Production capacity and mining plan optimization of fault/fracture-controlled EGS model in Gonghe Basin

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Abstract
Taking full advantage of geological conditions is beneficial to reduce the development cost and enhance the exploit of geothermal energy in the Gonghe Basin. In this paper, a thermal-hydraulic coupled model is put forward to study the heat extraction for Gonghe Basin based on local thermal nonequilibrium theory considering the natural fault. An excellent heat recovery system and reasonable combination of parameters are the premise of sustainable geothermal development. Two doublet systems are introduced to investigate the efficiency of the fault/fracture-controlled EGS model. A comparative analysis is performed from the aspect of production temperature, heat extraction ratio, flow impedance, injection pressure, thermal power, and electric power. Key parameters (injection rate, injection temperature, production pressure, number of fractures, vertical interval between the two storages, and the storage permeability) are discussed. The results show that the fault-fracture-controlled doublet model is more suitable for EGS to heat transfer than the common doublet model. The doublet model at a depth of 3300-3800 m has a temperature gradient of 0.04°C/m. For fault-fracture-controlled EGS model, the optimal values are 50 kg/s, 15 MPa, 60°C, 310 m, 4 × 10⁻¹⁴ m², and two for injection rate, production pressure and injection temperature, vertical interval, storage permeability, and fracture number, respectively. The best well pattern layout method for the Gonghe Basin is one injection well and two production wells. The production temperature varies from 196.8°C to 192.7°C when the heat extraction ratio is 0.13 at the end of the operation. Thus, the fault-fracture-controlled EGS model can provide a mining method and advance the development of geothermal energy for the Gonghe Basin in the future.

KEYWORDS
enhanced geothermal system, fault/fracture-controlled model, local thermal nonequilibrium, parameter optimization
1 | INTRODUCTION

1.1 | Background

Efficient power utilization and environmental protection have become a crucial global issue. Geothermal energy is one of the cleanest and most effective energy forms. It could promote the country’s energy structure transformation. To reduce and eliminate the influence of fossil energy, geothermal power has been considered an aspirational and environmentally safe energy in many countries. According to the literatures, geothermal energy is roughly divided into two categories depending on temperature: high-temperature geothermal heat resources (>150°C) and low-medium temperature geothermal heat resources (<150°C). As for low-medium temperature geothermal heat resources, the combined heat and power (CHP), combined cooling and power (CCP), and combined solar collector and geothermal heat pump systems are the main patterns of geothermal utilization. However, high-temperature geothermal heat resources are exploited by means of enhanced geothermal systems (EGS). Through the artificial formation of a geothermal reservoir, deep thermal energy is produced economically from low permeability rock mass (hot dry rock, HDR). The Fenton Hill site was the first tested HDR project in 1974, and the great potential and feasibility of the EGS concept have been heralded to exploit thermal energy after 40 years of engineering testing. Then, the Desert peak and Geyers projects (USA), Rosemanows project (UK), Soultz project (France), Ogachi and Hijiori projects (Japan), Gross Schoenebeck project (Germany), and Cooper Basin project (Australia) were built. It is noteworthy that China occupies 7.9% of the world’s geothermal energy reserves, at 3.06 × 10^18 kWh/y, and the HDR resource could reach 2.09 × 10^7 EJ within subsurface 3-10 km subsurface. China has a solid foundation for the reasonable development and utilization of geothermal energy, and geothermal energy will contribute to approximately 3% to the total energy consumed by 2030. Consequently, the utilization and development of geothermal energy are beneficial given the advance of reservoir stimulation techniques, including hydraulic sand fracturing, new drilling technology, and heat-resistant materials.

