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

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Abstract

An in-depth understanding of fluid flow and heat transfer behaviors in fractures is of great significance for optimizing heat extraction performance. Research on fluid flow and heat transfer characteristics in the single fracture is fundamental to study the reservoir with intersected fractures.

In this study, an innovative system of fluid flow and heat transfer test was newly developed. The large-scale rock sample (200 mm × 200 mm × 200 mm) with a horizontal smooth parallel-plate fracture was used. A total of 16 sensors were positioned around the fracture to observe the variation of rock temperature. A basic test was carried out and various types of data were monitored. Then, a thermo-hydro-mechanical coupled numerical model was calibrated based on the test data.

The flow rates and temperature distributions obtained by the test and simulations agreed well, thereby confirming that the established numerical model was reliable. 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 heat conduction. Besides, the results clarify the significance of considering the thermo-hydro-mechanical coupling effects 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 varying stress paths can be further studied.

Keywords

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

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1 Introduction

Geothermal energy, as a renewable and clean energy source, is primarily extracted from deep reservoirs for space heating on a global scale, and reinjection of production water after utilization has become a common practice to ensure the sustainable development. 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 fundamental to study the reservoir with intersected fractures. Currently, extensive studies have been conducted on these processes using analytical method, experimental method and numerical simulation method.

For experimental research, Zhao (1999) have studied the hydro-thermo 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. In addition, fluid flow and heat transfer characteristics of rock samples with rough fractures (Huang et al. 2019, 2021), hydraulic fractures (Ma et al. 2019), and intersected fractures (Ma et al. 2023) were performed by the system which had 6 temperature sensors at the external wall of the sample. 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. Numerical models corresponding to the experimental studies were established, to further analyze the fluid flow and heat transfer characteristics (Huang et al. 2021). Besides, fracture networks were also built to analyze the flow and heat transfer processes (Chen et al. 2018; Yao et al. 2020). However, current studies on fluid flow and heat transfer characteristics in the fracture were often simplifications of the geothermal engineering. For test, small-scale samples were used, and only limited data were available. For numerical simulation, most studies were focused on the coupled thermo-hydro modelling, with less consideration of mechanical deformation.

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 positioned in the large-scale granite rock sample, so that rich data could be acquired during the test. Then, a thermo-hydro-mechanical coupled numerical model was calibrated using the test data, which better explained the evolution processes 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), located 10 mm from the sample edge, 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 is placed in the groove. Tests show that good sealing can be achieved under relatively low axial pressure, preventing water in the fracture from connecting with the outside. Meanwhile, this preparation method also ensures the integrity of the internal fracture surface.

2.2 Main components

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.

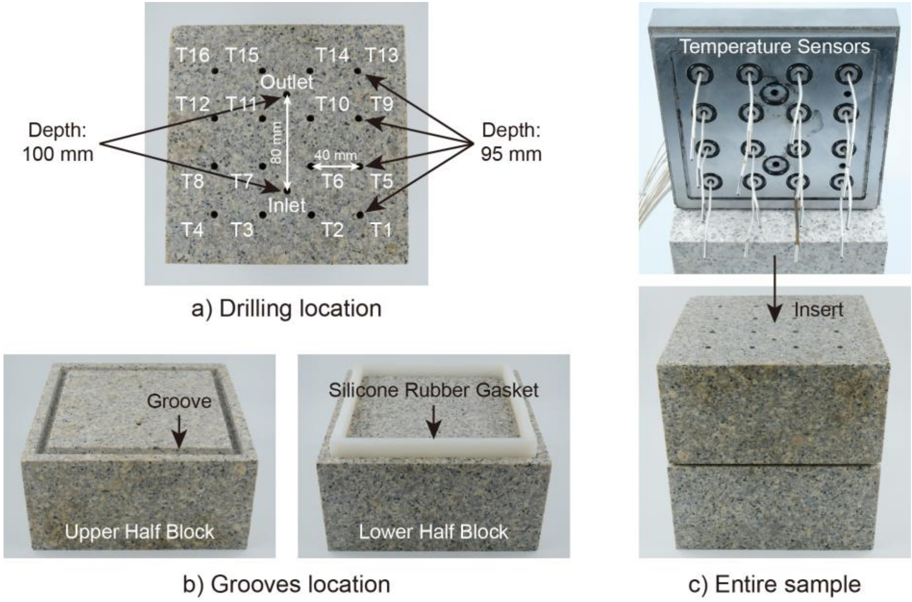

Fig. 1 Sample preparation process.

