Numerical Simulation Study on Heat Transfer Mechanism of Excavation Based Enhanced Geothermal System

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Abstract. The innovative excavation based EGS (EGS-E) scheme uses mining techniques to form deep underground access for creating artificial heat reservoir with multi-level fracture networks using excavation, blasting, and caving. The two-level heat transfer mechanism of distributed artificial heat reservoir has a dominant influence on the performance of excavation based Enhanced Geothermal System(EGS-E). However, due to the large-scale field testing and laboratory physical experiment are not yet realistic, the process of natural convection heat transfer within the surrounding rock enhanced permeability and water filled zones hasn’t been effectively studied. The simulation software COMSOL Multiphysics was used to numerically simulate the natural convection heat transfer within the enhanced stimulated surrounding rock around a single straight roadway with its circular opening, which should be an elemental unit for mining heat in deep underground engineering structure. The simulation results demonstrated that the temperature difference inside the surrounding rock of a roadway causes the density of working fluid to vary. Driven by buoyancy, the natural convection of working fluid occurs in the surrounding rock. It enhances the heat transfer inside hot dry rock, and its efficiency is significantly more remarkable than that of the conduction through hot dry rock itself, which can improve the efficiency of heat recovery with regards to EGS-E. Due to the low solid heat conduction efficiency of the surrounding dry hot rock, adjusting the speed of the water flow inside the pipe can effectively control the temperature of the water outlet to improve the heat collection life of the system.

Keywords: EGS-E, Natural convection, Hot dry rock, Surrounding rocks.

1. Introduction

Geothermal energy has broad prospect due to its wide distribution, vast reverses and anti-interference from ground environments. Wang et al. [1] used the volume method to calculate the geothermal resources of hot dry rocks in the continental part of China and figured out that the total at a depth of 3~10 km is 20.9×10^6 EJ. Geothermal resources can be divided into hydrothermal and dry hot rock types according to their genesis and output conditions [2]. Hydrothermal type is stored in highly
permeable pores or fractures in rocks and heat is mainly obtained by exploiting fluids there [3]. Hot dry rock type is mainly stored in low permeability of rocks 3~10 km deep. In order to effectively develop and utilize dry hot rocks, Las Amos National Laboratory in the US proposed the concept of enhanced geothermal system in 1970. The system uses hydraulic fracturing, chemical stimulation and other methods to enhance permeability in depths to create a heat reservoir; cold working fluid is injected into the artificial reservoir, through the fluid circulation system, fluid is heated to a certain temperature, and then transported to the power generation system at surface; the cooled circulating fluid is recharged to recycle [4]. Since then, Landau geothermal project in Germany, Soultz-sous-Forêts in northeastern France, and Hijiori in Japan have been tested to generate electricity [5], but the installed capacity was only a few MW, which made them difficult to meet the needs in scale. Relatively, in China, studying Geothermal energy extraction from hot dry rocks relatively started late. In recent years, the progress has mainly focused on resource evaluation, drilling, microseismic monitoring and numerical simulations [6].

Most EGS field testing projects needed to face complex geological environment and hydraulic fracturing had a great dependence on natural fractures, which could easily lead to insufficient heat deposit volume and heat exchange area, small working fluid flow, low output temperature, and risks of induced earthquake. For this reason, Tang et al. [7] proposed a new geothermal energy extraction scheme turning from petroleum into mining technology, i.e., Excavation based Enhanced Geothermal System (EGS-E). The system uses shafting and tunneling techniques such as excavation, blasting and caving to form an artificial heat reservoir with multi-level channels and fracture networks. Its core mechanism for the geothermal energy to be transmitted to the ground is a two-stage heat exchange system of ‘water-rock and water-water’ unit. The unique thermal energy reserved fracturing system and thermal energy exchange system of EGS-E can effectively solve the technical problems faced by traditional EGS-D. Tang et al. [8] established a method for estimating the heat recovery rate from large-scale artificial engineering system in deep underground heat extraction based on this theory. The steady-state heat transfer process between lined circulation tubes and heat exchange zones was simulated. Through studying the functions of tunnel ventilation and isolation liner, Kang et al. [9] further enriched the content of the excavation based Enhanced Geothermal System. The above-mentioned scholars’ research on EGS-E mostly focused on the conceptual design stage, and rarely involved the coupled analysis of seepage and heat transfer on a single circular heat mining tunnel.

