of utilization), high efficiency (the utilization ratio of power generation is over 73%), which is 5.2 and 3.5 times that of photovoltaic and wind power generation), environment-friendly nature (it reduces harmful emissions CO₂, SO₂, and NO/NO₂), security (harmless to human and ecology), and large chain integrity (exploration, drilling, manufacturing, power generation, heating, bath, tourism, etc). Enhanced geothermal system (EGS) is a method that the artificial stimulation can improve low permeability and porosity of HDR reservoir, and economically extract heat, which the concept was proposed by the Los Alamos National Laboratory (LANL) in the United States. The first EGS project at Fenton Hill was conducted by the United States in 1973. And other EGS projects at Desert Peak, Geysers, Raft River, Rosemanowes, Soultz, Habanero, Hijiori, Ogachi, Pohang, and DEEPEGS have launched in the world. In recent years, the utilization of geothermal resources has gradually increased in China, especially during the 12th Five-Year Plan period. The Chinese government proposed energy development in the 13th Five-Year Plan (2016-2020) to develop vigorously clean energy. The HDR resource at 3-10 km is 22.9 × 10⁶ EJ, which is equivalent to 1.56 × 10⁹ billion tons coal. There are five typical geothermal fields in China, which include southern Tibet, western Yunnan, Southeast Coast, North China, and Songliao Basin. The area studied in this paper is in Yitong Basin (border on Songliao Basin), which heat content is 1.69 × 10⁹ EJ in 3-10 km. There are many experimental and numerical studies on EGS in Songliao Basin. The geothermal resources are very abundant by judging based on heat flow and Curie depths in study area, and the fluid-rock interaction for CO₂-EGS is developed under temperature 150-170°C. The electricity generation is evaluated by H-T coupling for EGS based on numerical simulation in northeastern China. Besides, the parameter optimizations for thermal production are conducted by H-T-M coupling model in Songliao Basin.

The fracture network and heat transfer between working fluids and rock matrix are dominant features in EGS. Hydrothermal production capacity and operating time are the criteria for evaluating the commercialization of EGS, and the hydrothermal production in the EGS involves the interaction of heat transfer field and seepage field. The analytical solutions are difficult to accurately describe complex coupling processes, while the numerical simulation method can solve these problems better. The numerical methods mainly include four different approaches, namely discrete fracture network (DFN), equivalent porous media (EPM), fractured continuum (FC), and equivalent pipe network (EPN). Cao developed a transient 3D numerical model to describe THM coupling considering the thermal-pore-elastic model. The effects of fracture and fracture spacing on Tₚ₀ were conducted based on closed-loop multiple-fracture using a simplified model for EGS. Zeng showed numerical simulation of horizontal and vertical fracture based on Desert Peak geothermal field and analyzed the sensitivities of flow rate, injection temperature, and reservoir permeability. The reactive thermo-poroelastic model with BEM and FEM was analyzed to response to nonisothermal reactive flow in EGS, and the effect of fluid circulation on rock matrix properties was obtained. As working fluid, the supercritical carbon dioxide was injected into fractures in EGS (CO₂-EGS) and showed good results. TOUGH was applied in power generation of numerical simulation for EGS at Songliao Basin. However, the direct utilization for supply heating in EGS is urgently needed at Songliao (Yitong) Basin (cold and arid areas).

The economic analysis of EGS is a key factor for heating. However, utilization of hot dry rocks focuses on power generation in many studies. The investment analysis (drilling costs, constructing power station, risk, and uncertain costs) was considered in Yangbajing Basin. The drilling costs account for a large proportion in EGS. Maciej proposed a method to characterize cost of drilling and completion of geothermal wells based on the Monte Carlo approach. Yost conducted the uncertainties of drilling cost and duration Decision Aids for Tunneling in EGS. The economies of low-enthalpy heating and high-temperature power generation were evaluated separately in northern Canada. The different operation scenarios were optimized to find a high-production model based on complex TH coupling in Soultz EGS. The life-cycle assessment, energy consumption, and induced seismicity risks also were considered for heat benefits in EGS. In addition, the software packages were proposed to estimate and simulate EGS costs, and new cost elements (environmental effect) should be calculated. Thus, economic analysis of heating for EGS can provide advice for decision-making of the government and business.

In this paper, the simplified single-fracture coupled hydrothermal model with laboratory test was developed in the EGS project based on Yitong Basin data. The parameters of model were obtained by rock sample testing, and the effects of fracture permeability, well spacing, injection temperature, and injection rate on heat production and reservoir were analyzed. Furthermore, the economic analysis of heating was conducted from private and social perspectives by using the model.