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 on the upper metal plate, and temperature probes are inserted into the interior of the sample (Fig. 1c), so that the 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. And water bath heating is used to maintain the sample temperature at a constant value to simulate the real environmental conditions.

The fluid pressurization subsystem consists of water tanks and a plunger type pump. The water tanks include 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 in this study.

The data acquisition subsystem consists of temperature sensors, flowmeters, a data collector and a display screen. A total of 21 temperature sensors are arranged, of which 16 temperature sensors are located inside the rock (T1 - T16), 2 sensors are located at the inlet and outlet, 1 temperature sensor is located in the triaxial pressure chamber for monitoring the water bath heating temperature, and 2 temperature sensors are located in the hot and cold water tanks, respectively. PT100 type sensors are used to measure the temperature, with a range of -50 - 250 ℃ and an accuracy of ±1 ℃. Flowmeters are installed at the inlet and outlet pipes with a range of 8 - 250 L/h and an accuracy of ±0.5%. In addition, the triaxial pressure and the fluid pressure can be monitored. During the test, the internal temperature of the sample, the temperatures of the triaxial pressure chamber and the water tanks, the temperatures and flow rates at 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.

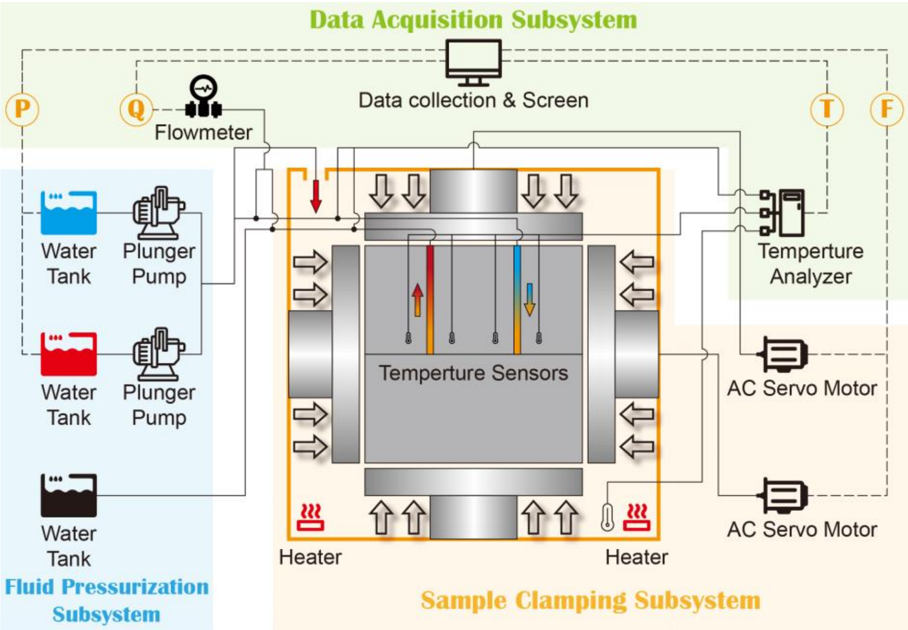

Fig. 3 Schematic diagram of the test system.

2.3 Test procedure

In this study, the fluid flow and heat transfer processes were investigated using the sample with a horizontal smooth parallel-plate fracture. The axial pressure was 20 kN and the water pressure was 500 kPa, for a duration of 180 minutes. It was noted that the pressure loss due to the pipes has been considered. The temperature of the hot water tank was 90 ℃. Because of the heat loss in the inlet pipe, the temperature at the inlet was about 85 ℃. 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 varying 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 temperature 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, thereby preheating the pipes.

