Research Article

Influence Factors on EGS Geothermal Reservoir Extraction Performance

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The heat extraction performance of the enhanced geothermal system is simulated by using COMSOL software. The effects of six factors, such as the thermal conductivity of heat reservoir, matrix permeability, fracture width, injection temperature, injection flow rate, and the number of wells, on the heat extraction performance of EGS heat reservoir for 40 years are analyzed. The results show that the matrix permeability and injection flow are the main factors affecting the heat production performance of the EGS geothermal reservoir, while the thermal conductivity, fracture width, and injection temperature have little effect on the heat production performance of the EGS geothermal reservoir. Although increasing the number of production wells can improve the uneven distribution of the flow field to improve the system heat performance, taking into account the existing drilling technology and cost, the cost is higher, and the two-well system is still the basic form of absorbing rock heat.

1. Introduction

Dry hot rock geothermal is a kind of deep thermal rock mass, buried 3-10 km deep; the temperature is generally above 150°C. It has huge reserves and is not restricted by geographical area and does not contain or contain a small amount of fluid. To develop dry hot rock geothermal energy [1, 2], it is necessary to artificially create cracks to create heat reservoirs, which are called enhanced geothermal systems (EGS) [3, 4]. Dry hot rock geothermal resources have become a new energy source of great concern in the world because of their advantages of cleanliness and pollution-free, large reserves, wide spatial distribution, safe mining process, little environmental impact, etc. and have attracted extensive attention from scholars at home and abroad [5, 6]. Among them, the EGS of the Soultz project in France is the most successful, and its heat production scale has been commercialized, playing a positive role in the commercialization of EGS projects in other countries [7].

The extraction of hot dry rock type geothermal energy resources is usually carried out by using the heat-extracting medium with better heat exchange efficiency to flow between the fractures of the artificial reservoir and the high-temperature geothermal rock mass [8]. Therefore, it is necessary to adopt various engineering techniques to form a continuous reservoir to increase the heat exchange area between the heat extraction medium and the fractured rock mass of the reservoir. In practical engineering, the geothermal reservoir is a part of the whole geothermal engineering system, in which the fluid parameters such as injection fluid pressure, temperature, flow rate, water chemistry, and outlet fluid pressure are all parameters that can be directly controlled, so they have great research significance [9].

Because there is a large gap between the reservoir structure, heat extraction mechanism, and seepage field characteristics of the actual geothermal reservoir and the heat transfer geothermal reservoir model in the laboratory [10], the laboratory simulation conditions are usually difficult to achieve the experimental simulation environment consistent with the practical engineering, so the research results are often very different from the actual situation. Although the field in situ test can accurately reflect the actual situation of the project, it requires a lot of manpower, material, and financial resources, so it is necessary to rely on numerical simulation to make up for the shortcomings of this research [11].
At present, the numerical simulation method has been widely used because of its economical and fast characteristics, which can efficiently simulate and analyze the coupling process of EGS heat transfer. Based on field experiments, Wu et al. [12] established a high-simulation three-dimensional EGS numerical model to simulate the key heat transfer processes related to EGS heat extraction and studied the effect of different heat transfer mechanisms such as heat convection of fracture flow and heat conduction of rock layer on the effect of EGS heat extraction performance.

Based on experiments, Okoruafo et al. [13] used Gaussian sequential simulation to generate 100 artificial fracture aperture distributions and studied the influence of anisotropy in the fracture aperture on the heat extraction performance of the EGS system. The results show that 70% of the fracture aperture distribution has good thermal performance under vertical flow configuration, so injection wells perpendicular to the shear or slip direction have favorable thermal performance.

Zeng et al. [14] studied the thermal extraction process in the Yangbajing granite geothermal reservoir. Based on the geological data of reservoirs with a depth of 950–1350 m, a mathematical model of thermal reservoirs is established. The simulation results show that the heat reservoir of the Yangbajing geothermal double-well system reaches 3.23–3.48 MW and can maintain power generation for 20 years. At the same time, the heat extraction efficiency of horizontal well and vertical well is compared and analyzed, and it is found that the heat extraction efficiency of the horizontal well is better than that of the vertical well, and the horizontal well is beneficial to reduce the pressure of the injection pump and has good thermal performance.