## 2 | BACKGROUND OF THE STUDY SITE

### 2.1 | Geological structure and formation lithology

Yitong Basin is narrow and long, which is situated between Changchun and Jilin. The distribution direction is NE 45-55°,
and the area is about 2200 km². Yitong Basin is a Cenozoic graben-type fault basin, which is divided into three first-order tectonic units (namely Chaluhe, Luxiang, and Moliqing), as shown in Figure 1. There are five tectonic evolution periods in the study site, namely fault depression development period (E2s-E2sh), depression development period (E2sh-E2y), differential settlement period (E3w-E3q), tectonic inversion period (E3q-Nc), and flexible depression period (Q), which provides advantageous conditions for the generation and circulation of geothermal resources. According to the drilling and logging data of well C27 (depth 5070 m), the sedimentary strata in the study area are mainly divided into Quaternary-Q (clay, 0-20 m), Neogene Chaluhe Formation-Nc (mudstone and glutenite, 20-450 m), Oligocene Qijia Formation of Paleogene-E3q (mudstone and sandstone, 450-960 m), Oligocene Wanchang Formation-E3w (glutenite, 960-1960 m), Eocene Yongji Formation-E2y (sandstone, 1960-2780 m), Eocene Sheling Formation-E2sh (mudstone and sandstone, 2780-3100 m), Eocene Shuangyang Formation-E2s (mudstone and sandstone, 3100-4054 m), and Paleozoic basement granite-γ (>4054 m) from top to bottom. The temperature in the depth of the basement is over
150°C, as shown in Figure 2. Besides, the tertiary sedimentary strata (4000 m) provide huge thickness of caprock for geothermal resources.

2.2 | Geothermal characteristics

Yitong Basin is a fault basin type in geothermal origin. Generally, the geothermal resources must have four conditions: heat source, thermal reservoir, caprock, and thermal channel. (a) **Heat source.** A large number of magma intruded into the shallow crust of Yitong Basin to form a good heat source. Also, friction heat source of fracture machinery and decay heat source of radioactive material (U$^{238}$, Th$^{232}$, K$^{40}$) supply heat source. (b) **Thermal reservoir.** The scale of the basement granite intrusions in the study area is large, of which 80%-85% are Yanshanian granites, and they have become good high-temperature geothermal reservoirs. (c) **Caprock.** The Cenozoic sedimentary strata in the study area are more than 4000 m, and sandstone, mudstone, and glutenite are mainly developed. The maximum thickness of mudstone is 187 m. The thermal conductivity and permeability are poor, forming a good caprock. (d) **Thermal channel.** Deep and large faults developed in the study area, and many secondary fault systems were derived. The cross-development of fracture system provides a good thermal transmission channel for heat source and reservoir.

The study area has higher heat flow and geothermal gradient. By calculating the measured formation temperature and thermal conductivity of formation rocks, the current average geothermal flow in Yitong Basin is 71.49 mW/m$^2$ (the average value is 60.40 in China). The heat flow of first-order tectonic units Chaluhe, Luxiang, and Moliqing is 70.50, 71.80, and 72.85 mW/m$^2$, respectively. According to geothermal data obtained from field drilling in the study area, the average geothermal gradient is 3.49°C/hm for Yitong Basin. The geothermal gradient of first-order tectonic units Chaluhe, Luxiang, and Moliqing is 3.36, 3.62, and 3.52°C/hm, respectively, as shown in Figure 3.

2.3 | Target reservoir determination

The C-27 well in the study area is to continue drilling on the basis of the original well in order to predict the oil and gas content in the bedrock. When the well is completed, the bedrock is drilled 1000 m and the well depth is 5070 m. According to C-27 well logging and formation data, the underground 4054-4168 m granite fractures are underdeveloped, which makes it more suitable to use EGS technology to transform into thermal reservoirs. The temperature is close to 160°C at the corresponding depth. Therefore, the depth 4054-4168 m granite is selected as thermal reservoir to simulate hydrothermal production.

3 | FORECASTING OF HYDROTHERMAL PRODUCTION

3.1 | Physical properties of reservoir rocks

In order to improve the accuracy of the numerical model, the granites in the study area were made into laboratory-scale standard rock sample $\Phi 50 \times 100$ mm to obtain the physical properties (density, porosity, thermal conductivity,
specific heat capacity, permeability) of the rocks, as shown in Figure 4A.

3.1.1 | Density
For standard specimens, diameter and mass are measured by vernier calipers and balance, respectively, after drying in an oven. The average density of granites was 2.672 g/cm³.

