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Experimental study of hydraulic conduct properties of a single granite fracture for high temperature geothermal energy production

Biao Shu
School of Geosciences and Info-Physics
Central South University
Changsha, China
biaoshu@csu.edu.cn

Runjun Zhu
School of Geosciences and Info-Physics
Central South University
Changsha, China
zhurunjun@csu.edu.cn

Jingqiang Tan
School of Geosciences and Info-Physics
Central South University
Changsha, China
tanjingqiang@aliyun.com

Shaohe Zhang
School of Geosciences and Info-Physics
Central South University
Changsha, China
zhangshaohe@163.com

Ming Liang
School of Geosciences and Info-Physics
Central South University
Changsha, China
liangming@csu.edu.cn

Abstract— Thermal energy recovered from Hot Dry Rock (HDR) or Engineered Geothermal Systems (EGS) is clean and renewable and may fulfill current energy demands. The long term flow characteristic of fractures is a key issue related to both the rate of geothermal production and the service life of the geothermal reservoir. We explore the long term fluid transport characteristics of a long (50 mm wide and 300 mm long) artificial fracture in granite at temperatures to 200 ℃. Permeability is measured under steady flow conditions in three stages: (1) stepped increments of temperature from 25 ℃ to 200 ℃; (2) constant temperature of 200 ℃ applied for 27 hours; (3) gradually decreased temperature from 200 ℃ to 25 ℃. The evolution of hydraulic aperture and permeability of the fracture is evaluated over these three regimes. Hydraulic aperture and permeability decrease with the increase in temperature. Uniform high temperatures result in a continued but gradual reduction in both hydraulic aperture and permeability. The reduction in hydraulic aperture and permeability of the fracture is permanent with marginal recovery as the temperature is reset to the original 25 ℃. Permeability increase during heating (stage 1), but decrease during high temperature production and then cooling (stages 2 and 3).

Keywords— *High temperature flow; hot dry rock; enhanced geothermal system; permeability; hydraulic aperture.*

I. INTRODUCTION

Currently, the influence of the greenhouse effect on the climate change has becoming very serious, and the need of green and renewable energy is more and more urgent [1, 2, 3]. Hot dry rock (HDR) geothermal energy is a type of such green and renewable energy of a huge reserve [4]. HDR usually refers to the hot rock that is stored in a depth between 3 to 10 km, and it contains no or very little water and fractures [5]. Usually, it is considered that the reservoir temperature of HDR should be higher than 150℃, in order to make sure the development of HDR commercially economical [6].

Enhanced geothermal system (EGS) is the main method to extract geothermal energy from HDR [7]. There are many challenges in the development of EGS, such as the rocks cutting in pressurized conditions [8] and permeability enhancement techniques [9]. Permeability enhancement techniques play a critical role in the reservoir stimulation of EGS [9]. Artificial fracture network is usually created by hydraulic, chemical or thermal stimulation so that heat transfer medium (such as water) can flow into the HDR reservoir and extract heat from the rocks during the flow. In EGS, low temperature water was pumped into the inlet well, and then hot water was pumped out of the outlet well [10, 11].

The permeability of the artificial fracture network is very important to the production efficiency of the EGS project [12]. If the permeability of fracture network deceases, the hydraulic conductivity of the fracture network, and ultimately the production efficiency, will decrease. The evolution of permeability is controlled by the fluid-rock interactions to a large extent [13], therefore, the assessment and quantification of induced permeability damage during the geothermal recovery processes is a vital part of the feasibility study of geothermal energy projects [14].

It is basically a Thermal-Hydraulic-Mechanical-Chemical (THMC) multiple coupling process during the flow in the fractures of EGS [15, 16]. After the water enters fractures and extract heat from hot rock, there are several things can happen: (1) Thermal damage occurred when low temperature water interacts with high temperature rock mass [17]; (2) The hydraulic abrasion of fluid flow to the fracture surface; (3) The creep of rock under high confining pressure [18]; (4) The chemical reaction between rock minerals and fluid water under high temperature and high pressure, including chemical dissolution and precipitation [18]. All of these processes can affect the flow characteristics of fracture to a certain extent. For example, Morrow et al. [19] conducted an experimental study of the permeability of intact granite and single granite fracture under 150℃. It showed that as the flow time increases, the permeability of fracture gradually decreases.