Reservoir fractures are the main fluid seepage channels in the process of hot dry rock geothermal resource exploitation. It is of great significance to study the seepage and heat transfer process in fractured rock mass of geothermal reservoirs for geothermal mining engineering [15]. The fractures in the thermal reservoir are densely distributed and the unit is small, which can be regarded as an equivalent continuous medium. The single fracture is the most basic unit of the fracture system, and the heat-flow coupling study on it can guide the study of complex fractures [16]. The single-fracture concept was first proposed by Smith in Los Alamos Scientific Laboratory in 1972 [17], with a relatively simple structure, which is the first generation of the EGS thermal reservoir model. Kohl et al. [18] established a two-dimensional single-fracture numerical model to simulate the long-term operation process of the hot dry rock reservoir system and studied the heat-fluid-solid coupling mechanism in the hot dry rock reservoir.

He et al. [19] simulated the influence of fracture morphology on the heat transfer characteristics of water flow in a single fracture, studied the water flow and heat transfer process in a single fracture under different surface roughness, and proposed a morphological condition factor (MCF) considering the influence of fracture morphology on heat transfer characteristics. Jiang et al. [20] established a three-dimensional transient model of the EGS underground heat transfer process, considering the thermal reservoir as an equivalent porous medium with a single pore. Two heat transfer equations are introduced to describe the convective heat transfer in the fracture and the heat transfer in the rock matrix, and the EGS project is selected as an example to prove the validity and rationality of the model.

Asai et al. [21] designed seven different fluid schemes (water injection mode, water injection time gradient) to study the influence of different fluid schemes on the thermal extraction rate of EGS reservoir under the premise of ensuring the constant water injection temperature and total water injection volume. It is found that the exponential flow water injection mode is the best choice to increase production.

Based on the assumption of local thermal nonequilibrium theory, Yao et al. [22] established a mathematical model and an ideal three-dimensional EGS numerical model to simulate the heat production process of EGS. Combined with the THM coupling process, they analyzed the distribution law of pressure, temperature, stress, and deformation of geothermal reservoirs. It is found that the changes in reservoir pressure and temperature will cause fracture displacement and change the seepage characteristics of reservoirs. Saeid et al. [23, 24] conducted one-dimensional and two-dimensional coupled simulations of low-temperature EGS, and through the comparison of different parameters, predicted the functional relationship between the service life of EGS and reservoir porosity, average initial reservoir temperature, and injection temperature.

In the study of EGS development in Guide Basin, Qinghai Province, Zhou et al. [25] analyzed the influence of fracture permeability, well spacing, injection temperature, and injection water rate on the heat extraction performance of EGS by numerical simulation and artificial neural network method. The results show that the injection flow rate has the greatest influence on the total heat extraction, followed by the injection temperature and well spacing, and the fracture permeability has the least influence.

Based on the above discussion and on the basis of summarizing the predecessors, this paper uses the COMSOL Multiphysics software to simulate the heat flow coupling model of a single-fracture high-temperature thermal extraction. The reliability of the proposed model and numerical method is verified by comparison with the analytical solution. At the same time, through sensitivity analysis, the effects of six factors, including thermal conductivity of thermal reservoir, matrix permeability, fracture width, injection temperature, injected water volume, and several wells, on the long-term heat extraction performance of EGS thermal extraction were studied. The research results provide support for the engineering design and operation of EGS.

2. Model Establishment

2.1. Conceptual Model. The main feature of the EGS thermal reservoir is that it contains a large number of open fractures and connected fractures. To facilitate the calculation, the fracture is simplified as a main fracture surface. The thermal reservoir model is established in the underground 3800–4300 m section. The overall size is 500 m × 500 m × 500 m, including the upper and lower matrix, the fracture surface, the injection well, and the production well. The thermal reservoir is a wellbore opening section, which is regarded as a
porous medium. Firstly, the fluid is poured into the open section of the injection well, and then, the fluid penetrates the thermal reservoir from the open section of the injection well, but most of the fluid flows into the open section of the production well through the fracture surface, and finally, the fluid is produced from the open section of the production well. The geometric model is shown in Figure 1. The diameter of the injection well and the production well is 0.2 m. The distance between the two wells is 400 m, and the distance from the two sides of the thermal reservoir is 50 m and 250 m, respectively.

The grid division of the EGS geothermal reservoir is shown in Figure 2. The number of grids in the computational domain is 4940819 units, and the average grid quality is 0.6421, which meets the requirements.