Sufficient reservoir volume and heat transfer area are necessary for a promising EGS site. Although the fractured reservoir of oil/gas production and geothermal exploitation has been investigated for many years, there are still complex problems that cannot be realized before the plan is implemented. Thus, the numerical simulation is an available method to predict conceptual subsurface designs. Huang et al developed a thermo-hydro-mechanical (THM) model for the Songliao Basin based on the TOUGH2 code. They investigated the effects of reservoir properties, dimensions, and production schemes during the simulation and production processes. The results demonstrated that reservoir properties and wellbore arrangement can increase the production. Ding et al presented a 2D model with a four-to-four flow network pattern to offer equal flow rates for each well. They found that the 2D model is more powerful to solve EGS problems than 3D numerical modeling, and an analytical solution for 2D porous flow was derived. Xu et al performed a numerical model with two horizontal wells for the Gonghe Basin using the local thermal nonequilibrium theory (LTNE) and evaluated the production temperature, energy efficiency, and economic and environmental benefits. The results indicated that the electric power mainly depends on fracture spacing and injection temperature, and the saving in greenhouse gas (GHG) emissions ranged between 0.27 and 0.92 Mt over an operation period of 30 years. Zeng et al proposed a conceptual model with a fractured granite reservoir in Yangbajing geothermal field and analyzed the main factors that affect EGS performance. They found that the reservoir permeability is a significant factor that affects energy efficiency, reservoir impedance, and electric power. Zhang et al established a 3D thermo-hydraulic model coupled with a numerical model to understand the performance processes for the Qiabuqia geothermal area based on the geological data of the GR1 borehole. The different sensitive parameters that affect electric power output and the optimal combination parameters are given. The injection flow rate is 70 kg/s, injection temperature is 60°C, and lateral well spacing is 500 m. Li et al performed a simplified representation of a reservoir with the horizontal wells and multiple fracturing stages and calculated the optimal flow rate, well spacing, and low number of stages. They found that stimulation with multiple stages significantly advances economic performance, and delays thermal breakthrough. In addition, Slatlem Vik investigated the thermoelastic effect on a multiple fracture EGS using a thermo-hydromechanical coupling by finite element method. They found that the deformation greatly increases the interactions between the adjacent fractures. Chen et al developed a CO2-EGS model to investigate the dynamic performance based on the unified pipe network method considering the complex fracture networks. Park et al employed a hydraulic stimulation simulator toolbox to comprehensively understand the performance of the EGS reservoir, analyzed the stress concentrations around borehole and predicted the temperature distributions within the parallel fracture system. Rührak et al developed a fully coupled THMC model to investigate the behavior of the fracture in a carbon dioxide-enhanced geothermal system. The results showed that the flow rate increases with the delay of simulation time due to matrix dissolution, which again exhibits exponential grow. On the whole, increasing attention has been significantly paid to geothermal development, and many scholars are studying the exploitation of a geothermal field from different aspects. The EGS test is extremely difficult and expensive before
the construction of a power plant. For example, Aliyu and Yao performed an extensive study on the Soultz geothermal system and Desert Peak geothermal reservoir, respectively.

1.2 | Overview of the study area

The study area is located on the northeastern edge of the Tibetan Plateau and lies in the subsidence area between the Qilian Mountains and Kunlun Mountains. The basin area and its periphery dry hot rock area encompass 3092.89 square kilometers. The detailed geographical coordinates can be found in. Complex tectonic structures and evolutionary history create excellent conditions for the Gonghe Basin, which is one of the favorable areas to develop geothermal energy. Data indicate that this area has abundant HDR resources of $4.3 \times 10^6$ EJ, which account for more than 20% of the total HDR resources of China.

Due to the characteristic and complexity of geological structure in Gonghe-Guide Basin, the study area is surrounded by several strike-slip faults. For example, the Qinghai South Mountain fault to the north, Heka South Mountain fault to the south, Ela Mountain fault to the west, and Zhama Mountain fault to the east. The faults have stronger permeability and aperture than common fractures. Accordingly, the natural faults provide a favorable prerequisite of water channel for heat recovery process. Then, the hydraulic fracturing technology is applied for reservoir stimulation in the target region and realizing the natural faults and fractures connected. This method reduces the mining cost to a certain extent. In fact, the interaction mechanism between faults and fractures is complex and changeable. Vahab et al. studied the interaction between hydraulically driven fracture and natural faults based on the staggered Newton algorithm through X-FEM technique. Zhang et al. proposed a virtual multidimensional internal bond model to investigate the propagation behavior of hydraulic fracture combined with the natural faults. In order to simplify the geothermal model, the natural fault as a plane is embedded in the model and without regard for the mechanical behavior of hydraulic fracture and natural fault.

The average temperature gradient in the basement granite is estimated at 6.7-6.8°C/100 m. According to the newest statistics, the highest temperature in this geothermal field has been estimated as 236°C at the depth of 3705 m, and the greatest temperature gradient is 8.8°C/100 m at depth of 3366 m. Given the characteristics of heat flow anomalies, a shallow buried bed with large thickness and easy mining access, four deep HDR geothermal boreholes (DR3, DR4, GR1 and GR2) were drilled in the geothermal field for geophysical detection and research. In addition, the Gonghe Basin is located in the notch of the joint between Qinling and Kunlun, and the fault zone igneous rock belt around the Gonghe Basin is well developed. This exceptional geological structure provides favorable conditions for heat conduction and convection in the deep granite layer. Reference describes the structure of geothermal field. The unique natural advantage is the most valuable premise to research and develop enhanced geothermal systems. Hence, an evaluation of the EGS model is studied in this paper based on the background of the Gonghe Basin.

In this paper, an innovative heat extraction system with a fault and artificial fracture is used to exploit geothermal energy. Few scholars studied EGS considering fault and fracture. In addition, it is necessary and significant to consider the active fault in the EGS model of the Gonghe Basin that is dependent on the special geological structures. Consequently, several numerical thermo-hydro models are established to investigate the production of a fault/fracture-controlled model over a 50-year period with time step of 0.5 years based on local thermal nonequilibrium theory by the commercial finite element software COMSOL Multiphysics. The fault/fracture-controlled doublet model is evaluated based on the criteria of production temperature, heat extraction ratio, injection pressure, flow impedance, production mass rate, water loss rate, thermal power, and electric power. To perform a deep analysis and achieve the best production of the fault/fracture-controlled model, another faulted model is proposed. Finally, the injection-production parameters, reconstruction plan for reservoir, and well layout are given systematically.

