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Optimization Simulation of Different Injection and Production Parameters of Enhanced Geothermal Systems

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ABSTRACT: Enhanced Geothermal System (EGS), as a key technology for the extraction and utilization of geothermal energy in deep strata and high temperature rock mass, has a broad application prospect in the field of energy. In order to understand the sustainable utilization capacity of the enhanced geothermal system, explore the influence law of different factors on the heat production capacity of geothermal Wells, and design a reasonable geothermal energy development and utilization program. The influence of different injection and production parameters on thermal recovery performance was studied by numerical simulation, and the main influencing factors were analyzed by orthogonal experiment. The results show that water injection rate has the greatest effect on the injection-production parameters, followed by well spacing and water injection temperature, and fracture opening and fracture number have the least effect. The optimal parameter combination is water injection rate of 10kg/s, well spacing 500m, water injection temperature 40℃, crack opening 0.09mm and crack number 60.

KEYWORDS: Enhanced geothermal system; Sustainable utilization capacity; Injection-production parameters; Numerical simulation; orthogonal experiment

I. INTRODUCTION

As a kind of clean and renewable energy, geothermal energy is of great significance for alleviating energy crisis and improving environmental quality. As a new geothermal energy mining technology, EGS can economically recover deep thermal energy from low permeability rock mass by artificially forming geothermal reservoirs. However, in practical application, the injection and production parameter setting of EGS has an important impact on mining efficiency and economic benefit. Therefore, the optimization of EGS injection and production parameters has important theoretical value and practical significance. Tang et al. took the enhanced geothermal system in Gonghe Basin, Qinghai Province, China, as the research object, and established a three-dimensional numerical model considering the different distances between production Wells. The analysis results show that the temperature of rock mass around reservoir fracture decreases with the development of thermal mining, and the production temperature decreases with the increase of mining life. The spacing between production Wells has a significant effect on thermal recovery performance, and the optimum spacing between production Wells in the study area is 800m. Musa D. Aliyu et al. established a three-dimensional numerical model of fracture network to study the effects of fracture number and spacing on reservoir productivity. The results show that the number and spacing of cracks have significant effects on production temperature, recovery efficiency and heat output. Taking the Yangbajing geothermal field in China as an example, Zeng et al. established the concept and numerical model of the fractured granite reservoir, evaluated the heat production and power generation potential of the fractured reservoir through numerical simulation, and analyzed the main factors affecting the heat production performance of the reservoir, and concluded that the production rate, reservoir permeability and injection temperature have important effects on geothermal development. Based on the actual test data and empirical parameters of a project, this paper analyzed the influence of different injection-production parameters on EGS heat recovery performance by numerical simulation method, and obtained the influence order and optimal level of injection-production parameters by orthogonal experimental analysis method, in order to provide theoretical basis for the design of efficient development scheme of enhanced geothermal system.

II. MODEL BUILDING

A. *Mesh generation*

This analysis adopts the form of one production and one injection of a pair of vertical Wells, and adopts the cuboid subdivision method, with 50 layers divided by 1500m in X direction and 30 layers divided by 1000m in Y direction. The cumulative thickness of 80m in the Z direction was divided into 8 layers, and NX*NY*NZ=50*30*8=12000 numerical calculation grids were divided. The specific model and numerical subdivision are shown in Figure 1:

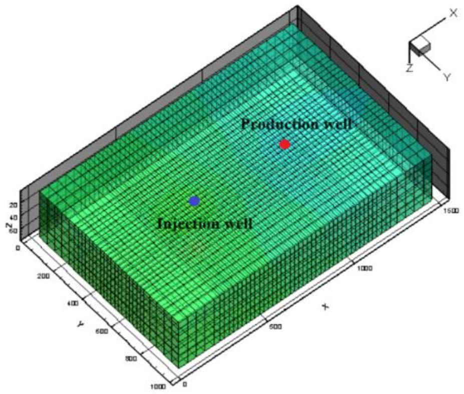

Figure 1. Grid profile diagram

B. Initial and boundary conditions

The temperature boundary is set at the top and bottom of the reservoir, and the pressure boundary is set at the top of the reservoir. The production well is exploited under constant pressure, and the initial pore pressure conforms to the hydrostatic pressure distribution. The reservoir boundary is not fractured, and the upper and lower boundaries are tight rocks. The reservoir boundary is set as impervious boundary. The external heat in the fracturing zone can enter the reservoir through heat conduction at the boundary and set the heat transfer boundary.

C. Parameter setting

The parameters involved in the model are selected according to the actual engineering and experience parameters, which mainly include the characteristic parameters of reservoir fractures and the related parameters of heat storage calculation.