3.1.2 | Thermal conductivity
The thermal conductivity of granites was measured by a thermal conductivity sensor (TCS) made in Germany (Figure 4A). The equipment has the advantages of high accuracy, fast speed, and no damage for rocks. After many measurements, the thermal conductivity of rock was 2.741 W/m·K.

3.1.3 | Specific heat capacity
The mixed cooling method and XY-BRR apparatus were applied for measuring rock specific heat capacity. The rock samples need to be crushed into powder to facilitate heat exchange between water and rock, and the average specific heat capacity \( c = 0.719 \text{ kJ/(kg·K)} \) of granites can be obtained.

3.1.4 | Porosity
Porosity characteristics play an important role in EGS. The scanning electron microscope (SEM) can observe microstructure and porosity characteristics of rocks, as shown in Figure 4B. It can be seen that the rocks were compact, and the pore size was small and mainly distributed in the range of 0.1-2 μm. Most of the pores existed alone and had poor connectivity. The granite porosity was about 5% under SEM. In addition, the porosity of rocks was also measured by KS-I gas porosity and permeability tester, which was based on Boyle’s law. The average porosity was 2.02% for rock samples.

3.1.5 | Permeability
The KS-I apparatus and Darcy’s law were applied to permeability measurement. The permeability value \( K = 0.2840 \text{ mD} \) can be obtained by Equation (1):
where $K$ is permeability; $P_0$ and $Q_0$ are atmospheric pressure and flow rate at atmospheric pressure, respectively; $\mu$ is gas viscosity; $L$ and $A$ are specimen length and cross-sectional area, respectively; and $P_1$ and $P_2$ are the pressure of the fluid inlet and outlet, respectively.

### 3.2 Numerical simulation methodology

This study is using TOUGH2 for numerical simulation based on field data and laboratory experiments. TOUGH2 is a program for numerical simulation of nonisothermal multiphase fluid and thermal migration in porous/fractured media, which belongs to the MULKOM code family and was developed by Berkeley Lawrence National Laboratory for geothermal storage engineering, nuclear waste disposal, aeration zone hydrology, geology, and carbon dioxide storage (carbon sequestration). The integral finite difference method is used to solve the problem, and the mass-energy equation can be written as follows:

$$\frac{d}{dt} \int_{V_n} M_k^{ij} dV_n = \int_{V_n} F_k^{ij} \cdot n d\Gamma_n + \int_{V_n} q_{k,j}^{ij} dV_n$$

where $k$ is mass term and $h$ is heat (energy).

**Mass accumulation term:**

$$M_k = \phi \sum_{\beta} S_{\beta} \rho_{\beta} X_{\beta}^{k} + (1 - \phi) \rho_N X_k^{k} K_d$$

**Heat accumulation term:**

$$M_h = \phi \sum_{\beta} S_{\beta} \rho_{\beta} u_{\beta} + (1 - \phi) \rho_N C_p T$$

**Advective mass flux:**

$$F_k = \sum_{\beta} X_{\beta}^{k} F_{\beta}$$

**Heat flux:**

$$F_h = -\lambda \nabla T + \sum_{\beta} h_{\beta} F_{\beta} + f_{\sigma} \sigma_0 \nabla T^4$$

where $F$ can be obtained by Darcy's law as follows:

$$F_{\beta} = \rho_{\beta} u_{\beta} = -k_{\beta} \rho_{\beta} \mu_{\beta} \nabla(P_{\beta} - \rho_{\beta} \xi)$$

Sink and source terms:

$$q_k = \sum_{\beta} X_{\beta}^{k} q_{\beta}$$

$$q_h = \sum_{\beta} q_{\beta} h_{\beta}$$

TOUGH2 adopts modular design. The Equations of State (EOS1) module can depict pure water, steam, and two-phase coexistence system, and the maximum temperature can reach 647.3 K. The two-phase saturation line, density, viscosity, and heat enthalpy can be calculated according to the model provided by the International Committee on Formalization.

### 3.3 Model parameterization

Based on the geological data and well C-27 logging data of the study area and also temperature factor, 4054-4168 m granite was selected as the target thermal reservoir ($z = 114$ m), and 3600-4054 m and 4054-4600 m correspond to the overlying and underlying layers, respectively, which established hydrothermal coupling geological model of $1500 \times 1000 \times 1000$ m. The grid refinement in reservoir model will be conducted, and the total grid number is 28 800. The open hydraulic fracturing was applied to transform thermal reservoir in order to improve permeability and increase production in this study. A vertical fracture connected injection well with production well was produced, and the model is shown in Figure 5. The ideal half-length of fractures produced by open fracturing can reach 300 m. The three-well model (two recovery wells and one injection well) was conducted, and the well spacing was

![Image](A) (B)

**FIGURE 4** Rock physical property testing: (A) rock specimen and thermal conductivity sensor; and (B) microstructure and porosity characteristics of rocks by SEM.
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The coordinates of recovery wells are (250, 500) and (1250, 500). The coordinates of injection wells are (750, 500). A set of fracture units with a thickness of 4 mm was preset in the plane where the reservoir’s three wells were located. The height of the single fracture was 114 m. The average conductivity of fracture can reach the order of $10^5$ mD·m. The main parameters of reservoir and fracture of the model are shown in Table 1.