2 | DESCRIPTION OF THE NUMERICAL MODEL

2.1 | Physical model

The characteristics of the fully developed fault in the Gonghe Basin provide a natural competitive advantage to construct an efficient EGS site. The application of the faults not only saves production costs for engineering but also improves the efficiency of geothermal development. Consequently, a doublet EGS model is presented in this paper based on the above geological survey and numerical model (as shown in Figure 1).
In EGS reservoir, the fracture networks are critical to the whole heat extraction cycle. In this system, the fault is more permeable than the fracture, and there is no doubt that the fault-fracture system can enhance the connectivity between the injection well and production well. The lower temperature fluid is injected from the horizontal well, and then heat is transferred with the rock matrix along the fault and fracture. Finally, thermal energy is exploited from high-temperature fluid by the vertical well.

In reality, the process of heat transfer in a fault or fracture is complex. The simplified model is presented in the Figure 2. The numerical model includes a horizontal injection well, a vertical production well, a natural fault, and an artificial fracture. The geothermal reservoir is a 500 x 500 x 500 m cube located at a depth of 3300-3800 m. To avoid the boundary effect, the injection well is 25 m away from the left of the reservoir at a depth of 3700 m with a length of 100 m, while the vertical production well is 50 m away from the top of geothermal reservoir with a length of 100 m. In particular, the fault is inclined to angles of 55° with 450 x 400 m intersection with fracture at a depth of 3400 m. The significant hydrogeology parameters are presented in Table 1.

| Parameter                        | Symbol | Value  |
|----------------------------------|--------|--------|
| Rock matrix                      |        |        |
| Porosity (%)                     | \( \phi_m \) | 10     |
| Permeability (m\(^2\))          | \( \kappa_m \) | \( 5 \times 10^{-15} \) |
| Thermal conductivity (W/m/K)     | \( \lambda_m \) | 3      |
| Heat capacity (J/kg/K)           | \( C_{p,m} \) | 1000   |
| Density (kg/m\(^3\))            | \( \rho_m \) | 2900   |
| Fracture system                  |        |        |
| Porosity (%)                     | \( \phi_f \) | 30     |
| Permeability (m\(^2\))          | \( \kappa_f \) | \( 1 \times 10^{-12} \) |
| Thermal conductivity (W/m/K)     | \( \lambda_f \) | 2.8    |
| Heat capacity (J/kg/K)           | \( C_{p,f} \) | 900    |
| Density (kg/m\(^3\))            | \( \rho_f \) | 2500   |
| Aperture (mm)                    | \( d_f \) | 2      |
| Fault zone                       |        |        |
| Porosity (%)                     | \( \phi_F \) | 100    |
| Permeability (m\(^2\))          | \( \kappa_F \) | \( 1 \times 10^{-10} \) |
| Thermal conductivity (W/m/K)     | \( \lambda_F \) | 2.5    |
| Heat capacity (J/kg/K)           | \( C_{p,F} \) | 750    |
| Density (kg/m\(^3\))            | \( \rho_F \) | 1200   |
| Aperture (mm)                    | \( d_F \) | 5      |

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### 2.2 Mathematical model

The fractured-faulted reservoir model for the Gonghe Basin is mainly used to simulate the thermo-hydraulic process and convective transport through the fracture and fault with a porous medium. The transient three-dimensional numerical model considers local thermal nonequilibrium between the rock matrix and water flowing in the fracture and fault. The following assumptions are adopted in the present study:

1. The water flows comply with the Darcy’s Law and keep a steady state in the fractures and rock matrix.
2. The water remains liquid and does not vaporize under the conditions of 40-80MPa pressure and 323-513 K temperature.
3. The model neglects the variation of fracture aperture and chemical effect.

4. The continuous porous media properties of rock matrix are isotropic. Porosity, specific heat, density, and thermal conductivity of the porous medium are assumed to be constant.

5. The water properties can be described by the equations related to temperature, as shown in the published paper.42

According to above assumptions, the governing equations of thermo-hydraulic coupling in the fault-fracture-controlled reservoir can be described as follows:

The continuity equation for the fluid flow in porous matrix can be described as follows:

$$
\frac{\partial (\rho_w, \varphi_m)}{\partial t} + \nabla \cdot \left\{ \rho_w \left( -\frac{\kappa_m}{\mu_w} \nabla P_m + \rho_w g \nabla z \right) \right\} = -Q_f \quad (1)
$$

Letters \( w \) and \( m \) stand for the water and rock matrix, respectively. \( \rho_w \) is the water density, \( \varphi_m \) is the porosity of rock matrix. \( Q_f \) represents the transferred mass between the rock matrix and fracture, fault. \( t \) is operation time. In addition, \( \nabla \) is the divergence operator, \( \kappa_m \) is the rock matrix permeability, \( \mu_w \) is water dynamic viscosity, and \( \nabla z \) is the vertical depth, \( \rho_w \) is the water density.