2.2. Mathematical Model

2.2.1. Basic Assumptions. To describe the law of seepage and heat transfer in the thermal reservoir during the heat transfer process of the EGS, the following basic assumptions are made for the thermal reservoir model:

(1) Water flows unidirectionally in the thermal reservoir
(2) The thermal reservoir rock mass is an isotropic continuous porous medium, and the permeability of the upper and lower matrix of the thermal reservoir is lower than the permeability of the fracture surface, that is, the thermal reservoir model is a double continuous medium model
(3) Ignoring the evaporation of circulating fluid, the heat transfer process fluid water is always liquid and does not consider the loss of fluid
(4) Ignoring the chemical reaction between the water and rock in the geothermal reservoir and the internal stress of the geothermal reservoir during the heat transfer process
(5) Without considering the effect of thermal radiation, only convective heat transfer and heat conduction are considered
(6) The expression of the thermal recovery process is the local thermal equilibrium method
2.2.2. Control Equations. Based on the double porosity continuous medium model of the EGS heat reservoir and the above basic assumptions, the water flow and heat transfer process in the model are described [26]. The governing equations of seepage field and temperature field of fracture and upper and lower matrix in heat reservoir are obtained [27] as follows:

Fracture surface seepage field equation:

\[ d_{f} \frac{\partial}{\partial t}(\rho_{w} \epsilon_{f}) + \nabla_{T}(\rho_{w} \bar{u}_{w}) = Q_{f}, \]  \( (1) \)

\[ \bar{u}_{w} = -K_{f} \frac{d_{f}}{\mu} \nabla_{T} p, \]  \( (2) \)

\[ Q_{f} = -K_{f} \frac{\partial p}{\mu} \frac{\partial n}{} . \]  \( (3) \)

In the formula, \( d_{f} \) is the crack width, \( m; \rho_{w} \) is the density of water, \( kg/m^{3} \); \( \epsilon_{f} \) is the porosity of the fracture; \( Q_{f} \) is the flow exchange between fracture surface and matrix, \( m^{2}/s; \) \( K_{f} \) is the permeability of fracture surface, \( m^{2}; \) and \( \mu \) is the dynamic viscosity of water.

The temperature field equation of fracture surface is

\[ d_{f} \rho_{w} c_{w} \frac{\partial T_{f}}{\partial t} + d_{f} \rho_{w} c_{w} u_{w} \nabla_{T} T_{f} - d_{f} \nabla_{T} (\lambda_{w} \nabla_{T} T_{f}) = W_{f}, \]  \( (4) \)

\[ u_{f} = \frac{K_{f}}{\mu} \nabla_{T} p, \]  \( (5) \)

\[ W_{f} = h(T_{f} - T_{i}). \]  \( (6) \)

In the formula, \( T_{i} \) is the temperature of the fissure water, \( K; \lambda_{w} \) is the thermal conductivity of water, \( W/(m-K); \) \( W_{f} \) is the heat absorbed by the fissure water from the matrix, \( W/(m^{2}-s); \) and \( h \) is the convective heat transfer coefficient between fissure water and matrix, \( W/(m-K). \)

The governing equation of open section and matrix seepage field is

\[ \frac{\partial}{\partial t}(\epsilon_{r} \rho_{w}) + \nabla \left( \rho_{w} \bar{u} \right) = Q_{m}. \]  \( (7) \)

Among them, the flow in the thermal reservoir satisfies Darcy’s law:

\[ \bar{u} = -\frac{K}{\mu} \nabla p. \]  \( (8) \)

In the formula, \( \epsilon_{f} \) is the porosity of the open section and the matrix; \( K_{f} \) is the permeability of the open section and matrix, \( m^{2}; \) and \( Q_{m} \) is the source term of seepage, \( kg/(m^{3}-s). \)

Temperature field control equation of the opening section and matrix:

\[ c_{r} \frac{\partial T_{r}}{\partial t} + \nabla (-\lambda_{r} \nabla T_{r}) + c_{w} \left( -\frac{K_{r}}{\mu} \nabla p \right) \nabla T_{r} = 0. \]  \( (9) \)

In the formula, \( c_{r} \) is the specific heat capacity of the opening section and the matrix, \( J/(kg-K); \lambda_{r} \) is the thermal conductivity of the opening section and the matrix, \( W/(m-K); \) \( c_{w} \) is the specific heat capacity of water, \( J/(kg-K); \) \( Tr \) is the temperature of the opening section and matrix, \( K. \)

2.3. Boundary and Initial Conditions. The simulation time of the entire EGS geothermal reservoir is 40 years, and the time step is 0.5 years. The initial conditions and boundary conditions used in the model are as follows:

(1) Boundary conditions of temperature field: the water injection temperature of the injection well is 20°C. The initial surface temperature of the geothermal reservoir is 300°C, which belongs to high-temperature geothermal resources. Due to the large size of the model, the top and bottom boundary conditions of the model are adiabatic.