In this paper, the numerical simulation software COMSOL Multiphysics was used to analyze the natural convection heat transfer within the surrounding rock around one straight roadway with its circular cross opening, which was taken as an elemental unit to assembly the deep engineering structures for mining heat.

Following manual excavation inducing stress redistribution, the surrounding rocks of a deep underground tunnel will undergo mechanical, hydraulic and some extent of chemical changes. The mechanical affected failure area is called Excavation Disturbed Zone (EDZ) [10]. EDZs can be generally divided into three zones: failure or highly damaged zone (HDZ), slightly damaged zone and distinctly deformed zone [11]. Corresponding to using three different technical evaluation methods through geological radar, ultrasonic detection technology and numerical simulation, Teng [12] studied the ranges disturbed phenomenon around a three-center horseshoe tunnel cross-section roughly with
averaged radius 4.6m by conservative drilling and blasting in shallow layered shale and found that the maximum depths of the excavation damage zone were 3.6, 3.8 and 4.3m respectively. In order to smooth the study in this article, some assumptions were made as follows: the excavation damage zone across the section is a 4.5m thick circular ring, corresponding to a circular hole with its 1.5m radius tunneled in granite; the permeability and porosity in the excavation damage zone of surrounding rock obey linear distribution, which gradually descend from the maximum values at the excavated wall as the inner boundary over to zero where the outer boundary is defined. High-pressure but low-temperature water is injected into the domain or zones where the enhanced permeability is contained. Because heat exchange between hot dry rock and fluid across their contacting interface is intensive and within fractures with enough thin apertures the internal convection heat transfer coefficient should be great, macroscopically temperature difference between water and rocks can be ignored, i.e., conventional local heat balance is adopted as an basic assumption here to describe this energy transfer process [13]. In this study, it was confirmed that the working fluid within reservoir sustains its liquid state, i.e., any phase change is not be concluded. Although water temperature could exceed 100°C but the pressure to which it subjected attains to a level far much higher than 1 atm everywhere.

After cold water with high pressure is injected into the fractured granite, the physical and mechanical properties of the granite will change. Cha et al. [14] believed that injecting cryogenic liquid will cause the formation to shrink and generate tensile stress, which is helpful for the reservoir to form its cracks. Tang et al. [15] regarded that the temperature inside rocks is lowered by cryogenic liquid and that near the contact boundary drops the fastest. The higher temperature gradient becomes, the greater tensile stress occurs, which turn to induce rock fractures. From the experimental point of view, Jin [16] revealed that when the cool fluid is injected into a hot fractured rock mass, secondary microcracks will occur from the main fractures in the surrounding rock due to the effect of thermal stress induced by temperature gradient. When the secondary cracks expand to a certain extent, they may interpenetrate with the primary microcracks to form effective seepage channels. In the damage
zone of the surrounding rock, the fractured granite can be regarded as a porous medium, where water flows and conveys heat through convection. Since this paper intends to study about the heat transfer mechanism for a fundamental unit under EGS-E scheme, the complex internal crack structure within specific rocks had been assumed as averaged porous effect. From the perspective of microscopic Representative Element Volume (REV) point of view, the seepage behavior and possible heat transfer process with regards to basic heat energy transport mechanism was preliminarily modelled and analyzed.

2. Numerical Methods

2.1. Premise Assumptions

(1) The permeability and porosity of the excavation damage zone are linearly descending distributed starting from tunnel opening. In the damage zone of the surrounding rock, the fractured granite can be regarded as a porous medium;

(2) The changes in permeability and porosity of the excavation damage zone caused by the thermal strain corresponding to matrix rock swelling or shrinkage are avoided and not included;

(3) The phase change of water caused by temperature change is avoided and not included;

(4) The heat is transferred only through heat conduction and heat convection, without considering the compressive and expansion mechanical work of gas and dissipation of liquid viscosity, thermomechanical dispersion or heat radiation;

(5) The water flow within fractured granite falls into a single-phase seepage flow, regardless of any chemical interaction between water and rock.

2.2. Governing equation

The simulation software COMSOL Multiphysics was used to conduct analysis on the coupling between fluid-thermal process within the damage zone of a single circular roadway.