The continuity equation for the fluid flow in fracture and fault can be described as:

$$
d_{F_f} \frac{\partial \rho_w \varphi_{F_f}}{\partial t} + \nabla_T \cdot \left\{ d_{F_f} \rho_w \left[ -\frac{\kappa_{F_f}}{\mu_w} (\nabla_T P_{F_f} + \rho_w g \nabla_T z) \right] \right\} = Q_f \quad (2)
$$

Here, \( F \) and \( f \) represent the fault and fracture, respectively. \( d_{F_f} \) represents the aperture, and \( \varphi_{F_f} \) is the porosity. \( P_{F_f} \) is the water pressure within fracture and fault, and \( \kappa_{F_f} \) represents the permeability of fracture and fault, and \( \nabla_T \) is gradient operator of fracture’s tangential plane.

In the present paper, the local thermal nonequilibrium equation is engaged in the heat transport between the fluid and rock matrix. Consequently, the energy conservation equation for heat transfer in the rock matrix is expressed as follows:

$$
\left[ (1 - \varphi_m) \left( \rho C_p \right)_m \right] \frac{dT_m}{dt} = \nabla \left( \lambda_{eff,m} \nabla T \right) - h_{gf} \alpha \left( T_m - T_w \right) \quad (3)
$$

The energy conservation equation for heat transfer in water is given as follows:

$$
\left[ \varphi_m \left( \rho C_p \right)_w \right] \frac{dT_w}{dt} + \nabla \left( \lambda_{eff,w} \nabla T \right) + h_{gf} a \left( T_m - T_w \right) = 0 \quad (4)
$$

Here, the \( \lambda_{eff,m} \) and \( \lambda_{eff,w} \) are the effective thermal conductivity for the rock matrix and water of the porous medium, respectively. \( u \) is the vector of Darcy velocity. \( h_{gf} \) is the heat transfer coefficient between the solid and fluid phase, \( \alpha_{sf} \) is the specific surface area, and \( h_{gf,a} = 50 \text{W/(m}^2\text{K}) \). According to the literature,39,43 the Bruggeman correction factor is 1.5, \( \lambda_{eff,m} = \lambda_m (1 - \varphi)^{1.5} \) and \( \lambda_{eff,w} = \lambda_w \varphi^{1.5} \).

The energy conservation equation for heat transfer in the fracture and fault is provided as follows:

$$
d_{F_f} \left( \rho C_p \right)_w \frac{dT_w}{dt} + d_{F_f} \left( \rho C_p \right) u_{F_f} \cdot \nabla_T T = \nabla_T \left( d_{F_f} \lambda_{F_f} \nabla T \right) + h \left( T_{F_f} - T_w \right) \quad (5)
$$

where, the \( h \) is the convection efficiency, and the value is 3000 W/m\(^2\)/K.44

2.3 Validation of numerical method

In this work, the numerical simulation is carried out based on the local thermal nonequilibrium theory. The same method has been proved in our previous paper.35 The thermo-hydro effect was presented by 2D model, and the numerical results were compared with the analytical solution. Besides, the validation method was utilized to test and analyze the Soutlz geothermal system by Aliyu et al.43 The simulator is used to investigate the geothermal field simulation.

2.4 Initial and boundary conditions

The numerical model is modified from the traditional doublet EGS model with the radius of injection and production well \( r = 0.2 \text{ m} \). For the complete system, the entire heat extraction period in EGS is 50 years, the initial temperature is defined as \( T(z) = T_{top} - (z + 3300 \text{ m}) \times 0.04^\circ \text{C/m} \), where the \( T_{top} \) is the top surface temperature of the established reservoir at 195 °C, the initial reservoir pressure is \( P = -0.0089 \text{MPa/m} \times z - 0.0 \) 444 MPa,19 and \( z \) is the depth of the reservoir. During the heat extraction process, the injection rate of the simulated domain is 50kg/s and the temperature at the injection well is 60°C to avoid scaling and chemical deposition.46 In addition, the production well is fixed with 15 MPa, and the no-flow boundary
and thermal insulation boundary are applied on the surface of the reservoir domain.

2.5 | Discussion for mesh independence and time discretization

The implicit time step algorithm, backward differentiation formulas (BDF), is used in this paper. In this way, it can remain stable unconditionally and reduce the computational cost of the solution.\(^{47,48}\) A higher precision mesh test and an appropriate time step are significant for a better forecast effect. To select the best mesh scale, five distinct mesh models are proposed, as shown in Table 2. In the numerical model, four types of mesh elements are utilized to describe the geometry of different dimensions: Tetrahedral elements are used for the rock matrix; the triangular elements for fracture, fault, and wells; the line elements for the all edges; and vertex elements for all points. Figure 3A presents the mesh scheme of the internal structure, and Figure 3B shows the local detailed mesh-refining scheme of the interaction between wells and fault. Figure 4 shows the production temperature of five mesh models during the 50-year period. From the results, no apparent significant difference noted among the five meshes, regarding the curves of production temperature convergence in the M4 model as a result of the mesh refinement. Figure 5 shows the production temperatures of M4 with the different time step. From the data, the differences are very slight. To save the computation time, the local refined model with the time step of 0.5a is selected as the computational case for study in this paper.

3 | COMPARATIVE ANALYSIS OF DOUBLET SYSTEM

After the target area of geothermal resources is determined, the application of a different structure of heat recovery has different results for the established heat storage. To demonstrate the advantages of the main model, a reference model is adapted from the literature\(^{29}\) and used for comparison, as shown in Figure 6. The reference model contains a horizontal injection well, a vertical production well, and a fracture with an inclination of 45°. Based on the above working conditions and model parameters, the results of the main model and reference model are compared in this paper.