As for the effect of temperature, Luo et al. [20] found that the permeability of fracture decreases as the temperature increases according to a high temperature flow experiment. Due to the significant decrease of the dynamic viscosity of water with the increase of temperature, the hydraulic conductivity of fracture actually increases. However, the sample size used in the experimental is only 25 mm in diameter and 50 mm in length, which is small, and the experimental temperature is only 100℃.

About the rock mechanical properties, when the rock was impacted by the thermal shock, tensile stress and then micro-cracks will occur at rock surface [21, 22]. Thermal stress induced by the injection of water into high temperature rock can damage not only the surface but also the interior of the rock, such as causing the increase of porosity and permeability and the decrease of density and elastic modulus [23]. Therefore, mineral grains at the fracture surface may be crushed and squeezed under confining pressure, and the fracture aperture can be reduced.

In the chemical dissolution, Morrow et al. [19] conducted an experimental study of the permeability in a φ25×25 mm (25 mm in diameter and 25 mm in length) single granite fracture under 150℃, while Caulk et al. [24] studied the flow characteristics in a φ38.5×38.5 mm fracture under a temperature of 120 ℃. Both studies found that there are many mineral elements (such as Potassium, Aluminum, and Silicon) dissolved in the water during the flow experiment. Also, as the flow time increases, the permeability decreases.

Yasuhara et al. [25] analyzed the chemical contents on the fracture surface before and after a flow experiment between 20 ℃ and 90 ℃ in samples of φ30×60 mm. It improved that mineral precipitation exist during the flow, but the precipitation is very slight and therefore it has very little effect on the fracture permeability.

To summary, there are some previous researches have explored the flow characteristics of rock fracture under high temperatures, usually using small size rock samples, and under a temperature of less than 150 ℃. Due to the short flow path, the flow results may be significantly affected by the boundary conditions. Besides, some of the tests were performed under a relative low temperature (such as 90 ℃) which is lower than the real EGS production temperature. Therefore, there is a need to conduct further experimental study on the flow characteristics for large size granite fracture under a higher temperature.

In this study, a single large size granite fracture (φ50×300 mm) was used in the flow test to evaluate the evolution of hydraulic characteristics of fracture during long term high temperature flow. The hydraulic aperture, permeability and hydraulic conductivity of granite fracture under different temperatures (up to 200 ℃) before and after long term high temperature water flow were measured and analyzed.

II. EXPERIMENT DESIGN

A. *Fracture sample*

The core samples used in the test was collected from Zhangzhou area, Fujian province, one of the most promising deep geothermal reservoir areas in China. The main mineral contents of this granite are 50% of feldspar, 30% of quartz, 13% of chlorite, 6% of biotite and the rest are opaque minerals. Granite core was cut into a 50 mm diameter and 300 mm long cylinder. A specifically designed Brazilian tension test machine was used to split the cylinder into two pieces along the axis, and therefore an artificial fracture was created.

The two pieces of rock sample were put together and fit closely. A thin layer of polymer waterproof tape was used to wrap the core sample before the core was installed into a thin soft copper sleeve. This sealing method was chosen after several different sealing methods were tried using dyeing tracer in the flow water. The polymer tape was used to prevent water leakage from the fracture to the periphery of the core cylinder. The thin copper sleeve was used to hold the confining pressure. Both polymer tape and the copper sleeve can withstand the high temperature. The following flow experiment shown that the sealing method described above is very successful. The water flew only inside of the fracture, and no leakage was observed at the periphery of the core cylinder. The final design of the flow experiment setup is shown in Fig. 1.

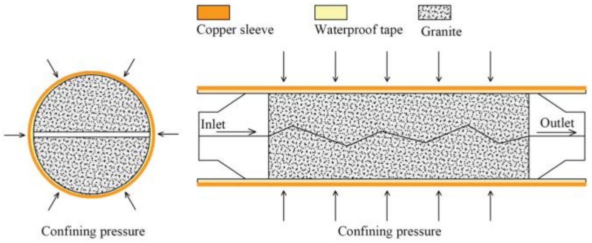

Fig. 1. Schematic diagram of the setup of the fracture.

B. *Flow experiment device*

The experimental device used in this study is a self-designed high temperature flow device. This device can provide a confining pressure of up to 50 MPa, and a test temperature of up to 350 ℃. It includes a core holder, a confining pressure load unit, a pump to inject fluid into the fracture, a heater to heat the rock sample to a designed temperature, and pressure and temperature sensors at both inlet and outlet of the fracture. The temperature, fluid pressure and flow rate are controlled and monitored by a computer.