Table I: Basic physical parameter

Argument	**Value**	**Argument**	**Value**
Porosity	0.23	Thermal conductivity	2.59 λ(W/(m·K))
Density	2.6 g/cm³	Coefficient of thermal expansion	1×10^{-5}
Specific Heat Capacity	0.878 J/g·°C	Pore compression coefficient	4.5×10^{-10} m²/N
Geothermal gradient	0.028 °C/m	Friction Angle	25°
Roof depth	2320 m	Cohesive force	100 Mpa
Reservoir thickness	80 m	Modulus of elasticity	2.7×10^{4} MPa
Top temperature	81 °C	Poisson's ratio	0.17

III. INFLUENCE OF INJECTION-PRODUCTION PARAMETERS ON THERMAL MINING

During the actual operation of geothermal system, its thermal recovery performance is significantly affected by the spacing of injection-production Wells, water injection rate and other factors. In order to explore the influence law of different factors on the heat production capacity of geothermal Wells, a reasonable geothermal energy development and utilization scheme is designed. The simulation and prediction of its operation for 30 years under the conditions of different well spacing, injection rate, injection temperature and fracture parameters are carried out, and the simulation results are summarized and analyzed. The simulation parameters are set in Table II.

Table II: Simulation parameter setting

Well spacing /m	**Water injection rate /(kg/s)**	**Water injection temperature /°C**	**Crack opening /mm**	**Number of cracks /strip**
200	10	10	0.09	15
300	20	20	0.12	30
400	30	30	0.15	45
500	40	40	0.18	60

A. Well spacing

In order to explore the influence of injection-production well spacing on the geothermal exploitation system, only the spacing of injection well and production well is changed for the same geothermal reservoir model, and the spacing sizes of four kinds of Wells are set as 200m, 300m, 400m and 500m respectively. The model is consistent with the operating parameters except for the different spacing of the well. The simulation results show that the model predicts the evolution of production temperature over time under different well spacing conditions as shown in Figure 2. As can be seen from the figure, when the well spacing is 200, 300, 400, 500m, respectively, the thermal breakthrough time is 1.5a, 4.0a, 7.5a, 12.0a, respectively, and the production temperature during 30 years of operation is 47.98, 55.35, 61.76, 67.46℃. Compared with a well spacing of 500m and 200m, the production temperature at 30a increases by 40.60%. It can be seen that increasing the well spacing can effectively improve the heat recovery performance, because with the increase of the well spacing, the heat transfer time and heat transfer area between the injected cold water and the hot reservoir are increased, and the heat transfer is more adequate. Therefore, the higher the corresponding production temperature and the later the heat breakthrough time, the longer the reservoir mining life.

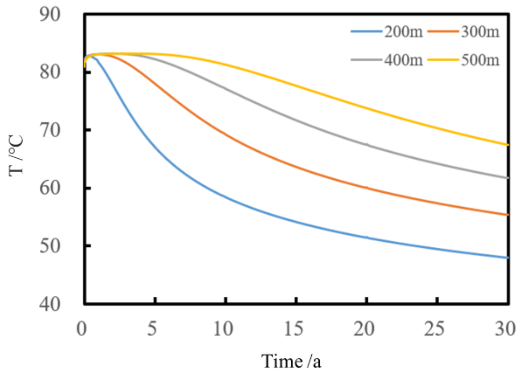

Figure 2. Production temperature of different well s pacing

B. Water injection rate

In order to explore the influence of water injection rate on thermal mining, only changing water injection rate to 10kg/s, 20kg/s, 30kg/s and 40kg/s was used to obtain the evolution of production temperature over time under different water injection rates, as shown in FIG. 3. It can be seen from the figure that with the increase of time, when the water injection rate is 40kg/s, the thermal breakthrough phenomenon first appears at about 7.5 years. Subsequently, other thermal breakthrough phenomena below 40kg/s water injection rate appeared successively, and the occurrence time gradually delayed with the decrease of water injection rate. And the higher the water injection rate, the faster the production temperature drops after the heat breakthrough. When the water injection rate is 10, 20, 30, 40kg/s, the production temperature of continuous mining for 30 years is 81.15, 74.12, 67.46, 62.43℃, respectively. Compared with the water injection rate of 10kg/s, the production temperature decreased by 8.66%, 16.87% and 23.07%, respectively. The main reason is that the increase of water injection rate accelerates the migration of low temperature cold water to the production well, and the heat transfer is insufficient, and the production temperature is lower.