In this work, four important criteria are used to assess the competitiveness of the main model and reference model: production temperature, heat extraction ratio, reservoir impedance, and injection pressure.

The heat extraction ratio (\(\alpha\)) is defined as follows:

\[
\alpha = \frac{\iint_{V_m} \rho_m C_p_m (T_0 - T(t))dv}{\iint_{V_m} \rho_m C_p_m (T_0 - T_{inj})dv}
\]  

(6)

where, the \(T(t)\) is the temperature of rock reservoir at time \(t\), \(T_0\) is the initial temperature of rock reservoir, and \(T_{inj}\) is the injection temperature.

The flow impedance of the reservoir is calculated by Equation (7):

\[
I_R = \frac{(P_{inj} - P_{pro})}{q}
\]  

(7)
where, the $P_{\text{inj}}$ and $P_{\text{pro}}$ are the injection pressure and production pressure, respectively. The parameter of $q$ is the total mass flow rate in the heat extraction process.

In addition, the heat production power and electric power are calculated by Equations (8) and (9), respectively.

Heat production power.

$$W_h = qc_{p,w}(T_{\text{pro}} - T_{\text{inj}})$$  \hspace{1cm} (8)

Electric power.

$$W_e = 0.45q(h_{\text{pro}} - h_{\text{inj}}) \left(1 - \frac{T_o}{T_{\text{pro}}}\right)$$  \hspace{1cm} (9)

where, the $T_{\text{pro}}$ and $T_{\text{inj}}$ represent the production temperature and injection temperature, respectively. $T_o$ is the heat rejection temperature at 288.15K.\(^49\)

### 3.1 Spatial and temporal distribution of temperature

Figure 7 depicts the temperature distribution in the reservoir and the fracture or fault of the main model and the reference model at different times. In Figure 7B, the low-temperature front has a strong penetration in the reference model compared with the main model. At 2-10 years, the heat extraction around the injection well has a high mining index, and the change in the high-temperature environment around the production well is not obvious. Nevertheless, the interior of the reservoir is almost occupied by the low-temperature front in the final working stage, which indicates the termination of operational life. As noted in Figure 7A, the direction of water flow occurs from the injection well to the production well along the fault and fracture, and there are tiny amounts of water in the rock matrix. At the initial operating stage, the low-temperature area is distributed around the injection well. Then, the heat exchange occurs between the water flow and the fault. The fault can be recognized as a preferential channel for working flow to extract heat from the reservoir. As the working time increases, the cold area increases gradually. At 20 years, the low-temperature water expands the fracture area and causes thermal breakthrough in the reservoir. In the entire system, the low-temperature region is mainly distributed around the fault and fracture given the weak permeability of the established reservoir. The reason for the difference between the two models is that the fault system has a larger aperture than fractures, which enhances the storage capacity of the EGS to make it more efficient.

### 3.2 Analysis of production temperature and heat extraction ratio

Figure 8 shows the evolution of production temperature and heat extraction ratio as functions of time for the main model and reference model. Judging from the change in the production temperature curve, the reference model maintains slightly ascendant trends for the first 10 years

![FIGURE 5 Results of time discretization](image1)

![FIGURE 6 The reference model for comparison](image2)
from 199.0°C to the maximum production temperature of 201.3°C. Then, the temperature drops steadily because a finite amount of heat is absorbed by the low-temperature water during the heat extraction process. As time goes on, the low-temperature front breaks the thermal balance in the reservoir and the production temperature drops. The production temperature curve of the main model slightly dropped 8.6°C from 199.0°C to 190.4°C. The reason for this slight reduction is that the fault plays a role in the thermal insulation chamber embedded in the reservoir after the low-temperature water extracts the heat from the rock matrix. With regard to the heat extraction ratio, the exploit rate of the reference model at 50 years is 0.76, in a state of over-exploitation. However, the low heat extraction ratio of the main model indicates that thermal energy is stored in the reservoir and is available to be mined. Under the same working conditions, the main model is more suitable for long-term operation. Regarding this
3.3 | Analysis of mass flow rate and water loss rate

Figure 9 presents the change of mass flow rate and water loss rate of the main model and reference model during the 50-year period when the injection mass rate is 50 kg/s. On the whole, with the exception of the increase in the reference model, the production mass flow rate curves of the two models basically exhibit a constant state. From the image, it can be seen that the reference model (32.7 kg/s) possesses a higher production mass flow rate than that of the main model (29.0 kg/s). Consequently, the water loss rates of the main model and reference model are 21.0 kg/s and 17.3 kg/s, respectively. The difference of production mass flow rate between the two models is attributed to the connectivity of the fault. Given that the fault has a larger aperture, higher permeability and porosity, and provides excellent heat transfer channels, the leakage rate of water flow is also increased. It is noteworthy that the difference in the water loss rate between the main model and reference model is 3.7 kg/s. From the perspective of EGS engineering, the value is too small to be ignored. Evidently, there is no appreciable distinction of production mass flow rate between the two models under the same working condition.
3.4 Analysis of injection pressure and water flow impedance