The Darcy's law equation:

\[
\frac{\partial}{\partial t}(\varepsilon_p \rho) + \nabla \cdot (\rho u) = Q_m
\]

\[
u = -\frac{K}{\mu} (\nabla p + \rho g)
\]

where, \(\varepsilon_p\) is the porosity of granite; \(\rho\) is the density of fluid; \(u\) is the Darcy velocity; \(K\) is the permeability of granite; \(\mu\) is the dynamic viscosity of fluid; \(\nabla p\) is the pressure gradient of the fluid; and \(\rho g\) is the buoyancy term.

Porous media heat transfer equation:

\[
d_z \left( \rho C_p \right)_{\text{eff}} \frac{\partial T}{\partial t} + d_z \rho C_p u \nabla T + \nabla \cdot q = d_z Q + q_0 + d_z Q_{\text{ed}}
\]

\[
q = -d_z k_{\text{eff}} \nabla T
\]

where, \(d_z\) is model thickness (the system default value is 1 m); \(\rho\) is the density of fluid; \(C_p\) is the heat capacity of fluid; \(T\) is the initial temperature; \(t\) is time; \(u\) is the Darcy velocity; \(\nabla T\) is temperature gradient; \(q, q_0\) are the heat flux density; \(k_{\text{eff}}\) is effective thermal conductivity; and \(Q, Q_{\text{ed}}\) are the heat
source.

Solid heat conduction equation:

\[
d_j \rho C_p \frac{\partial T}{\partial t} + d_j \rho C_p u \nabla T + \nabla \cdot q = d_j Q + q_o + d_j Q_{ad}
\]

\[
q = -d_j k \nabla T
\]

where, \(d_j\) is model thickness (the system default value is 1 m); \(\rho\) is the density of granite; \(C_p\) is the heat capacity of granite; \(T\) is the temperature of granite; \(t\) is time; \(u\) is the Darcy velocity; \(q, q_o\) are the heat flux density; \(\nabla T\) is temperature gradient; \(k\) is thermal conductivity; and \(Q, Q_o, Q_{ad}\) are the heat source.

Fluid heat transfer equation:

\[
\rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_p + Q_{ad}
\]

\[
q = -k \nabla T
\]

where, \(\rho\) is the density of fluid; \(C_p\) is the heat capacity of fluid; \(u\) is the velocity of fluid; \(q\) is the heat flux density; \(\nabla T\) is temperature gradient; \(k\) is thermal conductivity; and \(Q, Q_p, Q_{ad}\) are the heat source.

\(k-\omega\) turbulence equation:

\[
\rho \frac{\partial k}{\partial t} + \rho (u \cdot \nabla) k = \nabla \cdot [(\mu + \mu_r \sigma_k) \nabla k] + p_k - \beta_0 \cdot \rho \omega k
\]

\[
\rho \frac{\partial \omega}{\partial t} + \rho (u \cdot \nabla) \omega = \nabla \cdot [(\mu + \mu_r \sigma_\omega) \nabla \omega] + \alpha \frac{\omega}{k} p_k - \rho \beta_0 \omega^2
\]

where, \(\rho\) is the density of fluid; \(k\) is the turbulence kinetic energy of the fluid; \(t\) is time; \(u\) is the velocity of fluid; \(\mu\) is the dynamic viscosity of fluid; \(\mu_T=\rho k/\omega\); \(p_k=\mu T\nabla u \cdot (\nabla u + (\nabla u)^T)\); \(\omega\) is the dissipation rate of the turbulence kinetic energy; \(\sigma_k, \sigma_\omega, \alpha, \beta_0\) are empirical constants.

2.3. Numerical model

The surrounding rock is selected in the range of 200m×200m to ensure that the outer boundary of the model is far enough from the roadway and will not be affected by heating and cooling within 15 years; the total length of the roadway is 1000m, the radius of a single straight circular roadway is 1.5m, and enhanced permeability and water filled zones are a 4.5m thick circular ring, referring to the aforementioned assumptions. In order to simplify the study, several pipes laid on the wall of the roadway with the diameter of 0.1m are equivalent to a 0.1m thick circular ring. The gridded volume is 106200m³ which consists of 5356 hexahedrons and 8788 prisms. The total number of units is 14144. In order to study the temperature changes in different areas, cut line 1 (x=0m, y=[-100, -1.5]m, z=500m) and cut line 2 (x=0m, y=[1.5, 100]m, z=500m) are selected. In order to study the temperature attenuation of the outlet of the heat exchange pipe, which is installed on the inner wall of the tunnel, point 1 (x=0m, y=1.45m, z=-500m) and point 2 (x=0m, y=-1.45m, z=-500m) are selected.
Figure 2. Diagram of discretization grids on surrounding rock of a circular roadway.