(2) Boundary conditions of the seepage field: the initial pore pressure of the thermal reservoir model is set as hydrostatic pressure, and the initial pressure is assumed to be 40 MPa. The boundary condition for the inlet of the open section of the injection well is
the flow boundary condition, and the injection flow is 10 kg/s. To ensure the circulation of water and ensure that the water does not undergo a phase change, the outlet pressure of the open section of the production well is set to 10 MPa, and the thermal reservoir is surrounded by impermeable boundary conditions.

2.4. Initial Calculation Parameter Settings. In this paper, water is used as the working fluid of EGS. The overall initial temperature of the model is 300°C, the pressure is 40 MPa, and the fracture surface thickness is 3 mm. Other thermophysical parameters are shown in Table 1 below.

3. Validation of the Numerical Model

To test the reliability of the numerical simulation method used in the single-fracture geothermal reservoir model in this paper, the coupling relationship between the convective heat transfer in the fracture and the heat conduction in the matrix is verified. As shown in Figure 3, thermal extraction is carried out in a limited area of 50 m × 50 m, the initial temperature of the matrix is 1°C, the water injection temperature is 0°C, and the matrix is an isotropic, water-impermeable rock mass, and the crack width between the two matrices is the rectangular fluid domain of d.

The accuracy of the results of the numerical simulation method of fracture temperature was verified by the classical Lauwerier analytical theory of heat transfer in fractures [26]. Three different positions along the fracture direction were selected as monitoring points: monitoring point 1 (X = 5 m), monitoring point 2 (X = 25 m), and monitoring point 3 (X = 45 m).

The theoretical calculation and numerical calculation of the position of the monitoring point in the matrix and the temperature at different times are compared, and the results are shown in Figure 4. It can be seen that the farther the monitoring point is from the entrance, the slower the crack temperature rises with time. When 0 m < X ≤ 5 m, there is a small deviation between theoretical calculation and numerical calculation. When X > 5 m, there is almost no deviation between theoretical calculation and numerical calculation. Because the size of the model is much larger than 5 m and the running time is 40 years, the theoretical calculation and the numerical calculation are almost completely consistent, which proves that the numerical method adopted has certain reliability.

4. Simulation Results and Analysis

According to the outlet temperature and heat exchange of the production well, the parameter sensitivity analysis of the EGS geothermal reservoir is carried out, and six factors are comprehensively analyzed for EGS geothermal reservoir’s 10-year, 20-year, 30-year, and 40-year heat extraction performance effects.

4.1. Geothermal Reservoir Thermal Conductivity. It can be seen from Figure 5 that when the thermal conductivity was increased from 2 W/(m·K) to 6 W/(m·K), the water temperature at the outlet of the production wellbore increased from 293.5°C to 298.9°C, and the heat production power increased from 11487.4 kW to 11717.4 kW. After 40 years of running, the water temperature at the outlet of the production well increased from 265.1°C to 283.8°C, and the heat production power increased from 10294.6 kW to 11080.6 kW. In general, both the outlet temperature and the heat production power decrease with the increase of time, and the smaller the thermal conductivity, the greater the decrease. When the thermal conductivity is 2 W/(m·K), from 10 years to 40 years, the temperature decreases by 9.7%, and the heat production power decreases by 10.4%. When the thermal conductivity is 6 W/(m·K), from 10 years to 40 years, the temperature decreases by 5.1%, and the heat production power decrease by 5.4%.
4.2. Geothermal Reservoir Matrix Permeability. Permeability expresses the ability of fluid to pass through rock. To analyze the influence of matrix permeability on the fluid temperature and heat production power at the outlet of the production well, we select matrix permeability $k = 1 \times 10^{-18}$ m$^2$, $k = 1 \times 10^{-17}$ m$^2$, $k = 1 \times 10^{-16}$ m$^2$, and $k = 1 \times 10^{-15}$ m$^2$ to analyze the change of the fluid temperature and heat transfer at the outlet of the production well with the matrix permeability.