Figure 10 depicts the evolution of the injection pressure and water flow impedance with extraction time. Based on the curves of injection pressure, a small growth is noted in the injection well of the main model from 45.76 MPa to 60.77 MPa. At the first 18 years, the curve exhibits a rapid growing state and increases to 58.01 MPa. During the later years, although the injection pressure exhibits minimal fluctuation, it is almost in equilibrium. Obviously, the curve presents a three-stage pattern of increasing injection pressure in the reference model. To be specific, it has a relatively rapid growth stage from 48.42 MPa to 78.70 MPa in the first decade. During the period of 10-30 years, the injection pressure gradually increases from 78.70 MPa to 82.43 MPa. At the end of twenty years, the injection pressure increases by 6.58 MPa. As a result, the injection pressure of the reference model is 46.5% higher than that of the main model. Similarly, the changing trend of water flow impedance is consistent with the trend of change in injection pressure for the main model and reference model. This finding is explained by the fact that the heat transfer between the water and reservoir causes the reservoir temperature to drop rapidly or slightly, and the water viscosity is indirectly increased. Finally, the change in water viscosity has a significant impact on the development of flows. In addition, the higher the injection pressure and higher water flow impedance, more power is consumed. From the results, although the main model has a great advantage over the reference model, the value of the injection pressure and water flow impedance remains very large. Consequently, the injection pressure and water flow impedance can be reduced by reducing the injection mass flow rate and increasing the injection temperature, or employing the low viscosity fluid flow as the working medium in EGS engineering.

3.5 Analysis of thermal power and electric power

Figure 11 reveals the output of thermal power and electric power of the main model and reference model after 50 years of water circulation. An apparent distinction exists in the curves of thermal power and electric power for different mining patterns of EGS. The main model has a strong stable production capacity for thermal power and electric power, and the reduction rates are 5.36% and 5.50%, respectively. By contrast, in the process of heat extraction from the reference model, thermal power and electric power fluctuate remarkably. At the first 10 years, the output power increases. Then, the output data show a downward trend from 19.82 MW to 10.46 MW, for thermal power and from 8.52 MW to 4.40 MW for electric power. In conclusion, the reference model has almost halved the production power in 50 years. The main model with the fault is more applicable to heat extraction than the reference model in conjunction with Figure 8.

4 MODEL PRESENTATION AND OPTIMIZATION ANALYSIS

Based on the above comparative analysis of the doublet model, the main model's advantage is reflected. To better understand the model with fault and fracture, and using the main model as the study-processing model, a new strategy of the fractured-faulted EGS model is presented in Figure 12. This 3D numerical EGS model (600 × 600 × 600 m) at
a depth of 3200 m to 3800 m contains two storage scenarios that present the regional spatial structure after hydraulic fracturing. In particular, the equatorial radius and polar radius of the ellipsoid are as follows: \(a = 120\) m, \(b = 160\) m, and \(c = 80\) m. These radii are located at the coordinates of (150 m, 300 m, −3320 m) and (450 m, 300 m, −3680 m) for storage 2 and storage 1, respectively. Similarly, the injection well and production well are located at the center of the ellipsoid, and the length is 100 m. In addition, the spacing of the fractures is 80 m with an inclination of 5°. The fault area is 500 × 600 m, and the inclination is 68°. In this paper, different parameters (injection rate, injection temperature, production pressure, number of fractures, vertical interval between the two storages, and the permeability of storage) are studied using the multiparameter analysis method. The manual control parameters are optimized and evaluated. Meanwhile, four models are proposed to simulate the production of a well layout schematic. Some material parameters in the simulation differ as presented in Table 1, and the changed parameters are listed in Table 3. Because the Storage 1 and Storage 2 are introduced in the new strategy of the fractured-faulted EGS model, the relative parameters are changed after the hydraulic fracturing. The research ideas can be described as follows: First of all, the influence of basic parameters is analyzed, and then the results as the initial conditions of the next step are used to investigate the influence of the reservoir structure. Finally, the patterns of the well layout are studied based on the above studies.

4.1 | Effect of the basic parameters

Figure 13 shows production temperature variations in terms of injection rate, production pressure, and injection temperature based on Table 4. The production temperature curves from the injection rate range between 30 kg/s and 50 kg/s when the production pressure is 15 MPa and 25 MPa and the injection temperature is 30°C and 60°C, respectively. Figure 13A shows the model results with different injection rates under a production pressure of 15 MPa and an injection temperature of 30°C. It can be seen that the higher the mass flow rate, the faster the temperature curve drops. For the injection rate of 30 kg/s, the production temperature obtains a higher level of performance and descends later than that of the larger rate. In the first 15 years, the temperature increases from 195.8°C to 196.7°C. And after 50 years, the temperature dropped to 190.6°C. However, when the injection flow rate is 60 kg/s, the temperature has an apparent change and the thermal breakthrough occurs earlier. The maximum temperature of 196.6°C appears at 5.5 years. Afterward, the production temperature gradually drops to 180.8°C. This finding is explained by the fact that the larger injection rate causes a fast migration velocity of the water flow, and the heat transfers between the water and fault and fractures are not substantial.
Therefore, the reservoir temperature is reduced. Figure 13B shows the evolution of production temperature when the injection temperature increases by 30°C. A similar change trend exists with the exception that each working condition increases 1°C or 2°C at the end of operation.