2.4. Simulation parameters and boundary conditions

Table 1. Simulation parameters of working fluid. [17]

| Material name | Parameter                           | Value          |
|---------------|-------------------------------------|----------------|
| Water         | Heat capacity [J·kg⁻¹·K⁻¹]          | 4174           |
|               | Initial density [kg/m³]             | 995.7          |
|               | Thermal conductivity [W·m⁻¹·K⁻¹]    | 0.618          |
|               | Initial dynamic viscosity [pa·s]    | 8.015×10⁻⁴     |
|               | Specific heat rate [-]              | 1              |

Table 2. Simulation parameters of rock. [18]

| Material name | Parameter                           | Value          |
|---------------|-------------------------------------|----------------|
| Granite       | Heat capacity [J·kg⁻¹·K⁻¹]          | 1000           |
|               | Density [kg/m³]                     | 2700           |
|               | Thermal conductivity [W·m⁻¹·K⁻¹]    | 2.8            |
|               | Maximum permeability [m²]           | 1.0×10⁻¹¹      |
|               | Maximum porosity [-]                | 0.15           |
|               | Thermal diffusivity [m²/d]          | 0.1134         |

The outer boundary of the model is set as thermal insulation and the temperature for the whole domain of surrounding rock is 250°C in the initial, except for the roadway wall where the temperature is the same as the temperature of the water flow in the pipe as the inner boundary condition. The inlet temperature of the pipe is 30°C, and the flow velocity is 0.05m/s. All walls in contact with fluid are assumed as non-slip boundaries. The properties of water when the water fluid temperature is between 273.15 and 533.15K are described as follows [19].
\[
\rho_{H_2O} = 838.5 + 1.4T \cdot 3.0 \times 10^5 T^2 + 3.7 \times 10^4 T^3 \\
\mu_{H_2O} = 1.4 - 0.02T + 1.4 \times 10^4 T^2 - 4.6 \times 10^7 T^3 + 8.9 \times 10^{10} T^4 - 9.1 \times 10^{13} T^5 + 3.8 \times 10^{16} T^6 , T \in [27315, 413.15] \\
\mu_{H_2O} = 0.004 - 2.1 \times 10^{-5} T + 3.9 \times 10^{-9} T^2 - 2.4 \times 10^{-11} T^3 , T \in [413.15, 533.15] \\
C_{p,H_2O} = 12010 - 807T + 0.3T^2 - 5.4 \times 10^4 T^3 + 3.6 \times 10^7 T^4 \\
\lambda_{H_2O} = -0.9 + 8.9 \times 10^{-3} T - 1.6 \times 10^{-5} T^2 + 7.9 \times 10^{-9} T^3 \\
\]

(6)

where, \(\rho_{H_2O} (\text{kg/m}^3)\) is the density of water; \(\mu_{H_2O} (\text{Pa} \cdot \text{s})\) is the dynamic viscosity of water; \(C_{p,H_2O} (\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1})\) is the heat capacity of water; \(\lambda_{H_2O} (\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1})\) is the thermal conductivity of water; and \(T (K)\) represents the temperature in Kelvin.

3. Simulation results
Since the inner wall of the roadway has a low temperature boundary of 30°C, the water temperature in vicinity of the wall within the damage zone of surrounding rock turns low and the density becomes high. The density difference causes the natural convection phenomenon to occur within the water flow under the action of buoyancy [20]. It can be seen from Figure 3 that the water flow is the fastest and the natural convection is the strongest inside the surrounding rock in vicinity of roadway wall. This is mainly because the temperature gradient, permeability and porosity of the roadway wall are the largest.

![Figure 3](image-url)  
(a) Velocity cloud graph when \(t=5\) years \((Z=500m)\); (b) Streamline diagram when \(t=5\) years \((Z=500m)\).