The test procedure of how to use this device can be described below:

- Install the core sample (with an artificial fracture) in the core holder, and then apply the designed confining pressure. There is a steel sleeve of lots of holes right outside the soft copper sleeve, to allow the confining oil pressure to be applied on the sample as well as to fix the rock sample and prevent expansion.

- Increase the temperature. Resistive heater is used to heat the confining oil and then the confining oil heat the core sample. After the temperature reaches the designed value, it is kept for two hours to make sure the center of the core sample is fully heated up.
- Set the pressure at the outlet of the flow device to a minimum value using the pressure control valve, to make sure that the water is in liquid state, rather than gas state, under high temperature.
- Inject water by the pump into the fracture at a constant flow rate. After the pressure measured at the inlet comes to a stable value, record the inlet pressure, as well as inlet and outlet temperatures.

C. *Experiment procedure*

In the flow experiment, the confining pressure was set up to 20 MPa; the temperature was set up between 25 ℃ and 200 ℃; and the fluid inject rate was kept constantly at 1.0 ml/min.

The flow experiment was divided into three stages: (1) stage 1, stepped increments of temperature from 25 ℃ to 100 ℃, 150 ℃, and finally 200 ℃; (2) stage 2, constant temperature of 200 ℃ applied for 27 hours; (3) stage 3, gradually decreased temperature from 200 ℃ to 150 ℃, 100 ℃, and finaly 25 ℃.

III. THEORETICAL BASES

In this paper, we mainly study the hydraulic characteristics of the facture, so the equivalent hydraulic aperture is used. The modified cubic law can be used to describe the fluid flow in a single fracture, as shown in Eq. (1) [26]

$$q = \frac{Pdb_e^{\,3}}{12\mu L} \tag{1}$$

where q is the flow rate (m^3/s), P is the pressure difference between the inlet and the outlet (Pa), d is the width of the fracture (equals to the diameter of the core sample) (m), b_e is the equivalent hydraulic fracture (m), μ is the dynamic viscosity of water (Pa s), L is the flow distance which is the length of the fracture (m). From Eq. (1), the equivalent hydraulic aperture b_e can be calculated.

The flow rate in this test is quite small, so the Darcy's law of fluid flow can be used to calculate the permeability of single fracture [24]. The equation of Darcy's law is given by

$$k_e = \frac{q \cdot \mu \cdot L}{P \cdot A} \tag{2}$$

where k_e is the permeability (m^2), A is the cross section of fracture (m^2) and it equals to $d \times b_e$.

The permeability of a single fracture can be obtained by combing Eqs. (1) and (2), and expressed by

$$k_e = \frac{b_e^{\,2}}{12} \tag{3}$$

The relationship between the dynamic viscosity of water and temperature is a very important factor to the fluid flow in the fracture. The dynamic viscosity of water can be calculated using Eqs. (4) and (5) [27].

When 273<T<413,

$$\mu = 1.3799 - 0.0212 \cdot T + 1.3604 \times 10^{-4} \cdot T^2 - 4.6454 \times 10^{-7} \cdot T^3 + 8.9042 \times 10^{-10} \cdot T^4 - 9.0790 \times 10^{-13} \cdot T^5 + 3.8457 \times 10^{-16} \cdot T^6 \tag{4}$$

where T is the Kelvin temperature (K).

When 413<T<553,

$$\mu = 0.0040 - 2.1074 \times 10^{-5} \cdot \mathrm{T} + 3.8577 \times 10^{-8} \cdot T^2 - 2.3973 \times 10^{-11} \cdot T^3 \tag{5}$$

The Kelvin temperature and the Celsius temperaturecan be converted by

$$T = t + 273.15 \tag{6}$$

where t is the Celsius temperature (℃).

Combing Eqs. (4), (5) and (6), the relationship between dynamic viscosity of water and Celsius temperature is shown in Fig. 3. According to Fig. 2, the dynamic viscosity of water decreases as the temperature increases. It decreases very quickly when t<140℃, and slowly when t>140℃.