### 3.4 | Initial and boundary condition

Gradient assignment was used for initial pore pressure and temperature in the numerical model. The pore pressure was set to hydrostatic pressure, and the pore pressure gradient was 1 MPa/100 m, while the pore pressure at the top of the reservoir was set to 40 MPa. The top and bottom temperatures of the reservoir model were 152°C and 156°C, respectively. The injection rate and initial injection temperature of the EGS were 10 kg/s and 50°C, respectively. The variations of thermal physical properties for rocks and water are neglected. The 20-year operation of EGS project was considered. The production rate of the system is equal to the injection rate, and the fluid loss during operation was neglected.

The constant pressure $\sigma_0$ was loaded at the top of the model. Fixed supports and roller boundary were applied to the bottom boundary and lateral boundaries of the model, respectively. The forced flow of fluid along the fracture plane can be regarded as one-dimensional heat convection. The heat conduction occurs mainly in the direction perpendicular to the fracture plane, and the heat recharge to the fracture was carried out. The effect of thermal radiation on the whole hydrothermal coupling process was neglected.

### 3.5 | Results and discussions

The variations of production temperature, flow impedance, and heating power with time were important for the heating system in EGS reservoir. The critical thermal criteria for

| Parameters                        | Value          |
|-----------------------------------|----------------|
| Rock density (kg/m³)              | Reservoir 2672 | Fracture 2440 |
| Rock porosity                     | 0.02           | 0.25          |
| Rock permeability (mD)            | 0.284          | $10^5$        |
| Rock thermal conductivity (W/(m·K)) | 2.741      | 2.741         |
| Rock specific heat (J/(kg·K))     | 719            | 719           |
| Water density (kg/m³)             | 940            |
| Water specific heat (J/(kg·K))    | 4200           |
| Water thermal conductivity (W/(m·K)) | 0.68        |
| Initial temperature (°C)          | $T = 152 + 0.035Z$ |
| Initial pressure (MPa)            | $P = 40 + 0.01Z$ |
| Injection temperature (°C)        | 50             |
| Injection rate (kg/s)             | 10             |
| Injection specific enthalpy (kJ/kg)| 75.64        |
| Productivity index (m³) (reference case) | $5.3 \times 10^{-12}$ |
| Operation cycle (y)               | 20             |
heating required that the water temperature of the production should not be less than 55°C. The production temperature drop of thermal reservoir should be within 10%, and the flow impedance of the EGS should not exceed 0.1 MPa/(kg/s), which the reasonable economic development benefit can be obtained.37,50

The flow impedance can be calculated by Equation (10):

$$I_R = \frac{P_{inj} - P_{pro}}{q}$$  \hspace{1cm} (10)

and Equation (11):

$$I_R = \frac{\mu L}{k\rho A} = f(T)$$  \hspace{1cm} (11)

The heating power can be calculated by Equation (12):

$$W_h = q \left( h_{pro} - h_{inj} \right)$$  \hspace{1cm} (12)

where $q$ is the flow rate; $P_{inj}$ and $P_{pro}$ are the bottom pressure of injection well and production well, respectively; and $h_{pro}$ and $h_{inj}$ are production and injection specific enthalpy, respectively.

3.5.1 | Variation of temperature and pressure with time

The variation of temperature and pressure can be used to evaluate reservoir life in EGS. Figure 6 shows the variation of production temperature and heating power with time. Due to the continuous injection of cold water, the production temperature decreases, and the speed of decline gradually accelerates. It showed that the velocity of convective heat transfer between fracture and fluid was obviously greater than that of heat conduction in rocks. In order to keep reservoir temperature from thermal breakthrough, the injection fluid temperature 50°C was applied. The production temperature decreased from 155.50 to 148.02°C during 20 years, and the cumulative decrease was 4.81% during 20 years, which did not develop thermal breakthrough. The evolution of heating power with time is similar to temperature, and the heating power decreases from 1.74 to 1.61 MW, with a cumulative decrease of 7.47% during 20 years.

