International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Fluid flow and heat transfer behaviors of fractured rock sample: physical test

Jiacheng Wang, Zhihong Zhao*, Yaoyao Zhao
Department of Civil Engineering, Tsinghua University, Beijing, China
zhzhao@tsinghua.edu.cn

Abstract

An in-depth insight into fluid flow and heat transfer processes of water through the rock fracture is essential for the utilization of geothermal energy from high-temperature reservoirs. Fractures in natural rocks often exist in the form of networks. However, research on fluid flow and heat transfer characteristics in the single fracture is the basis of studying the reservoir with complex fracture networks.

In this study, an innovative system of fluid flow and heat transfer test was developed, which could simulate the whole process of the geothermal engineering. The large-scale rock sample (200 mm × 200 mm × 200 mm) with a horizontal smooth parallel-plate fracture was used. A total of 16 temperature sensors were distributed around the fracture to observe the variation of rock temperature. Meanwhile, various types of test data were monitered. A thermo-hydro-mechanical coupled numerical model was calibrated using the test data, in order to further explain the evolution processes of temperature and flow fields inside the rock.

The test and simulation results of the flow rate and temperature distribution agreed well, thereby confirming that the established numerical model was reliable. Combining the test data and numerical simulation, the results show that the flow rate initially increases and then slightly decreases due to the combined effects of the nonlinear viscosity of water and the thermal expansion of the rock, and the rock temperature increases and stabilizes gradually with the high-temperature zone forming and expanding. Besides, the results clarify the significance of taking the thermo-hydro-mechanical coupling effects into account when investigating the characteristics in the fractured rock.

This test can be viewed as a valuable reference for the following researches. Applying this test system, fluid flow and heat transfer characteristics of rock samples with fracture networks under high-temperature environment and different stress paths can be further studied.

Keywords

Heat transfer, Fluid flow, Rock fracture, Physical test, Large-scale

ISRM

NBG

1 Introduction

Geothermal water production from deep reservoirs has been mainly used for space heating worldwide, and reinjection of production water into geothermal reservoirs after utilization has become a common practice to ensure the sustainable utilization of geothermal energy. In both conventional geothermal reservoirs and Enhanced Geothermal Systems (EGS), the heat stored in reservoirs are extracted by fluid flowing through the fractures. A comprehensive understanding of fluid flow and heat transfer behaviors in fractures is of great significance for optimizing heat extraction performance. Fractures in natural rocks often exist in the form of networks, but research on fluid flow and heat transfer characteristics in the single fracture is the basis of studying the reservoir with complex fracture networks. At present, researchers have conducted in-depth research on fluid flow and heat transfer characteristics in the fracture through analytical method, experimental method and numerical simulation method.

In experimental research, Zhao (1999) first began to study the hydro-thermal properties of rock fractures. Lu and Xiang (2012) conducted experiments of saturated water flow and heat transfer for a meter-scale model of regularly fractured granite. Huang et al. (2021) applied two cement mortar specimens based on 3D printing technology to analyze the effects of fracture roughness on fluid flow and heat transfer. Jilin University manufactured a hot dry rock laboratory simulation system, which was suitable for cylindrical rock samples, and did a series of studies including rough fractures (Huang et al. 2019), hydraulic fractures (Ma et al. 2019), and intersecting fractures (Ma et al. 2023). However, due to the limitation of experimental conditions, it is difficult to obtain the temperature distribution inside the fractured rock and study the complex conditions by experiment. Some researchers establish corresponding numerical models on the basis of experimental studies, so as to further analyze the fluid flow and heat transfer characteristics. Bai et al. (2016) investigated the local heat transfer coefficient of water flowing through a single fracture within a cylindrical granite specimen under confining pressure by combining the numerical modeling approach and the experimental results. Chen et al. (2018) obtained an equivalent heat transfer coefficient from numerical experiments with respect to the flow rate, mechanical aperture and the equivalent hydraulic aperture. Yao et al. (2020) presented a heat-flow coupling model for simulation of heat transfer process in complex fractured rock masses considering non-Darcy flow. Liu et al. (2021) compared the differences between three-dimensional and two-dimensional numerical models for single rock fractures in terms of fluid flow and heat transfer behaviors.