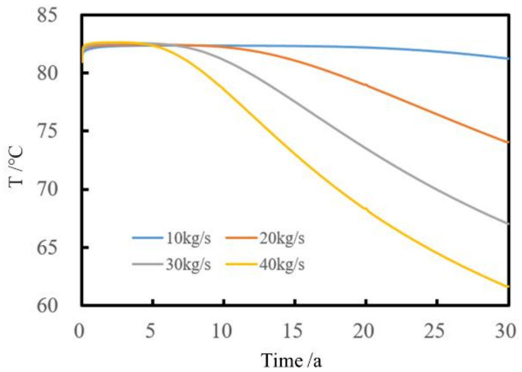

Figure 3. Production temperature at different water injection rates

C. Water injection temperature

In order to explore the influence of water injection temperature on hot mining, by changing the water injection temperature only to 10℃, 20℃, 30℃ and 40℃, the production temperature evolution over time under different water injection temperature conditions was obtained, as shown in Figure 4. It can be seen from the figure that different water injection temperatures have little influence on production temperature, especially in the initial stage of heat recovery and before the reservoir thermal breakthrough, the production temperature is almost unchanged. Only after the thermal breakthrough, the flow production temperature increases slightly with the increase of water injection temperature, and the thermal breakthrough time is almost unchanged under different water injection temperatures. When the water injection temperature is 10, 20, 30, 40℃, the production temperature in 30 years of continuous mining is 66.86, 67.46, 68.6, 70.28℃, respectively. When the injection temperature is 10℃ and 40℃, the difference of production temperature is only 3.42℃, which is 4.87% lower.

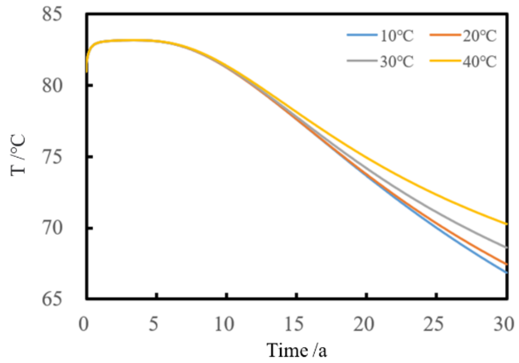

Figure 4. Production temperature under different injection temperature conditions

D. Crack opening

In order to explore the influence of fracture opening on hot mining, the original water injection rate and other model parameters were kept unchanged, and the production temperature evolution over time under different fracture opening conditions was obtained by changing the fracture opening to 0.09mm, 0.12mm, 0.15mm and 0.18mm only. As can be seen from the figure, when the fracture opening is 0.09, 0.12, 0.15, 0.18mm, respectively, the production temperature of system heating for 30 years is 67.46, 65.67, 64.16, 63.18℃, respectively. When the crack is 0.18mm and the crack opening is 0.09mm, the production temperature of 30 years is reduced by 6.34%. The production temperature is negatively correlated with the fracture opening degree, because at the same water injection rate, the increase of fracture opening leads to the increase of thermal reservoir permeability and the enhancement of fracture conductivity, resulting in too short residence time of low temperature cold water in the thermal reservoir and insufficient heat transfer. Therefore, the production temperature decreases with the increase of fracture opening degree, that is, the exploitation degree of geothermal reservoir is relatively low.

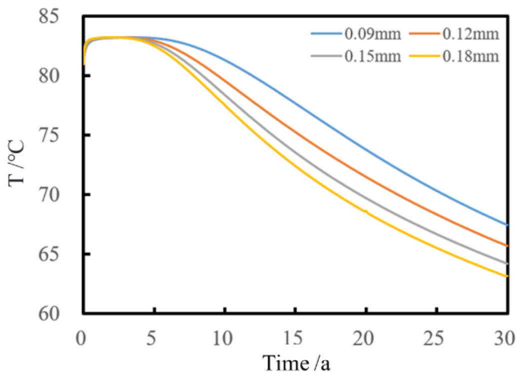

Figure 5. Production temperature under different crack opening conditions

E. Number of cracks

In order to explore the influence of fracture number on hot mining, only the fracture number was changed to 15, 30, 45 and 60, and the other models were consistent with the operating parameters. The results of production temperature evolution over time under different fracture numbers were obtained by simulation calculation, as shown in Figure 6. It can be clearly seen from the figure that during the mining period of 30 years, the production temperature and thermal extraction rate under different fracture number decreased with the increase of time. With the increase of fracture number, the faster the decline rate, the earlier the thermal breakthrough appeared. When the number of fracture strips is 15, 30, 45 and 60, the production temperatures at 30 years of recovery are 67.46, 66.07, 65.13 and 64.39℃, respectively. When the number of cracks was 60, the production temperature decreased by 4.55% compared with that when the number of cracks was 15. It can be seen that the production temperature decreases with the increase of the number of cracks. This is because at the same water injection rate, the increase in the number of fractures leads to the increase in fracture density, the enhancement of reservoir connectivity, and the increase in permeability, thus reducing the heat transfer time between the injected cold water and the hot reservoir, so the corresponding production temperature is lower.