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

6. After the axial pressure stabilizes, switch the valve, and apply the 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 the temperature sensors are also considered in the model.

3.1 Coupled thermo-hydro-mechanical modelling

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 transfer is described by the convection-diffusion equation (Eq. 3). And the fracture displacement of normal direction is described as Eq. 4. More details can be found in the authors' previous publications (Ma et al. 2022). In this study, the finite element software, COMSOL Multiphysics, is used to solve the governing equations.

$$\rho_f S_{fr} d_{fr} \frac{\partial p_{fr}}{\partial t} + \nabla_T \cdot (d_{fr}\rho_f \mathbf{u}_{fr}) = f_Q \tag{1}$$

$$\mathbf{u}_{fr} = -\frac{{d_{fr}}^2}{12\mu}(\nabla_T p_{fr} - \rho_f \mathbf{g}) \tag{2}$$

$$d_{fr}(\rho_i C_i)_{eff} \frac{\partial T}{\partial t} + d_{fr}\rho_f C_f \mathbf{u}_{fr} \cdot \nabla_T T = \nabla_T \cdot (k_{eff} \nabla_T T) + f_T \tag{3}$$

$$\sigma_n' = \sigma_n - p_{fr} = K_n u_n \tag{4}$$

Where	ρ_f	Fluid density
	S_{fr}	Storage coefficient of fracture
	d_{fr}	Fracture aperture
	p_{fr}	Fluid pressure
	t	Time
	$\mathbf{u}_{fr}$	Darcy's velocity vector in fracture
	f_Q	Lateral exchange of fluid between fracture and rock
	μ	Fluid viscosity
	$\mathbf{g}$	Gravity vector
	$(\rho_i C_i)_{eff}$	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 sample. For fluid flow, all boundaries are impermeable. For heat transfer, the indoor temperature is defined as the initial temperature, and all boundaries consider the heat convection between the sample and the 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 are presented in Table 1. In this study, the dynamic viscosity of water is nonlinearly related to temperature.

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.

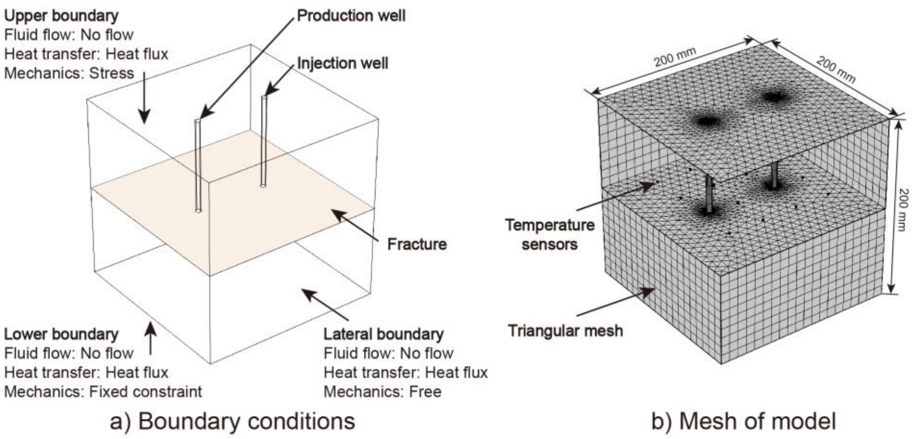

Fig. 4 Numerical model of the fractured rock sample.

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 flowmeters were monitored. In the following text, the characteristics of fluid flow and heat transfer were analyzed, by combining the test and simulation data. The temperature distribution around the fracture and the flow rates at the inlet and outlet were used to calibrated the model, using two primary measures, including R-Square (R^2) and mean absolute error (*MAE*). Subsequently, the mechanical 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 from these two methods. The values of R^2 and *MAE* were 0.96 and 0.02 L/min respectively. This indicated that the test and simulation results agreed well, thereby confirming that the established numerical model was reliable. Due to the good sealing of the gasket, the flow rates at the inlet and outlet were very close.