However, currernt studies on fluid flow and heat transfer characteristics in the fracture were often simplifications of the geothermal engineering. For tests, small-scale samples were used, and only limited data were available. Besides, most of the simulation studies were focused on coupled thermo-hydro modeling, with less consideration of mechanical field. This study aims to conduct the whole process of the geothermal engineering, from injection to fluid flow in the fracture, then to production. An innovative system of fluid flow and heat transfer test was developed, and various sensors were distributed in the large-scale rock sample, so that rich data could be acquired with time during the test. Then, a thermo-hydro-mechanical coupled numerical model was calibrated using the test data, which could better explain the evolution processes of temperature and flow fields inside the rock.

2 Test system

2.1 Sample preparation

Granite samples of 200 mm × 200 mm × 200 mm are usually used. The sample is processed by wire cutting (or Brazilian splitting test) into an upper and a lower half block, each with the size of 200 mm × 200 mm × 100 mm (Fig. 1a). A total of 18 holes with a diameter of 5 mm are drilled vertically downward on the upper half block. Among these, 16 holes have a depth of 95 mm to arrange temperature sensors, and 2 holes penetrate through the upper half block for water inlet and outlet. The 16 holes (T1~T16) for temperature sensors are equally spaced in both directions, and the distance between the centers of holes is 40 mm. The holes for water inlet and outlet are spaced 80 mm apart.

In addition, grooves are carved on the bottom surface of the upper half block and the top surface of the lower half block (Fig. 1b), 10 mm away from the edge of the sample, and the width and depth of the grooves are both 10 mm. A silicone rubber gasket with a cross-section of 8 mm × 23 mm will be placed in the groove. Tests have shown that good sealing can be achieved under relatively low axial pressure, so that the water in the fracture is not connected with the outside. Meanwhile, this method of sample preparation can also ensure the integrity of the internal fracture surface to a certain extent.

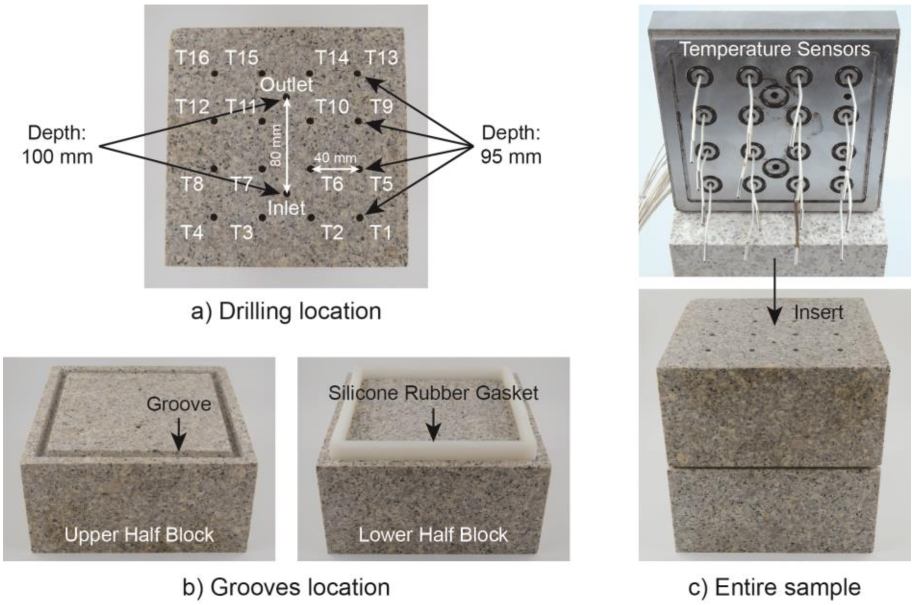

Fig. 1 Sample preparation process.