Figure 7 shows the distribution of temperature field in the vertical section where the fracture was located for 0.1a, 1a, 2a, 5a, 10a, and 20a. The temperature at injection wells drops rapidly to the temperature value (50°C) of injection fluid, and the fluid flowed along fracture from injection well to production wells under pressure. The area affected by the temperature of the cold fluid gradually enlarges with time, and the influence area of low temperature had reached the production well in 10 years. It showed that the temperature of thermal reservoir was extracted by fluid in the form of thermal convection and the thermal conduction from the surrounding rocks had hysteresis effect.

3.5.2 | Effect of fracture permeability

Ensuring that other conditions remain unchanged, two kinds of permeability ($K_3 = 5 \times 10^5$ mD, $K_1 = 0.2 \times 10^5$ mD, $K_3 = 5K_2 = 25K_1$) were added to the original simulated
conditions. The evolution of production temperature and flow impedance with time at different fracture permeabilities is shown in Figure 9. The production temperature drops slowly in low permeability \((K_1)\) and high permeability \((K_3)\) will cause thermal breakthrough (temperature drop 21.9°C). When the fracture permeability increased, the fluid “retention time” was very short and “short-circuit” phenomenon was easy to occur, which the thermal breakthrough time of the reservoir will be short. The increase in permeability will reduce the injection pressure and make fluid flow more easily in single fracture. The flow impedance had a negative correlation with permeability. That is to say, the flow impedance will increase by 1.5-2 times for every 5-fold reduction in permeability \((I_{RK1}/I_{RK2} = 2.0, I_{RK2}/I_{RK3} = 1.5)\). Therefore, although the increase in reservoir fracture permeability can reduce the flow impedance, the production temperature will decrease greatly, which was prone to occur thermal breakthrough and shorten the life of the EGS.

3.5.3 Effect of well spacing

It is assumed that the length of single fracture formed by multistage hydraulic fracturing was sufficient and the conductivity was constant. The cases of well spacing \((D = 400, 600 \text{ m})\) were conducted to evaluate spatial distribution of pressure and temperature in ensuring that other conditions remain constant. Figure 10 shows the spatial distribution of temperature and pressure for fracture profile at 20 years under different well
spacings. The increase in well spacing will improve fluid flow path and heat transfer area, which the more heat will be extracted under large well spacing. The low-temperature area of injection well had little relation with well spacing. However, the low-temperature area of the production wells was small under large well spacing, and the time of reaching thermal breakthrough will be prolonged. Because fracture permeability was constant under different well spacings, the variation of injection pressure was not obvious. Therefore, the increase in well spacing will correspondingly enhance the life of EGS reservoir in theory. However, with the increase in well spacing, the difficulty of reservoir fracturing strengthened correspondingly, and the filtration of the EGS will expand when the fracturing range was enlarged, which will affect the stable operation of the project.

3.5.4 | Effect of injection temperature

The injection temperature 30°C, 40°C and 60°C were increased to contrast with injection temperature $T = 50°C$. The variations of heating power and flow impedance with the injection temperature (30, 40, 50, 60°C) by operating 20 years are shown in Figure 11. The injection of low-enthalpy fluid will rapidly reduce the temperature near the injection well, and the value of the $\mu/\rho$ will increase with the decrease in temperature, which the flow impedance decreases with the increase in injection temperature based on Equation (11). Because of the large well spacing, the production temperature was almost unaffected by the injection fluid temperature. The heating power was mainly determined by the specific enthalpy of injection, and the heating power was negatively correlated with injection temperature. However, the four temperatures (30, 40, 50, and 60°C) selected in this study do not cause thermal breakthrough in EGS reservoir. Otherwise, the supercooled fluid injection will not increase the heating power.

3.5.5 | Effect of injection rate

The reasonable flow rate can enhance heat production power without thermal breakthrough. Ensuring that other conditions remain unchanged, four injection rates ($q = 8, 10, 12, \text{and } 16 \text{ kg/s}$) were compared and analyzed in EGS operation. Figure 12 shows the evolution of production temperature and injection pressure with time under different flow rates. The large injection rate can extract more heat from the reservoir in the same heat transfer area, which can reduce the temperature of production. The thermal breakthrough occurred in reservoir at $q = 16 \text{ kg/s}$. Because the fracture permeability was constant, the injection pressure increased with the increase in injection rate. The higher the injection rate, the higher the injection pressure rise in the EGS operation. The water-flowing fracture in reservoir was controlled by minimum principal stress after hydraulic fracturing. Thus, the injection pressure should be less than the minimum principal stress of the reservoir in order to prevent “secondary damage” to reservoir and fluid loss. In addition, the occurrence of microseism should be prevented. The upper limit of the minimum principal stress of the reservoir was 54.5 MPa based on the logging data. The injection pressure had exceeded the minimum principal stress in injection rate $q = 16 \text{ kg/s}$, which the flow rate was not appropriate in this study.