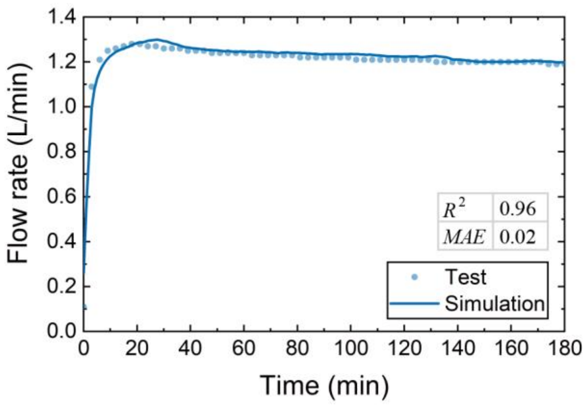

Fig. 5 Comparison of the inlet flow rates obtained by the test and simulation.

Fig. 5 demonstrates that the flow rate initially increases in the first 30 minutes 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 the Darcy's Law. With the continuous injection of hot water, the thermal expansion of the rock around the fracture caused its closure, 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 positioned around the fracture. Fig. 6a presents the temperature curves of these sensors over time obtained by the test. The temperature difference between the highest and lowest values is approximately 8 ℃. In the central area (T6, T7, T10 and T11), the temperature was relatively higher than that at the four corners (T1, T4, T13 and T16).

Fig. 6 also shows the comparisons of T1, T4, T10 and T11 obtained by the test and simulation. The temperature curves agreed well, with R^2 values exceeding 0.95. Because of the space limitation, the other 12 temperature sensors had similar comparison results and were not presented here. Due to the fact that the processed fracture in the test was non-ideal 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.