2.2 Main component

This study utilizes the Physical Test System for Multi-field Coupling Effects newly developed by Tsinghua University (Fig. 2), and the schematic diagram is shown in Fig. 3. The test system can simulate the fluid flow and heat transfer behaviors caused by the injection of high-temperature water into low-temperature rock fracture or low-temperature water into high-temperature rock fracture under high-pressure conditions. The test system mainly consists of a sample clamping subsystem, a fluid pressurization subsystem, and a data acquisition subsystem.

Fig. 2 Physical Test System for Multi-field Coupling Effects newly developed by Tsinghua University.

The sample clamping subsystem is the place where fluid flow and heat transfer occur within the rock fracture. 16 temperature sensors are fixed in the upper metal plate, and temperature probes are inserted into the interior of the sample, so that temperature distribution around the rock fracture can be monitored in real time. In addition, the triaxial pressure chamber provides the target pressure and temperature. An AC servo motor is used to apply pressure of 0~500 kN with an accuracy of ±0.05%. The pressure in X, Y, and Z directions can be controlled independently. Water bath heating is used to maintain the sample temperature at a constant value to simulate the real environmental temperature.

The fluid pressurization subsystem consists of water tanks and a plunger type pump. The water tanks are divided into a hot water tank, a cold water tank, and a tail water tank, where the hot and cold water tanks are used to maintain the temperature of the injected water, and the tail water tank is used to collect the tail water from the outlet. This plunger type pump can provide water pressure of 0~5 MPa with an accuracy of ±0.03%. A constant pressure mode is used to provide fluid flow conditions for the rock fracture in this study.

The data acquisition subsystem consists of temperature sensors, flow sensors, data collector and display screen. A total of 19 temperature sensors are arranged, of which 16 temperature sensors are located inside the rock (T1~T16), 2 temperature sensors are located in the inlet and outlet, and 1 temperature sensor is located in the triaxial pressure chamber for monitoring the water bath heating temperature. PT100 type sensors are used to measure the temperature, with a range of -50~250 ℃ and an accuracy of ±1 ℃. Flow meters are installed at inlet and outlet pipes with a range of 8~250 L/h and an accuracy of ±0.5%. In addition, the AC servo motor and plunger type pump can monitor the triaxial pressure and water pressure. During the test, the internal temperature of the sample, the temperature of triaxial pressure chamber, the temperature and flow rate of the inlet and outlet, the triaxial pressure, and the fluid pressure data are recorded through the collector and displayed on the screen in real time.