It can be seen from Figure 6 that with the increase of the permeability of the upper and lower matrix, the outlet temperature and heat production power of the production well bore both increase. The greater the permeability, the greater the increase, and the outlet temperature and heat production power generally decrease with the increase, and the smaller the permeability, the greater the decrease. The high permeability matrix $k = 1 \times 10^{-15}$ m$^2$ after 10 years of operation, the outlet temperature is 296.4°C, and after 40 years of operation, the outlet temperature is 272.5°C, the temperature decreases by 8.1%, and the heat production power is 11607.1 kW after 10 years of operation, 10606.3 kW after

**Figure 5**: Evolution of outlet temperature and heat transfer under different thermal conductivities.

**Figure 6**: Evolution of outlet temperature and heat transfer under different matrix permeabilities.
40 years, and the heat production power is reduced by 8.6%. When the matrix permeability is extremely low, such as $k = 1 \times 10^{-18}$ m$^2$ after 10 years of operation, the outlet temperature is 231.1°C; after 40 years, it is 160.5°C; the temperature drops by 30.5%; the outlet heat production power is 8865.9 kW after 10 years; 40 years later, it was 5900.6 kW, and the heat production power was reduced by 33.4%. The temperature drop of the high-permeability matrix and the very low-permeability matrix varies greatly during the production process, indicating that the matrix permeability has a greater impact on the outlet fluid temperature, and the high-permeability matrix can obtain higher outlet temperature and heat production power for a long time.

4.3. Geothermal Reservoir Crack Width. It can be seen from Figure 7 that when the crack width was increased from 2 mm to 4 mm, the outlet temperature decreased from 298.9°C to 292.9°C, and the heat exchange decreased from 11715.5 kW to 11461.1 kW after 10 years of operation. After 40 years of operation, the fluid temperature decreased from 284.9°C to 261.6°C, and the heat exchange rate decreased from 11125.1 kW to 10148.2 kW. In general, both the outlet temperature and the heat production power decreased with the increase of time. The larger the crack width, the larger the drop. When the crack width is 2 mm, from 10 years to 40 years, the temperature decreases by 4.7%, and the heat exchange decreases by 5%. When the crack width is 4 mm, from 10 years to 40 years, the temperature decreases by 10.7%, and the heat exchange decrease by 11.5%. This is because increasing the fracture width will lead to an increase in fracture permeability. The fluid will more easily flow from the injection well to the production well along the fracture surface, reducing the heat exchange with the substrate leads to a decrease in the outlet temperature of the production well. It is therefore important to find a value that matches the matrix permeability and fracture permeability. And in practical engineering, the fluid will be injected continuously, and the crack will be squeezed continuously during the flow in the geothermal reservoir, resulting in the continuous increase of the crack width and the reduction of the operating life. Therefore, to obtain a higher mining temperature for a long time, the mining should be stopped for some time, so that the overall EGS thermal reservoir has a certain recovery period.
4.4. Injection Water Temperature. In the process of heat extraction, the injection water temperature is a relatively easy factor to control. The injection temperatures were selected as 10°C, 20°C, 30°C, 40°C, and 50°C, respectively. It can be seen from Figure 8 that with the increase of the injected water temperature, the outlet temperature and heat exchange also gradually increase. Under the same injection flow rate of 10 kg/s, the injection temperature increased from 10°C to 50°C, and after 10 years of operation, the outlet temperature increased from 296.2°C to 296.8°C, and the heat exchange increased from 11600.7 kW to 11624.6 kW. After 40 years of operation, the outlet temperature increased from 271.5°C to 275.5°C, and the heat exchange increased from 10564.8 kW to 10730.1 kW, an increase of 1.6%, and the overall increase was very small. Therefore, after the injection flow rate is determined, the injection water temperature does not need to undergo special treatment (such as heating or cooling) according to the water source’s temperature.

4.5. Injection Water Flow. The injection water volume of 8-16 kg/s was selected to analyze. It can be seen from Figure 9 that when the flow rate was increased from 8 kg/s to 16 kg/s, the outlet temperature decreased from 298.5°C to 286.1°C after 10 years of operation. After 40 years of operation, the outlet temperature decreased from 271.5°C to 275.5°C, and the heat exchange increased from 10564.8 kW to 10730.1 kW, an increase of 1.6%, and the overall increase was very small. Therefore, after the injection flow rate is determined, the injection water temperature does not need to undergo special treatment (such as heating or cooling) according to the water source’s temperature.

Therefore, to obtain a higher heat exchange rate for the system, a large flow can be injected at the beginning of the operation, but the injection flow should be reduced as much as possible in the later stage.