4 | ECONOMIC ANALYSIS OF HEATING

4.1 | Energy efficiency for heating

The reservoir temperature continues to decrease with the operation of heating system, which the flow impedance and energy consumption will increase correspondingly. The energy
efficiency ($\eta$) can reflect the distribution of economic benefits, and $\eta$ can be calculated by Equation (13).\textsuperscript{32}

$$\eta = \frac{W_t}{W_i}$$  \hspace{1cm} (13)

$$W_i = W_{inj} + W_{out1} + W_{out2}$$  \hspace{1cm} (14)

$$W_{inj} = \frac{q (P_{inj} - \rho gh)}{\rho \eta_i}$$  \hspace{1cm} (15)

$$W_{out1} = W_{out2} = \frac{q (\rho gh - P_{pro})}{\rho \eta_i}$$  \hspace{1cm} (16)

where $W_i$ is internal energy consumption (total energy consumption of pump sets), which mainly includes the energy consumption of injection well $W_{inj}$ and production well $W_{out1}$; $h$ is the depth of well; $q$ is the flow rate; $P_{inj}$ and $P_{pro}$ are the bottom pressure of injection well and production well, respectively; $g$ and $\rho$ are gravity acceleration and fluid density, respectively; and $\eta_i$ is the operating efficiency of the pumps, which can be taken as 0.8.\textsuperscript{51}

Figure 13 shows the evolution of internal energy consumption $W_i$ and energy efficiency $\eta$ with time. At the beginning of system operation, the production temperature and heating power were larger, and the internal energy consumption was smaller, while the energy efficiency reached the maximum $\eta = 18.0$. The energy efficiency decreased from 18.0 to 11.7 with the operation of EGS, and the average of $\eta$ was 13.35 in
Due to the continuous injection of fluids, the flow impedance increased with the decline in reservoir temperature, and the internal energy consumption increased with time. The value of $W_t$ increased from 0.096 to 0.138 with the operation of EGS, and the average of $W_t$ was 0.128 in 20 years. Therefore, the operating costs will increase and the economic benefits will decline with time. The energy efficiency and internal energy consumption can be used as reference factors in heating economic analysis.

4.2 | Design for heating

The geothermal heating was different from geothermal power generation. The latter required continuous operation without interruption for the EGS project, whereas the former only needs to operate in the heating period every year. The annual heating period in the study area was about 180 days (from late October to late April). However, the continuous operation was used in this simulation, which was mainly based on the following factors: (a) long-term shutdown of pumps will corrode pipelines; (b) maintenance was still needed during summer pump shutdown, and the heating operation costs will increase without heat production; and (c) irreversible fluid conductivity of fracture will decrease when the fracture closure pressure increased during pump shutdown. Thus, the production heat can be used in other aspects (agriculture, fisheries, and aquaculture) during the nonheating period. And the heating during heating period and applied to other aspects during nonheating period were considered for design.

The costs for heating in EGS mainly included well drilling, reservoir fracturing, surface device, operation, and maintenance, which can be regarded as private-perspective costs. There was a certain probability of occurrence of microseism in fracturing and operation for EGS. The microseism costs should also be taken into account from environmental perspective, which can be regarded as social-perspective costs. The private perspective was mainly evaluated by heating area in terms of revenue. In addition to direct revenue, the carbon dioxide emission reductions were equivalent to benefits and calculated in social perspective. The amount of carbon dioxide was calculated on the basis that production heat was equal to coal.

4.3 | Costs for heating

4.3.1 | Cost of drilling

The well drilling costs account for most of the EGS project at the present drilling technology. The hardness of formation determined the cost of drilling. In general, the drilling cost of upper bedrock was lower than that of the basement granite.
Figure 14 shows the evolution of drilling costs with depth. The drilling cost increased linearly with depth before 4000 m and increased exponentially after 4000 m. The average costs of drilling for vertical well are $1100/m\textsuperscript{56} and $600/m\textsuperscript{57} in Gonghe Basin, western China. The granite directly determines drilling difficulty, and the granite burial in Gonghe Basin is shallower than that in the study area. According to the costs of production well and reinjection well were both 2.56 M CNY (1600 m) for Xiong County Mode.\textsuperscript{17} Thus, the drilling cost was set at 1000 CNY/m at depth 0-1000 m, and for every 1000-m increase in depth, drilling cost will increase by 1000 CNY/m. The drilling cost was fixed at 13 million CNY for each well, which was suitable for the numerical model in Section 3. The costs and revenues of economic analysis for heating are shown in Table 2.