Figure 13C shows the model results with different injection rates under a production pressure of 25 MPa and an injection temperature of 30°C. In general, there is a minimal difference between Case a and Case c when the injection rates are 30 kg/s, 40 kg/s and 50 kg/s. In particular, when the injection rate is 60 kg/s, the production temperature decreases from 196.5°C to 178.5°C during 4.5-50 years of operation. Thus, when the production pressure is increased by 15 MPa, the temperature is reduced by 12.1°C. This finding is attributed to the fact that higher production pressure discourages the migration of fracture and fault flows, which result in the water flow extraction of heat from the reservoir at the beginning of operation. As a result, the extent of the reduction of the reservoir temperature is reduced.

**TABLE 4** Human control parameters

| | Production pressure (MPa) | Injection temperature (°C) | Vertical interval (m) | Permeability of storage | Number | Injection rate (kg/s) |
|---|---|---|---|---|---|---|
| a | 15 | 30 | 360 | $1 \times 10^{-14}$ | 2 | 30 |
| b | 15 | 60 | 360 | $1 \times 10^{-14}$ | 2 | 40 |
| c | 25 | 30 | | | | 50 |
| d | 25 | 60 | | | | 60 |
temperature for Case c is greater than Case a, and the production temperature decreases. Moreover, the results obtained when the injection temperature increased to 60°C are presented in Figure 13D. Production temperature increases as the injection temperature increases, and the injection temperature has an obvious impact on the higher injection rate. Overall, the production pressure plays a significant role in extracting heat from the reservoir when the injection rate is high. The injection temperature has a slight influence on the production temperature. To achieve the high efficiency, an injection temperature of 60°C for production pressure and an injection rate of 15 MPa and 50 kg/s are the best sintering parameters.

4.2 | Effect of thermal reservoir structure

The numerical analysis depends on the statistics of Table 5. In particular, the vertical interval represents the spacing of the two storage scenarios. A vertical interval of 260 m reveals that the coordination of Storage 2 is (200 m, 300 m, −3370 m) and Storage 1 is (400 m, 300 m, −3630 m), and an interval of 310 m reveals that the coordinates of Storage 2 are (175 m, 300 m, −3345 m) and Storage 1 are (425 m, 300 m, −3655 m). Figure 14 shows the reservoir temperature contours of Y = 300 m at a time of 50 years for different conceptual models. An apparent distinction exists in the different number of fractures and the difference is small at different vertical intervals. On the whole, the more fractures, the lower the reservoir temperature. In particular, the low-temperature region in Storage 1 is the largest and extends to Storage 2 along the fault. In addition, when the permeability of storage is $4 \times 10^{-14}$ m², the low-temperature region is less than that of $3 \times 10^{-14}$ m². The results can be explained by the fact that the higher permeability provides beneficial running for water flows in the storage and the migration velocity is reduced, which leads to a weakened heat convection effect between the water and rock matrix and a heat conduction effect in the highest flight. Consequently, the heat transfer is improved significantly with increase of permeability of storage in certain range.

Figure 15 shows the production temperature variations in terms of storage position, permeability of storage, and the fractures number. Figure 15A shows the results of the model with different fracture number under the vertical interval of 260 m and storage permeability of $3 \times 10^{-14}$ m². A small downward trend in the production temperature curve of $N = 1$ is noted after 20 years, decreasing by 6.3°C from 197.7°C to 191.4°C. For $N = 3$, the production temperature descends quickly from 194.9°C to 158.8°C during the period of 10-50 years. Overall, $N = 2$ and $N = 3$ have a similar variation tendency and thermal

| Production pressure (MPa) | Injection temperature (°C) | Vertical interval (m) | Permeability of storage | Number of fractures | Injection rate (kg/s) |
|--------------------------|---------------------------|-----------------------|------------------------|--------------------|----------------------|
| a                        | 15                        | 60                    | 260                    | $3 \times 10^{-14}$ | 1                    | 50                   |
| b                        | 60                        | 4                     | 4 × $10^{-14}$         | 2                  |                      |
| c                        | 310                       | $3 \times 10^{-14}$   | 3                     | 3                  |                      |
| d                        | 310                       | 4 × $10^{-14}$        |                        |                    |                      |

FIGURE 14 | The temperature field contours of reservoir at $Y = 300$m
breakthrough time of 10 years. However, the production temperature of N = 2 obtains a higher level of performance compared with N = 3 at the end of operation. This finding is attributed to the reduced number of fractures, and subsequently reduced mass flow rate in the storage scenario. As a result, the water flow can sufficiently extract the heat from the reservoir and the thermal breakthrough is delayed. In contrast, when the number of fractures increases, the thermal breakthrough is obvious and large quantities of water penetrate into the storage and rock matrix, which causes a rapid reduction in the production temperature. Figure 15B shows the evolution of production temperature when the storage permeability increases to $4 \times 10^{-14}$ m$^2$. Of note, production temperatures of N = 1, N = 2, and N = 3 are promoted at the end of operation due to further opening of the heat transfer channel.