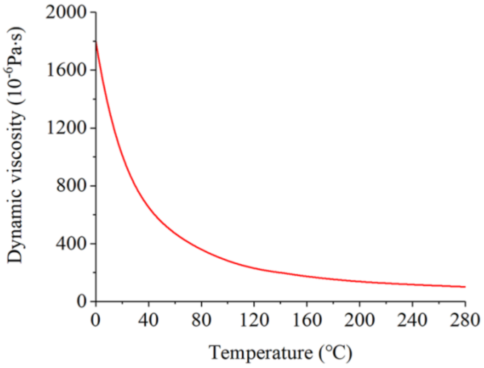

Fig. 2. Relationship between dynamic viscosity of water and Celsius temperature.

In this research, the flow rate is very small, and at the same time, the whole core holder is hot, so the water will be heated up before it flows into the fracture. The temperature difference between the inlet and outlet is not very large, so for simplicity, the average temperature of inlet and outlet temperatures was used to calculate the dynamic viscosity of water. The average temperatures of water during test are around 22, 90, 139, and 186 ℃, separately under core sample temperature of 25, 100, 150, and 200 ℃.

The vaporization temperature of water under different pressures are shown in Fig. 3. From the curve, we can see that in order to keep the water in a liquid state at 200 ℃, the pressure should be larger than 1.62 MPa. Therefore, the water pressure in the fracture was set up to a certain pressure larger than 1.62 MPa, so that the water wonnot be vaporized at anytime. The water pressure at outlet was set up to 1.86 MPa under any temperatures during this flow experiment, and the water pressure at inlet was always larger than the outlet pressure. Therefore, the water was liquid all the time during the test.

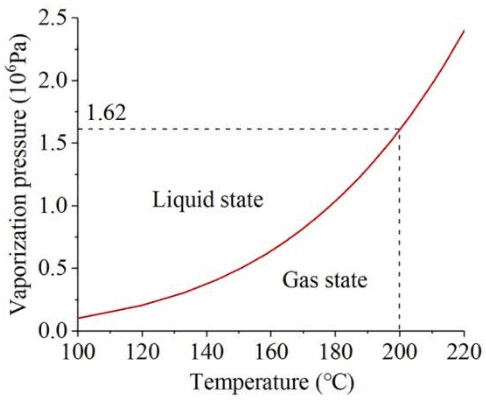

Fig. 3. Relationship between temperature and vaporization pressure of water.

IV. RESULTS ANALYSIS

A. *Fluid flow characteristics in stage 1*

In flow experiment stage 1, the testing temperature was set to 25 ℃, 100 ℃, 150 ℃, and 200 ℃, respectively. At all these four temperatures, we keep the flow rate a constant value, and measure the pressure difference between the inlet and outlet. The smaller the pressure difference is, the easier the fluid flows. The pressure difference versus the temperature in stage 1 is shown in Fig. 4.

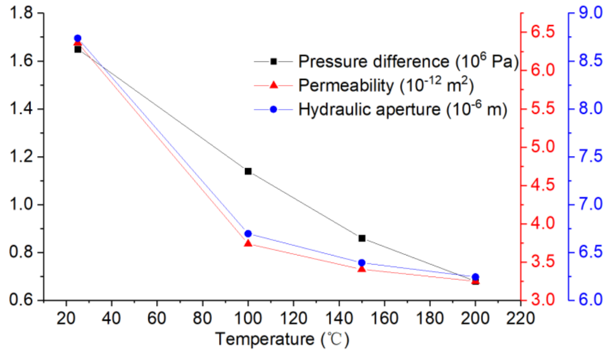

Fig. 4. Pressure difference, hydraulic aperture and permeability under different temperatures in stage 1.

From Fig. 4, we can see that the pressure difference between the inlet and outlet decreases significantly, which means that the fluid flow become easier and easier, as the experiment temperature increases.

The dynamic viscosity was calculated first, and then the equivalent hydraulic aperture and permeability were calculated by Eqs. (1) and (3), separately. As it is shown in Fig. 4, the equivalent hydraulic aperture and the permeability decrease a lot as the temperature increases.

B. *Fluid flow characteristics in stage 2*

A long term high temperature flow experiment was performed after the sample temperature reached 200 ℃ in stage 1. Keep the temperature at 200 ℃ and the inject flow rate at 1.0 ml/min for 1620 minutes (27 hours). The pressure difference was recorded continuously, as shown in Fig. 6. The hydraulic aperture and permeability were calculated by Eqs. (1) and (3), and shown in Fig. 5.