4.6. Number of Production Wells. Consider the effect of the number of production wells on the water temperature and heat transfer at the outlet of the production wells. Based on ensuring that there is only one injection well and the parameters such as injection temperature and flow rate remain unchanged, four system schemes of 3 wells, 5 wells, 7 wells, and 9 wells are designed, as shown in Figure 10.
From Figure 11, we can see that the more production wells, the higher the outlet temperature and heat power production. When the number of production wells is 3, 5, 7, and 9, and the running time is for 10 years, the outlet fluid temperatures are 292.8 °C, 298.1 °C, 299.3 °C, and 299.6 °C, and the heat exchange rates are 11457.9 kW, 11679.9 kW, 11732 kW, and 11744.7 kW, respectively. After 40 years of operation, the outlet fluid temperature reaches 262.20 °C, 278.25 °C, 286.83 °C, and 290.93 °C, respectively, and the heat exchange is 10172.3 kW, 10846.5 kW, 10206.9 kW, and 11378.9 kW, respectively. In addition, judging from the drop in outlet water temperature, the more wells, the lower the drop. The temperature drop of 9 wells is the lowest, about 3%, while the drop of 3, 5 to 7 wells is about 12.6%, 7.2%, and 4.4%, respectively. The reason is that in the temperature field and flow field distribution of the fracture surface over the past 40 years (Figure 12), from the 3 wells system to the 9 wells system, the low-temperature area continues to increase, and the heat absorption range also becomes larger and larger, and the increase decreases more than the 5 wells system. The low-temperature area of 9 wells is closer to the surrounding edges, and there is no problem of weak and uneven flow in the edge area of the system like 3 wells.

Therefore, the greater the number of production wells, the better the distribution of the flow field, and the more advantageous it is in terms of heat exchange. However, compared with the dual-well system, although the outlet temperature of the 9 wells system is 290.93 °C after 40 years of operation, which is 18.4 °C higher than that of the dual-well system; the cost is higher considering the existing drilling technology and cost. Therefore, the dual-well system is still the basic form of absorbing geothermal from the rock mass.

5. Conclusions

This paper comprehensively analyzes six influence factors on the heat extraction performance of EGS geothermal thermal reservoir in 10, 20, 30, and 40 years. Conclusions are as follows:

1. The initial temperature, matrix permeability, and injection water flow are the main factors affecting the thermal reservoir and extraction performance of EGS, while the thermal conductivity, crack width, and injection water temperature have little effect.

2. For an EGS system with an initial temperature of 300 °C, the outlet temperature of the geothermal reservoir can be maintained at about 300 °C for 3 years.
of operation and gradually decreases after 3 years and then drops to 272.5°C after 40 years

(3) The increase in the number of production wells improves the distribution of the flow field and also has advantages in heat transfer. However, after 40 years of operation in the same computational domain, the outlet temperature of the 9-well system is 290.93°C, which is only 18.4°C higher than that of the dual-well system. Considering the existing drilling technology and costs, currently, the cost is relatively high. Therefore, the dual-well system is still the basic form of absorbing heat from the hot dry rock mass

### Symbols

- $d$: Crack width (m)
- $\epsilon$: Fracture porosity, dimensionless
- $\rho_f$: Fluid density (kg/m$^3$)
- $Q_f$: Crack face and matrix flow exchange (m$^2$/s)
- $K_f$: Permeability of crack face (m$^2$)
- $\mu$: Dynamic viscosity of water (Pa·s)
- $T_f$: Temperature of crack face water (K)
- $h$: Convective heat transfer coefficient between crack water and bedrock (W/(m·K))
- $\epsilon_o$: The opening section, matrix porosity, dimensionless
- $K_o$: The open section, matrix permeability (m$^2$)
- $Q_{so}$: The seepage source term (kg/(m$^3$·s))
- $c_o$: Specific heat capacity of the opening section and the matrix (J/(kg·K))
- $\lambda_o$: Thermal conductivity of the opening section and the matrix (W/(m·K))
- $c_w$: Specific heat capacity of water (J/(kg·K))
- $T_o$: Temperature of the opening section, matrix, (K).

### Subscripts

- $l$: Crack
- $u$: Liquid
- $r$: The opening section, matrix
- $d$: Stratum
- $m$: Source-sink term.

### Data Availability

Data can obtained from the corresponding author.

### Conflicts of Interest

The authors declare that they have no conflict of interest.

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