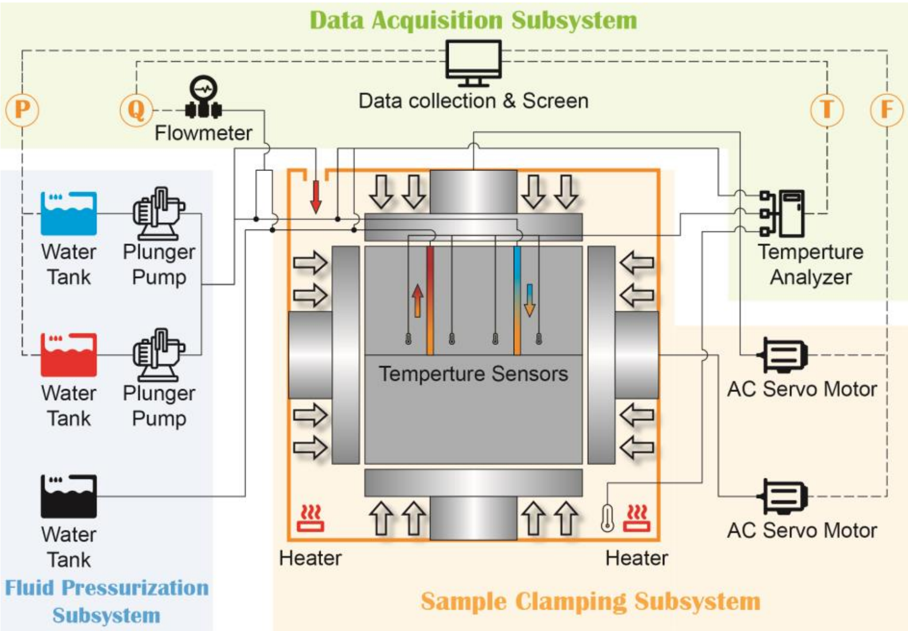

Fig. 3 Schematic diagram of the test system.

2.3 Test procedure

The fluid flow and heat transfer processes were investigated using the sample with a horizontal smooth parallel-plate fracture. In this study, a basic test was conducted. The axial pressure was 20 kN and the water pressure was 500 kPa. It was noted that the pressure loss due to the pipes of the test system has been considered. The temperature of the hot water tank was 90 ℃. Because of the temperature loss of the inlet pipe, the temperature of the injection well was about 80 ℃. Besides, the environmental temperature of the rock sample was about 10 ℃. This test can be viewed as a pioneering research. Applying this test system, fluid flow and heat transfer characteristics of rock samples with fracture networks under high-temperature environment and different stress paths can be further studied.

The specific test steps are as follows:

1. Place the silicone rubber gasket in the groove of the lower block, and put the upper block on them.

2. Insert the 16 temperature sensors into the fractured sample which has been drilled.

3. Place the assembled sample into the triaxial pressure chamber, and start heating the hot water tank to the target value.

4. After the water temperature of the hot water tank stabilizes, open the valve to allow the hot water to flow through the inlet pipe and drain into the tail water tank.

5. After the water temperature of the inlet stabilizes, apply axial pressure to the target value.

6. After the axial pressure stabilizes, switch the valve, and apply water pressure to the target value. The hot water starts to flow into the sample.

7. Start the test, monitor and record various types of data in real-time.

3 Numerical simulation

The numerical model of the rock sample is exactly the same as the test, including the upper and lower half blocks, as well as the inlet and outlet holes, which represent the injection and production wells. Besides, 16 points representing temperature sensors are also considered in the model.

3.1 Coupled thermo-hydro-mechanical modeling

Fracture is approximated by a pair of surfaces, in which fluid flow is described by the continuity equation (Eq. 1) and the tangential version of Darcy's law (Eq. 2). Heat transport in the fracture is described by the convection-diffusion equation (Eq. 3). And the fracture displacement of normal direction is described as Eq. 4. More technical details can be found in the authors' previous publications (Ma et al. 2022).

$$\rho_{\mathrm{f}} S_{\mathrm{fr}} d_{\mathrm{fr}} \frac{\partial p_{\mathrm{fr}}}{\partial t} + \nabla_{\mathrm{T}} \cdot (d_{\mathrm{fr}} \rho_{\mathrm{f}} \mathbf{u}_{\mathrm{fr}}) = f_{\mathrm{Q}} \tag{1}$$

$$\mathbf{u}_{\mathrm{fr}} = -\frac{{d_{\mathrm{fr}}}^2}{12\mu} (\nabla_{\mathrm{T}} p_{\mathrm{fr}} - \rho_{\mathrm{f}} \mathbf{g}) \tag{2}$$

$$d_{\mathrm{fr}} (\rho_i C_i)_{\mathrm{eff}} \frac{\partial T}{\partial t} + d_{\mathrm{fr}} \rho_{\mathrm{f}} C_{\mathrm{f}} \mathbf{u}_{\mathrm{fr}} \cdot \nabla_{\mathrm{T}} T = \nabla_{\mathrm{T}} \cdot (k_{\mathrm{eff}} \nabla_{\mathrm{T}} T) + f_{\mathrm{T}} \tag{3}$$

$$\sigma_{\mathrm{n}}' = \sigma_{\mathrm{n}} - p_{\mathrm{fr}} = K_{\mathrm{n}} u_{\mathrm{n}} \tag{4}$$