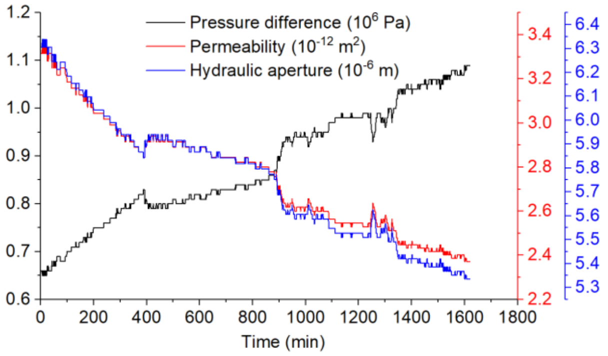

Fig. 5. Pressure difference, hydraulic aperture and permeability in stage 2.

According to Fig. 5, we can see that as the flow time increases, the pressure difference gradually increases, but the hydraulic aperture and permeability decrease. This means that as the time goes on, the fracture becomes more and more tightly closed, and the fluid is hard to flow in the fracture. This is very different from what happened in stage 1.

C. *Fluid flow characteristics in stage 3*

After stage 2, gradually cool down the rock sample to 150 ℃, and then resume the flow rate, and measure the pressure difference between the inlet and outlet. Keep decreasing the temperature to 100 ℃ and 25 ℃ respectively, and performing the same flow experiment. The testing results in stage 3 are compared with those in stages 1 and 2, as shown in Fig. 6.

From Fig. 6, we can see that, the pressure difference increases significantly in stage 3, and at the same time, the hydraulic aperture and permeability decrease slightly, as the temperature decreases from 200 ℃ to 25 ℃.

It shows that even though the temperature is decreased to the original value (25 ℃), the hydraulic aperture and permeability do not increase back to the original values but further decrease. This means that the long term high temperature flow in stage 2 has caused permanent damage to the fracture and permanent influence to the flow characteristics, so that they can’t be recovered even the temperature decreases. The significant increase of pressure difference in stage 3 from 200 ℃ to 25 ℃ is due to the increase of the dynamic viscosity plus the further decrease of hydraulic aperture and permeability.

From the experiment, we found that the hydraulic aperture decreased only 0.9712×10^{-6} m in the whole 27 h high temperature flow experiment, but it decreased 0.8254×10^{-6} m when temperature decreased from 200 ℃ to 25 ℃

in stage 3. This means that the temperature decrease can significantly affect the hydraulic aperture.

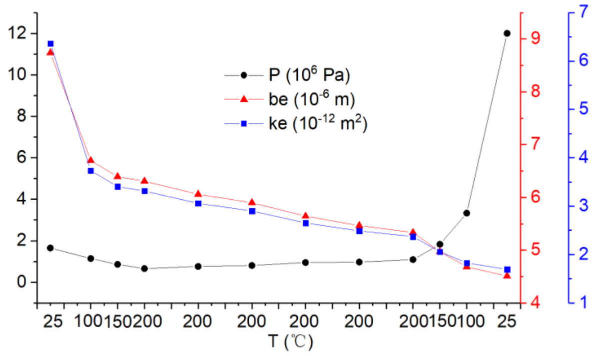

Fig. 6. Flow characteristics changes during the whole flow experiment.

V. DISCUSSION AND CONCLUSIONS

High temperature flow-through experiments were conducted on a large artificial fracture in granite (φ50 mm×300 mm). The flow experiment was conducted as temperatures were first incremented to 200 ℃, held constant and then decremented back to 25 ℃. The major findings from this experiment are:

- An increase in temperature can cause thermal expansion and decrease the elastic modulus of granite, and therefore cause a decrease of the hydraulic aperture and permeability of fracture.
- Dissolution, precipitation, and mechanical damage of the granite during long term high temperature flow can cause permanent damage to the flow characteristics of the fracture. Even as the temperature decreases after the long term high temperature stage, hydraulic aperture and permeability do not recover to the original values.
- The hydraulic aperture and permeability both decrease with a decrease in temperature.

The study found that the permeability, as well as the hydraulic conductivity of fracture in long term high temperature flow decrease, and they cannot be recovered even if the temperature decreases. The findings in this study provide essential guidance for the development of EGS. From this study, we can see that it is going to be a very important issue to maintain the hydraulic conductivity and heat transfer efficiency in the production period of EGS. To maintain the hydraulic conductivity for long term production, it is suggested to study some useful methods, such as chemical stimulation, to recover the hydraulic aperture of fracture network. Besides, it may be interesting to consider using proppants in the EGS to maintain hydraulic conductivity.

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