3.1. Comparison of natural convection and solid conduction heat transfers
It can be seen from Figure 4-5 that natural convection can extend the low-temperature boundary to the edge of the damage zone, and greatly improves the heat collection efficiency of the hot dry rock, compared with solid heat conduction. After the cold water is heated by the outer dry hot rock, it floats to the top of the damage zone. Moreover, the specific heat capacity of the water is greater than that of the granite, so the temperature drop at the top of the damaged zone is slightly lower than the solid heat conduction. To sum up, natural convection improves the heat collection speed of hot dry rocks.

It can be seen from Figure 6-7 that at the same water flow velocity, natural convection can effectively maintain the water flow temperature in the pipe at the top of the roadway, and the temperature decays more slowly. This is because natural convection enhances the heat transfer inside
the hot dry rock. In addition, natural convection makes the temperature of the water outlet in the pipe at the bottom of the roadway lower, which is mainly due to the accumulation of cold water at the bottom of the roadway.

Figure 4. (a)–(c) are temperature cloud diagrams of natural convection when \( t = 1, 5, 15 \) years \((Z=500m)\); (d)–(f) are temperature cloud diagrams of solid heat conduction when \( t = 1, 5, 15 \) years \((Z=500m)\).

Figure 5. (a)–(b) respectively are temperature change curve at cutline 1 and cutline 2 when \( t = 15 \) years \((Z=500m)\).
3.2. Parameter sensitivity analysis

3.2.1. Permeability

In this part, we have selected 6 different linear permeability (Note: the permeability and porosity in the excavation damage zone of surrounding rock obey linear distribution, which gradually descend from the maximum values at the excavated wall as the inner boundary over to zero where the outer boundary is defined). The maximum values of the six linear permeability are $1 \times 10^{-10}$, $5 \times 10^{-11}$, $1 \times 10^{-11}$, $5 \times 10^{-12}$, $1 \times 10^{-12}$ and $1 \times 10^{-13}$ m$^2$. Other simulation parameters are the same as before (as shown in Table 1 and Table 2). The temperature change curve with 6 different linear permeability at cutline 1 are shown in the figure 8.

It can be seen from Figure 8 that permeability of hot dry rock has a very important influence on the natural convection in the damage zone of the surrounding rock. When the permeability of hot dry rock is higher than $1 \times 10^{-12}$ m$^2$, natural convection occurs in the damaged zone of surrounding rock.
3.2.2. Temperature gradient

In this part, we have selected 3 different inlet temperatures, respectively 30°C 、 50°C 、 80°C. Other simulation parameters are the same as before (as shown in Table 1 and Table 2). The temperature change curve at cutline 1(t=15 years) are shown in the figure 9.

It can be seen from Figure 9 that temperature gradient has a very important influence on the heat transfer efficiency. As the distance from the roadway wall increases, the heat transfer effect gradually decreases. This is mainly because the solid heat transfer efficiency of the outer dry hot rock is lower than that of natural convection, so the effect of different temperature gradients on the heat transfer efficiency is weakened in the place far away from the roadway wall.

3.2.3. Water velocity

In this part, we have selected 3 different flow rates, respectively 0.1m/s 、 0.05m/s 、 0.01m/s. Other simulation parameters are the same as before (as shown in Table 1 and Table 2). The temperature change curve at point 1 and point 2(t=15 years) are shown in the figure 10.

It can be seen from Figure 10 that due to the slow thermal compensation of the surrounding rock mass, water velocity has a very important influence on the Outlet temperature. Adjusting the speed of the water flow inside the pipe can effectively control the temperature of the water outlet to maintain it within a certain range.
4. Conclusions

(1) This article uses COMSOL Multiphysics software to conduct a heat-fluid coupling study on the roadway damage zone in the excavation-enhanced geothermal system (EGS-E). The results show that natural convection improves the heat transfer efficiency of the roadway damage zone.

(2) When the permeability of hot dry rock is higher than $1 \times 10^{-12} \text{ m}^2$, natural convection will occur inside the damage zone.

(3) The greater the temperature gradient, the higher the heat transfer efficiency of natural convection. However, as the distance from the roadway wall increases, the influence of natural convection gradually weakens.

(4) Due to the low solid heat conduction efficiency of the surrounding dry hot rock, adjusting the speed of the water flow inside the pipe can effectively control the temperature of the water outlet to maintain it within a certain range.

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