Where

Where	ρ_{f}	Fluid density
	S_{fr}	Storage coefficient of fracture
	d_{fr}	Fracture aperture
	p_{fr}	Fluid pressure
	t	Time
	$\mathbf{u}_{\mathrm{fr}}$	Darcy's velocity vector in fracture
	f_{Q}	Lateral exchange of fluid between fracture and reservoir rock
	μ	Fluid viscosity
	$\mathbf{g}$	Gravity vector
	$(\rho_i C_i)_{\mathrm{eff}}$	Effective volumetric heat capacity of the fracture-fluid mixture
	T	Temperature
	C_{f}	Specific heat capacity of fluid
	k_{eff}	Effective thermal conductivity of the fracture-fluid mixture
	f_{T}	Received out-of-plane heat flux
	σ_{n}'	Effective stress of normal direction
	σ_{n}	Stress of normal direction
	K_{n}	Stiffness of normal direction
	u_{n}	Displacement of normal direction

3.2 Model setup

Fig. 4 shows the numerical model of the fractured rock sample. For fluid flow, all boundaries are impermeable. For heat transfer, the indoor temperature is defined as the initial temperature field in the rock sample, and all boundaries consider the thermal convection between the sample and external environment, with a heat transfer coefficient of 15 W/(m^2·K). For geomechanics process, axial stress is applied on the top boundary. The lateral boundaries are free, and the bottom boundary is fixed (Fig. 4a). The properties of the sample are presented in Table 1. In this study, the nonlinear relationship between viscosity and temperature of water is considered.

After setting up the coupled thermo-hydro-mechanical processes as well as the boundary and initial conditions, meshing is performed (Fig. 4b). The rock sample is discretized into finite triangular prism elements, and the computational domain consists of approximately 50,360 elements in this study.

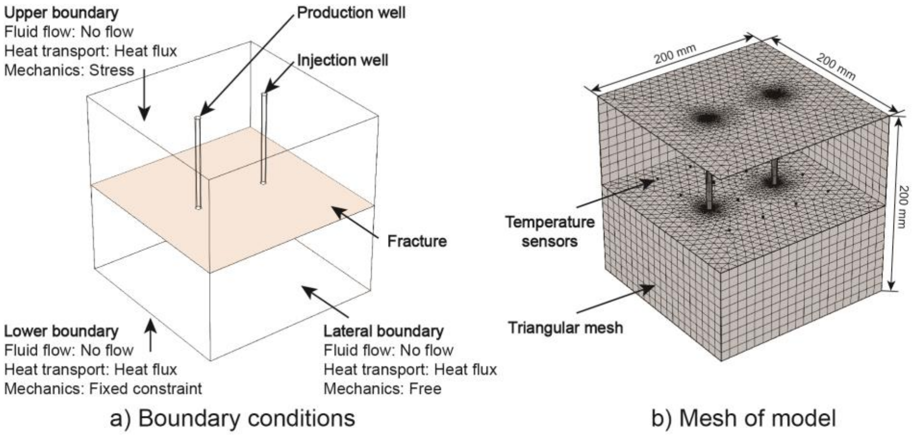

Fig. 4 Numerical model of the fractured rock sample.

Table 1 Input parameters of the fractured rock sample

Rock parameter	Value	Fracture parameter	Value
Density	2520 kg/m^3	Aperture	0.088 mm
Porosity	0.005	Normal stiffness	80 GPa/m
Heat capacity	1200 J/(kg·K)	Shear stiffness	40 GPa/m
Thermal conductivity	3 W/(m·K)		
Poison's ratio	0.2		
Thermal expansion coefficient	5×10^{-6} 1/K		
Young's Modulus	100 GPa		

4 Results

The test lasted for 180 minutes. During the test, the values of temperature sensors and flow meters were monitored in real time. In the following text, the characteristics of fluid flow and heat transfer were analyzed, by combining the test data and numerical simulation results. The temperature distribution around the fracture and the flow rates of the inlet and outlet were used to calibrated the model, and then the mechanical deformation characteristics were analyzed.