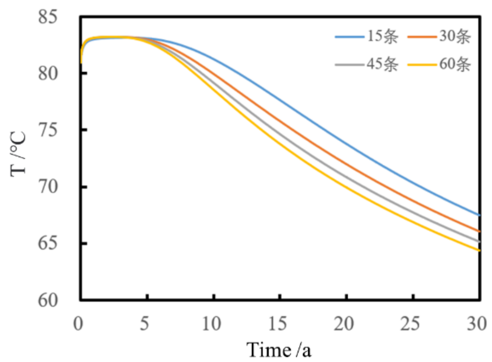

Figure 6. Production temperature under different fracture number conditions

IV. ANALYSIS OF MAIN INFLUENCING FACTORS

In order to compare and analyze the influence of different parameters on geothermal exploitation. On the basis of single factor analysis, 5 influencing factors such as well spacing, injection rate, injection temperature, fracture opening and fracture number were selected, and 4 levels were selected for each factor. Taking the production temperature of geothermal exploitation for 30 years as an index, $L_{16}(4^5)$ orthogonal experiment was conducted, and the results were analyzed in Table 3.

Table III: Orthogonal experimental results

Number	**Well spacing /m**	**Water injection rate /(kg/s)**	**Water injection temperature /°C**	**Crack opening /mm**	**Number of cracks /strip**	**Production temperature /°C**
1	200	10	10	0.09	15	58.59
2	200	20	20	0.12	30	50.92
3	200	30	30	0.15	45	50.83
4	200	40	40	0.18	60	54.23
5	300	10	20	0.15	60	67.23
6	300	20	10	0.18	45	55.47
7	300	30	40	0.09	30	61.53
8	300	40	30	0.12	15	54.72
9	400	10	30	0.18	30	74.82
10	400	20	40	0.15	15	69.11
11	400	30	10	0.12	60	56.39
12	400	40	20	0.09	45	55.89
13	500	10	40	0.12	45	79.59
14	500	20	30	0.09	60	71.88
15	500	30	20	0.18	15	63.18
16	500	40	10	0.15	30	56.26
k_1	53.64	70.06	56.68	61.97	61.4	
k_2	59.74	61.85	59.31	60.41	60.41	
k_3	64.05	57.98	63.06	60.86	60.45	
k_4	67.73	55.28	66.12	61.93	62.43	
Range	14.09	14.78	9.44	1.56	1.98	
Optimal level	500	10	40	0.09	60	
Order of influence	2	1	3	5	4	

The k value is the average production temperature of the corresponding factor at the same level, and the range is obtai ned by the difference between the maximum and minimum v alues of k under the same factor. According to the magnitude of the range, the order of impact on the production temperat ure of geothermal extraction for 30 years is: water injection r ate>well spacing>water injection temperature>crack openin g>number of cracks. The factor level with the highest k valu e is selected as the optimal level, that is, the optimal paramet er combination is water injection rate of 10kg/s, well spacing of 500m, water injection temperature of 40 ℃, crack openin g of 0.09mm, and 60 cracks. Therefore, optimizing the water injection rate and the spacing between injection and product ion wells can have a better mining effect on geothermal reser voirs, followed by the effects of water injection temperature, fracture opening, and number of fractures.

CONCLUSIONS

(1) Increasing the well spacing can effectively improve the heat recovery performance. The greater the well spacing, the better the heat transfer, the higher the production temperature and the longer the reservoir mining life. The increase of water injection rate accelerates the migration of cold water to production Wells, and the heat transfer is insufficient. The lower the production temperature, the shorter the production life of the reservoir.

(2) Water injection temperature has little influence on production temperature, and the production temperature only increases slightly with the increase of water injection temperature, which has little influence on the mining life of the reservoir. The opening degree and the number of cracks are negatively correlated with the production temperature. The increase of crack opening degree and the number of cracks make the fluid and heat storage and heat transfer insufficient and the production temperature decrease.

(3) Using the production temperature after 30 years of geothermal exploitation as the evaluation index, the orthogonal experimental analysis method shows that the order of influence of injection and production parameters from main to secondary is as follows: water injection rate, well spacing, water injection temperature, fracture opening and fracture number. The optimal parameter combination is water injection rate of 10kg/s, well spacing 500m, water injection temperature 40℃, crack opening 0.09mm and crack number 60.

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