4.3.2 Cost of reservoir fracturing

The hydraulic fracturing technology can improve reservoir permeability. The cost of hydraulic fracturing was related to in situ stress of reservoir and well spacing, and the cost of reservoir thermal stimulation was independent of depth.\textsuperscript{58} The single fracture of the model was used in this study, which was relatively simple to create and the cost will fall. Thus, the cost of 2.5 million CNY for reservoir fracturing was fixed in this study.

4.3.3 Cost of surface device

The surface devices mainly included pump set and pipe network. The function of pumps enabled circulating fluids to flow in reinjection well and production wells, which ensured smooth operation of the system by regulating flow. The detailed functions, materials, and types of pumps were introduced.\textsuperscript{59,60} The heat extracted was conveyed to the user through the pipeline network. The reinjection pump was placed on the ground, which was easy to maintain. The lifetime of reinjection pump was generally 10 years.\textsuperscript{47} However, the production pump was usually placed hundreds of meters in wells, which was more difficult to maintain than injection pump. Because of the extraction of unfiltered fluids, the lifetime of production pump was difficult to fix. Thus, the lifetime of the production pump was simplified to 10 years. And the investment of pump set and pipe network were estimated 0.8 million CNY in all lifetime.

4.3.4 Cost of operation and maintenance

The cost of operation mainly included water and electricity, and others (such as staff salary). The operation time of the EGS was set to 20 years based on computational model. The circulating fluid will lose a part and need to be replenished, which fluid loss rate was assumed to 8%.\textsuperscript{46} The cost of maintenance referred to pump, pipe network, and others. The depreciation rate of 5% was considered in operation and maintenance. Therefore, the cost of operation and maintenance was identified as 0.5 million CNY in the first year. The low inflation rate was ignored in 20 years.\textsuperscript{61}

| Category                          | Unit     | Value |
|-----------------------------------|----------|-------|
| EGS property                      |          | Section 3 |
| Lifetime of EGS                   | y        | 20    |
| Number of well                    |          | 3     |
| Number of pump                    |          | 3     |
| Fluid loss rate                   |          | 8%    |
| Depreciation rate                 |          | 3%    |
| Cost                              |          |       |
| Well                              | Million CNY | 13   |
| Pump                              | Million CNY | 0.8  |
| Lifetime of pump                  | Y        | 10    |
| Reservoir fracturing              | Million CNY | 2.5  |
| Operation and maintenance         | Million CNY | 0.5  |
| (first year)                      |          |       |
| microseism for creation           | Million CNY | 0.5  |
| microseism for operation          | Million CNY | 0.3  |
| Revenue                           |          |       |
| HLI for heating                   | W/m\textsuperscript{2} | 50    |
| HLI for others                    | W/m\textsuperscript{2} | 25    |
| Heating price for heating         | CNY/m\textsuperscript{2} | 28.5  |
| Heating price for others          | CNY/m\textsuperscript{2} | 20    |
| CO\textsubscript{2} price         | CNY/t    | 55    |
4.3.5 Cost of microseism for social perspective

Microseism may be induced by artificial factors such as fluid injection-production and hydraulic fracturing in EGS project. The occurrence of microseism will damage the lives safety and property of people, and even cause human panic, which should be paid attention to from social perspective. The first EGS project was forced to shut down due to a microseismicity in South Korea. The induced microseism hazard was usually defined by stratigraphic structure, exposure, and vulnerability of buildings to evaluate risks. The annual occurrence probability of induced seismicity (IS) was derived in operation and creation based on hazard intensity. There were many large faults in the study area, and the natural earthquakes will occur in a certain probability (Figure 1). However, the target EGS was located in the oil field and the probability of microseism caused by fracturing was small for many years. Therefore, the occurrence probability of microseism was set at 0.1 in operation and creation for EGS, and the cost of microseism was fixed at 0.5 million CNY for reservoir and 0.3 million CNY per year for EGS operation.

4.4 Revenue for heating

4.4.1 Direct revenue for private perspective

The direct revenue referred to collect costs of the heating for consumer in the heating period and other aspects (agriculture, fisheries, and aquaculture) in the nonheating period. The relationship between heating area and heating load can be expressed by Equation (17), and the annual heating load in 20 years can be determined by production heating power, as shown in Figure 6. The residential building was considered to heat in this study, and the integrated heating load index (HLI) was 50 W/m² based on the criterion of Ministry of Housing and Urban-Rural Construction, China, for research area. The indoor temperature should not be lower than 18°C. Besides, the heating price was 28.5 CNY per square meter for residents. However, the integrated HLI was small in the nonheating period and the value was fixed at 25 W/m². The heating price was 20 CNY per square meter for other aspects.

\[
Q_h = \sum_{i=1}^{n} A_i \cdot q_{hi}
\]  

where \(i\) is the building type (residential, industrial plant); \(A_i\) is the heating area of buildings; \(Q_h\) is the total heating load; and \(q_{hi}\) is the integrated HLI.