4.1 Fluid flow characteristics

The comparison between the flow rates obtained by the test and simulation could be used to verify the correctness of the numerical model. Fig. 5 displays the inlet flow rates obtained through these two methods. The test and simulation results agreed well, thereby confirming that the established numerical model was correct and reliable. Due to the good sealing of the gasket, the flow rates of the inlet and outlet were very close.

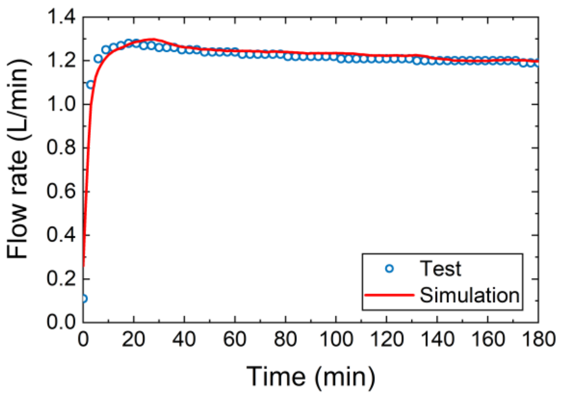

Fig. 5 Comparison of the inlet flow rates obtained by the test and simulation.

Fig. 5 demonstrates that the flow rate initially increases and then slightly decreases. Resulting from the rapid decrease in viscosity of water with increasing temperature, the flow rate increased in the initial stage according to Darcy's Law. With the continuous injection of hot water, the thermal expansion of the rock around the fracture caused the closure of the fracture, which could be seen in Fig. 8. Hence, the flow rate decreased slowly in the later stage.

4.2 Heat transfer characteristics

A total of 16 temperature sensors (T1~T16) were distributed around the fracture. Fig. 6 shows the comparisons of T1, T2, T3 and T4 obtained by the test and simulation. The temperature curves agreed well. Because of the space limitation, the other 12 temperature sensors had similar comparison results. Due to the fact that the processed fracture in the test was not real smooth parallel-plate, and the numerical model could not set the actual environmental conditions, there were deviations in temperature curves between the test and simulation.

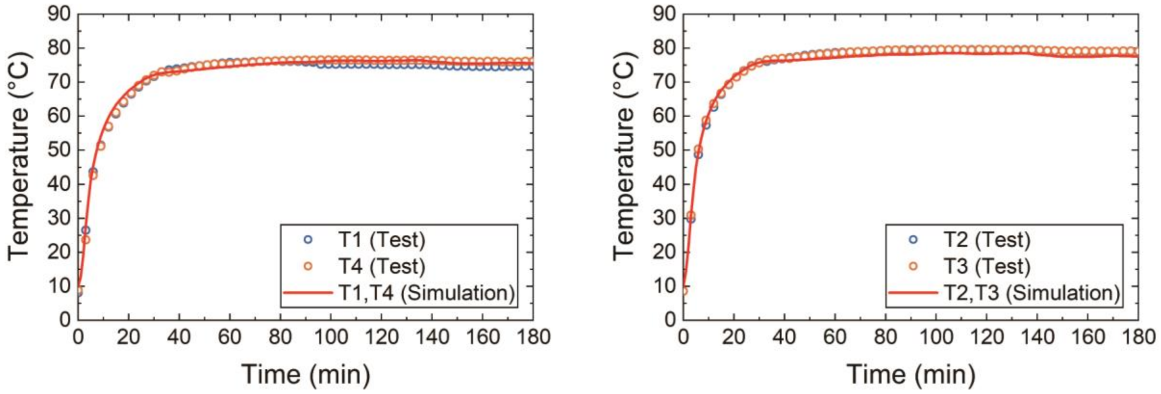

Fig. 6 Comparison of temperature sensors (T1, T2, T3 and T4) obtained by the test and simulation.