Figure 15C presents the model results with different fracture numbers when the vertical interval is 310 m and storage permeability is $3 \times 10^{-14}$ m$^2$. In general, a marked change is noted between Case a and Case c when the fracture number is 1, 2, and 3, respectively. In particular, when the fracture number is 1, the production temperature increases from 196.8°C to 198.1°C at the first 25 years. In addition, the production temperature of N = 2 and N = 3 increases as the vertical interval increases, and these values are increased by 20.5°C and 21.2°C, respectively. A large interval can provide convenience for heat transfer along the fault and fractures. The results obtained when the storage permeability is $4 \times 10^{-14}$ m$^2$ are presented in Figure 15D. The production temperature increases with the increasing of the vertical interval and storage permeability. The variations of production performance are relatively stable. These variations decrease gradually during the entire period of the EGS operation with the exception of N = 1. Overall, the storage permeability, vertical interval, and number of fractures have a significant effect on EGS performance. Based on the above analysis, the best thermal reservoir structure is Case d with N = 2.

4.3 | Effect of the well pattern layout method

Based on the analysis above, the injection temperature is 60°C, production pressure is 15 MPa, injection rate is
FIGURE 16  Well pattern layout methods based on faulted-fractured EGS model

FIGURE 17  The performance of four well pattern layout method for EGS model
50 kg/s, vertical interval is 310 m, storage permeability is $4 \times 10^{-14} \text{ m}^2$, and $N = 2$. Consequently, eight well pattern layout methods are proposed based on the key parameters as shown in Figure 16. The basic parameters are presented in Tables 1 and 3. The well spacing of the injection well or production well is 150 m.

Figure 17 shows the evolution of production temperature and heat extraction ratio of storage as a function of time for the different fault/fracture-controlled EGS models. The simulation results show that every curve has its own characteristic during the period of heat extraction. As seen, the case of one injection well and one production well has a worse performance than the case of one injection well and two production wells when their heat extraction ratios are generally identical. During the first 16.5 years, the production temperature of one injection well and one production well case increases from 196.8°C to 197.1°C and then gradually decreases to 190.7°C. For the case of one injection well and two production wells, the production temperature increases from 196.8°C to 197.0°C in the first 25.5 years, and the temperature is subsequently reduced to 192.7°C. This finding is attributed to the fact that adding one production well is equivalent to increasing the heat transfer region and heat transfer area, which is more favorable to efficiently produce power. Similarly, small differences in production temperature and heat extraction ratio are noted between two injection wells and one production well versus two injection wells and two production wells for production. Compared with the two other models, the thermal breakthrough time is diminished and the maximum production temperature increases to 197.6°C and 197.4°C for the case of two injection wells and one production well along with two injection wells and two production wells, respectively. In addition, the production temperatures of the two cases are 189.0°C and 188.4°C at the end of operation, respectively. The heat extraction ratio is approximately 0.16 because a larger number of injection wells have a higher injection mass flow rate. Low-temperature water reduces the temperature and life-span of the storage system and the reservoir.

As for the three and four production wells models, the production temperatures are quite different from one production and two productions model. From Figure 17C, the temperature curves of one injection three productions model and one injection four productions model are of high similarity except the final ten years, the terminal production temperature is 192.8°C and 193.1°C, respectively. So, the production temperature increased by 0.4°C when adding two production wells. Two injections model perform poorly under the same working condition. From the heat extraction ratio data, increasing the number of production wells has little effect on the heat mining performance. Overall, the case of one injection well and two production wells is more suitable to extract heat from the fault-fracture-controlled EGS model in the Gonghe Basin.

5  | CONCLUSIONS

In this paper, the fault/fracture-controlled model is proposed to simulate the heat extraction from EGS based on the geological data of Gonghe Basin by local thermal nonequilibrium method. Comparing the temperature contours of fault/fracture-controlled doublet EGS model with the common model shows that the interior low-temperature region of the reservoir is obviously reduced. The production temperature of the EGS model can remain high at 199.0°C to 190.4°C during the entire process of heat extraction. With regards to the heat extraction ratio, the reference model has a larger value of 0.76, which indicates that the life-span of the reference model is less than that of the main model. Under these conditions, the injection mass flow rate is 50 kg/s, and the production mass flow rate of the main model generally remains at 29.0 kg/s. In terms of injection pressure, the main model is 46.5%, which is less than the reference model when the maximum injection pressure is 89.01 MPa at the end of operation. The reduction rates of thermal power and electric power are very small for the main model at 5.36% and 5.50%, respectively. Therefore, the fault-fracture-controlled doublet model is more suitable for the Gonghe Basin.

Depending on the analysis of injection rate, production pressure, and injection temperature, the optimal values are 50 kg/s, 15 MPa, and 60°C, respectively. The vertical interval for wells, reservoir permeability, and the number of fractures are 310 m, $4 \times 10^{-14} \text{ m}^2$, and $N = 2$, respectively. The best well pattern layout method for Gonghe Basin is one injection well and two production wells.

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