4.4.2 Indirect revenue for social perspective

Geothermal energy can effectively reduce carbon dioxide emissions compared with coal. The indirect revenue was considered by \(CO_2\) saving from social perspective. The coal heating was mainly used in northeast China at present. The indirect revenue in EGS project was calculated compared with standard coal heating. 1 t standard coal produced about 2.7 t \(CO_2\) based on heat calculation, and the carbon dioxide price was set at 55 CNY/t based on China Carbon Emission Trading Network (www.tanpaifang.com).

4.5 Result and discussion for heating

4.5.1 Heating for private perspective

Figure 15A shows the proportion of main component of the EGS costs for private perspective. The drilling and operation costs exceed 90% of the total investment, of which 71.43% was drilling cost. Therefore, reducing the drilling cost can effectively reduce the development and utilization cost of EGS project, especially in granite. New methods and processes had been proposed to improve the drilling efficiency in rocks of high temperature and pressure. The evolution of heating costs and revenues with time for private perspective is shown in Figure 16. The production temperature will decrease with EGS operation, which annual revenue for heating will cut down correspondingly. The accumulated revenue of heating was 32.64 million CNY, which was unable to cover drilling costs in 20 years. Therefore, heating was uneconomical by EGS project compared with power generation in short time. However, the life of EGS was generally over 30 years. The revenue will be higher than cost in follow-up time under the normal operation of reservoirs. In addition, cost reduction was an important way to achieve economic efficiency. In fact, the fractures formed by hydraulic fracturing were intricate. The results were obtained based on idealized single-fracture model, which had worse heating power than the fracture network model in a certain extent.

4.5.2 Heating for social perspective

Microseism and carbon dioxide savings were considered from social perspective. The drilling accounts for most of the EGS costs. The cost of microseism proportion was 6.02%, as shown in Figure 15B. Thus, the drilling was a bottleneck for EGS project in economic efficiency at present. Figure 17 shows the evolution of microseism cost and carbon dioxide savings revenue with time for social perspective. The annual \(CO_2\) savings were decreased with EGS operation due to the
reduction in heating power (Figure 6). The accumulated revenue of CO₂ savings was slightly less than the cost of microseism. However, the occurrence of microseism was a certain probability in the EGS operation. Controlling the injection rate can effectively reduce the occurrence of microseism in the process. In addition, application of geothermal heating can reduce carbon dioxide emissions compared with coal and natural gas, which was good for environment and humanity health. Coal was still the main heating source at present. Thus, the economy was considerable from social perspective.

5 | CONCLUSIONS

The simplified single-fracture coupled hydrothermal model with laboratory test was investigated, and the effects of four factors on heat production are discussed. Also, the heating economy considering costs and revenue was analyzed from private and social perspectives. Some of the detailed conclusions are as follows:

1. The density, porosity, thermal conductivity, specific heat capacity, and permeability of rocks were obtained to be 2.672 g/cm³, 2.741 W/m·K, 0.719 kJ/(kg·K), 2.02%, and 0.2840 mD by laboratory test, respectively, which the parameters were established in coupled hydrothermal model. The production temperature and heat power were decreased with operation of 20 years due to reservoir temperature dropped. The increase in $\mu/\rho$ for injection fluid will enhance injection pressure and flow impedance in EGS reservoir.

2. The factors of fracture permeability, well spacing, injection temperature, and injection rate on production and reservoir on EGS project were discussed, which had important influences on heat production and reservoir temperature. And higher permeability, smaller well spacing, lower injection temperature, and higher injection rate will be prone occur thermal breakthrough and shorten the life of the EGS. The injection pressure had exceeded the minimum principal stress in injection rate $q = 16$ kg/s, so injection rate should be controlled to avoid reservoir secondary fracturing and microseism.
3. Compared with private perspective, the microseism and carbon dioxide savings were considered for social perspective in economic analysis of heating. Heating with EGS was uneconomical based on the single-fracture hydrothermal coupling model and research area due to expensive drilling costs. Reducing the drilling costs can effectively reduce the total heating costs in EGS project, especially in hard rock. However, the heating with EGS can be considered from social perspective based on environment and humanity health.

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