Temperature variation in the fractured rock at different times is presented in Fig. 7. The rock temperature increased and stabilized gradually, and the high-temperature zone formed and expanded with heat conduction. The effect of heat convection was considerably strong in the fracture because of the high flow velocity, which was several orders of magnitude larger than that in the rock. In this study, we considered the thermal convection between the sample and external environment, so that the temperature of boundaries were relatively low.

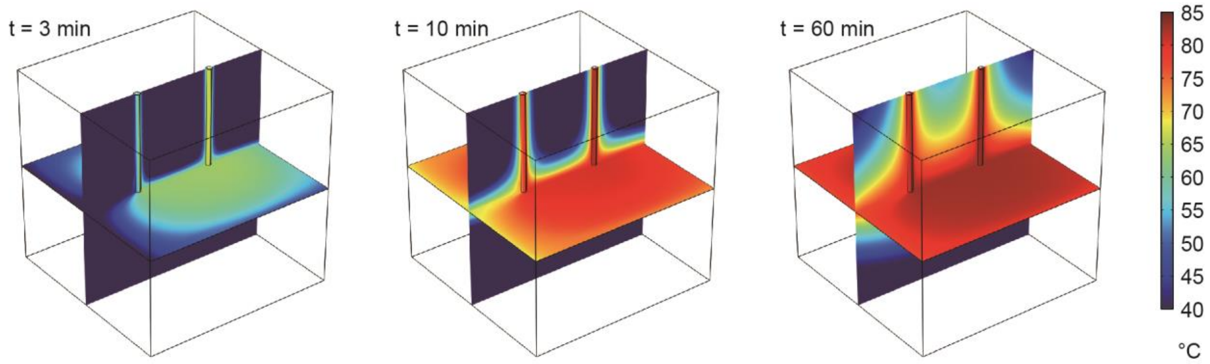

Fig. 7 Evolution of temperature in the fractured rock sample from numerical simulation.

4.3 Mechanical deformation characteristics

As for mechanical field, it focused more on the fracture aperture and effective stress. Fig. 8 displays the evolution of the fracture aperture using coupled thermo-hydro-mechanical rock model. The results clarify the significance of taking the THM coupling effects and thermal expansion for material into account when investigating the fluid flow and heat transfer characteristics in the fractured rock.

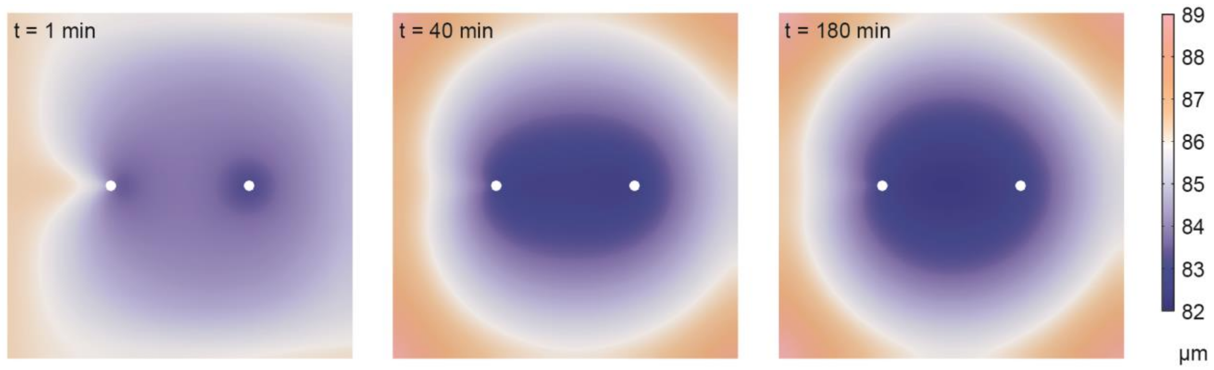

Fig. 8 Evolution of fracture aperture from numerical simulation.