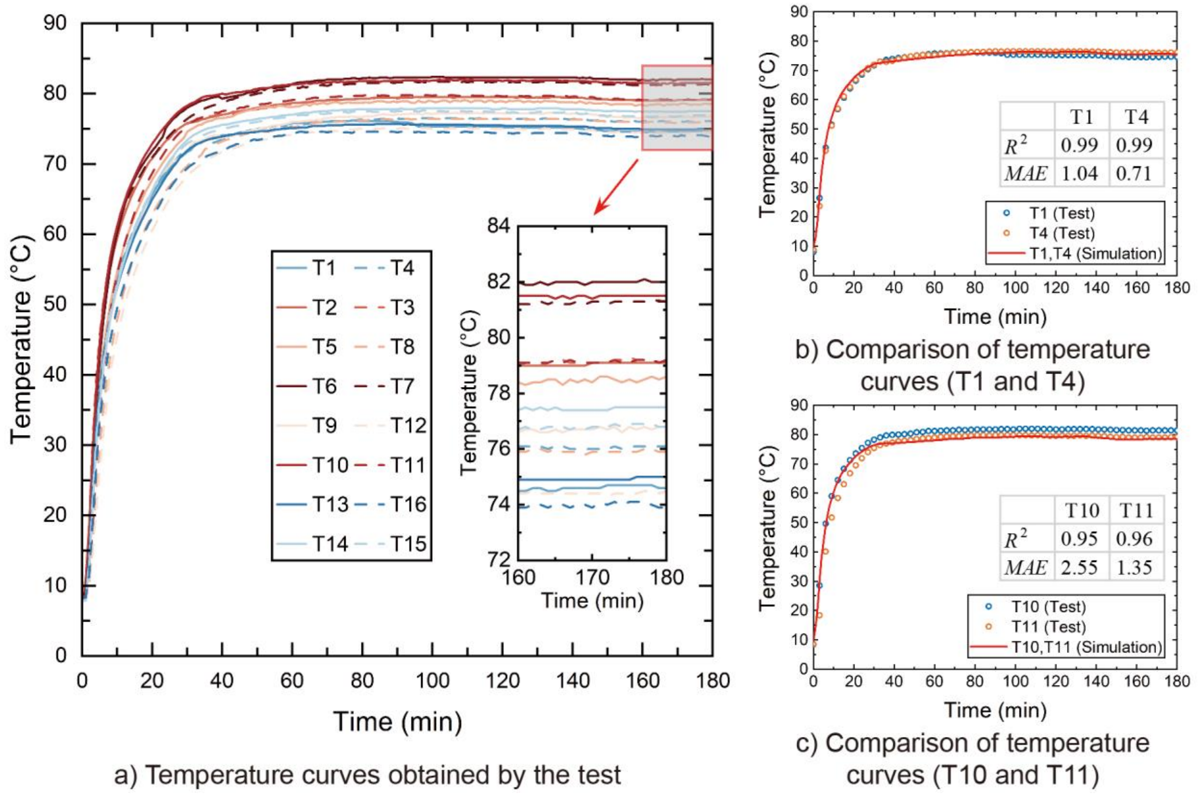

Fig. 6 Temperature curves of the sensors.

Temperature variations in the fractured rock at different times are 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 heat convection between the sample and the external environment, so that the temperature of boundaries was relatively low.

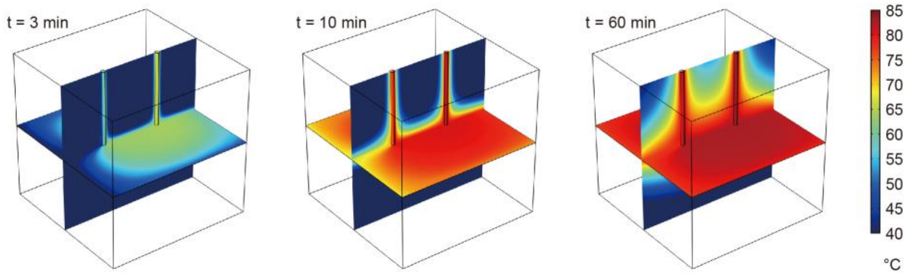

Fig. 7 Evolution of temperature in the fractured rock sample from numerical simulation.

4.3 Mechanical deformation characteristics

For the mechanical field, it focused more on the fracture aperture and the effective stress. Fig. 8 displays the evolution of the fracture aperture using the coupled thermo-hydro-mechanical rock model. Due to the continuous injection of hot water, local thermal expansion of the rock surrounding the fracture occurred, resulting in a reduction in the fracture aperture in the central area. The results clarify the significance of taking the thermo-hydro-mechanical coupling effects and the thermal expansion property of the material into account when investigating the characteristics in the fractured rock.

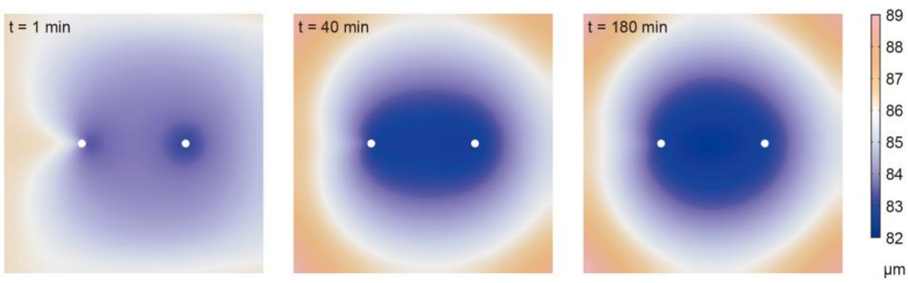

Fig. 8 Evolution of fracture aperture from numerical simulation.

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 positioned around the fracture to observe the variation of rock temperature over time. Then, a thermo-hydro-mechanical coupled numerical model was calibrated using the test data. 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 varying stress paths can be further studied.

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