5 Conclusion

In this study, an innovative system of fluid flow and heat transfer test was developed, and the large-scale rock sample with a horizontal smooth parallel-plate fracture was used. A total of 16 temperature sensors were distributed around the fracture to observe the variation of rock temperature with time. Then, a thermo-hydro-mechanical coupled numerical model was calibrated using the test data. Combining the test data and numerical simulation, the results show that the flow rate initially increases and then slightly decreases due to the combined effects of the nonlinear viscosity of water and the thermal expansion of the rock, and the rock temperature increases and stabilizes gradually with the high-temperature zone forming and expanding. Besides, the results clarify the significance of taking the thermo-hydro-mechanical coupling effects into account when investigating the characteristics in the fractured rock. Applying this test system, fluid flow and heat transfer characteristics of rock samples with fracture networks under high-temperature environment and different stress paths can be further studied.

References

Zhao J (1999) Experimental study of flow-rock heat transfer in rock fractures. Chinese Journal of Rock Mechanics and Engineering (2): 119-123.

Lu W, Xiang Y (2012) Experiments and sensitivity analyses for heat transfer in a meter-scale regularly fractured granite model with water flow. Journal of Zhejiang University SCIENCE A (12): 958-968. DOI:10.1631/jzus.A1200153.

Bai B, He Y, Li X, Hu S, Huang X, Li J, Zhu J (2016) Local heat transfer characteristics of water flowing through a single fracture within a cylindrical granite specimen. Environmental Earth Sciences: 1-16. DOI:10.1007/s12665-016-6249-2.

Chen Y, Ma G, Wang H (2018) Heat extraction mechanism in a geothermal reservoir with rough-walled fracture networks. International Journal of Heat and Mass Transfer: 1083-1093. DOI:10.1016/j.ijheatmasstransfer.2018.05.103.

Huang Y, Zhang Y, Yu Z, Ma Y, Zhang C (2019) Experimental investigation of seepage and heat transfer in rough fractures for enhanced geothermal systems. Renewable Energy: 846-855. DOI:10.1016/j.renene.2018.12.063.

Ma Y, Zhang Y, Huang Y, Zhang Y, Hu Z (2019) Experimental study on flow and heat transfer characteristics of water flowing through a rock fracture induced by hydraulic fracturing for an enhanced geothermal system. Applied Thermal Engineering: 433-441. DOI:10.1016/j.applthermaleng.2019.03.114.

Yao C, Shao Y, Yang J, Huang F, He C, Jiang Q, Zhou C (2020) Effects of non-darcy flow on heat-flow coupling process in complex fractured rock masses. Journal of Natural Gas Science and Engineering: 103536. DOI:10.1016/j.jngse.2020.103536.

Huang Y, Zhang Y, Gao X, Ma Y, Hu Z (2021) Experimental and numerical investigation of seepage and heat transfer in rough single fracture for thermal reservoir. Geothermics: 102163. DOI:10.1016/j.geothermics.2021.102163.

Liu G, Zhao Z, Chen Y, Ma F, Wang G (2021) Comparison between typical numerical models for fluid flow and heat transfer through single rock fractures. Computers and Geotechnics: 104341. DOI:10.1016/j.compgeo.2021.104341.

Ma F, Liu G, Zhao Z, Xu H, Wang G (2022) Coupled Thermo-Hydro-Mechanical modeling on the Rongcheng geothermal field, China. Rock Mechanics and Rock Engineering (8): 5209-5233. DOI:10.1007/s00603-022-02914-8.

Ma Y, Gan Q, Zhang Y, Huang Y (2023) Experimental research on the heat transfer characteristics of fluid flowing through rock with intersecting fractures. Geothermics: 102587. DOI:10.1016/j.geothermics.2022.102587.