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Experimental Investigation of Heat Transfer by Water Flowing Through Rough Fractures

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ABSTRACT

Having an accurate understanding of the flow and heat transfer characteristics of water flowing through fractures with different fracture geometry is important for building an accurate heat transfer model of enhanced geothermal systems. This paper presents experimental investigation of convective heat transfer of water in five artificial rough and tortuous fractures with different geometry that were created using the 3D printing method. The effects of volumetric flow rate, and the fracture roughness on the heat transfer characteristics were studied. The results showed that the fracture geometry significantly influences the heat transfer characteristics of water flowing through rocks.

1. INTRODUCTION

Energy is an important foundation for the economic development of a country. Geothermal energy, as a pollution-free and renewable energy resource that can be used to handle environmental problems caused by extensive use of fossil fuels, can potentially meet the gradually increasing energy requirements. Geothermal energy has attracted wide attention worldwide (Ghassemi, 2012; Olasolo et al., 2016). According to the Annual Energy Outlook (Nygren, 2018), geothermal energy generation is projected to reach 400 billion kilowatthours (BkWh) by 2050 in the United States. Official figures released by China's Ministry of Land and Resources, the total hot dry rock (HDR) resources distributed at depths of 3-10 km are 260,000 times the capacity of the annual energy consumption in mainland China (Zhao and Wan, 2014). The extraction of thermal energy from HDR is essentially a process of fluid flow and heat transfer in the high-temperature fractured rock mass. Therefore, an accurate understanding of the fluid flow and heat transfer process in fractures is important for geothermal energy extraction and utilization.

Experimental research is an important method to study the characteristics of fluid flow and heat transfer process. Many researchers have explored the fluid flow and heat transfer process by experimental approaches. Zhao et al (1993) proposed a formula for calculating the heat transfer coefficient under the assumption that the sample surroundings have reached a uniform constant temperature, and an invariable average temperature is used to replace the fracture surface temperature. The effects of mass flow rate and initial rock temperature on the convective heat transfer characteristics of carbon dioxide in a rock fracture were studied by Jiang (2017). Li et al (2017) and Zhang et al (2017) conducted experimental investigations of laminar convection heat transfer in rough and smooth parallel-plate fracture. Bai et al (2017) proposed a method to calculate the overall heat transfer coefficient based on the experimental and analytical study of heat transfer characteristics for flowing water and granite fracture wall.

Many researchers study heat transfer process mainly based on one single smooth and horizontal fracture. Only a few studies the effects of fracture surface tortuosity on heat transfer characteristics have been conducted. This study aims to investigate the heat transfer characteristics of water flowing through six samples with different fracture surface roughness through experimental studies. The effects of fracture surface roughness on the heat transfer characteristic are discussed.

2. EXPERIMENT

2.1 Experimental apparatus

All the tests were conducted using the HDR Laboratory Simulation System which was developed independently by our research group. Figure.1 shows a schematic diagram of the experimental system. This system consists of five parts: a permeating pressure subsystem, a temperature control subsystem, a confining pressure subsystem, a specimen holder subsystem and a data acquisition subsystem. The water injection device used in the test is double-pump water injection system, which is a high-pressure embolic pump produced by Teledyne ISCO of the United States. The volume of a single pump is 100 ml and the maximum pressure that can be applied is 10000 psi (68.95 MPa). The flow rate range is 0.00001-30 ml/min of a single pump and 0.00001-45 ml/min when the two pumps working together. The main purpose of the specimen holder subsystem is to fix the artificial rock sample. The fracture surface of the rock sample is placed horizontally inside the cylindrical rubber sleeve. The confining pressure subsystem manly fills water between the rubber sleeve and the core holder. The maximum confining pressure of this system is 40 MPa. The confining pressure was maintained at 1 MPa which is higher than the fluid pressure in order to prevent water from flowing through the gap between the sample and the holder. The temperature control subsystem which is capable of heating to 200 °C, consist of a temperature display panel and an electric heater; the electric heater is wrapped around the specimen holder. Heating is provided by the electric heating coil. The high-temperature resistance wire is evenly distributed in the heating coil. When the current passes through the resistance wire, the heating coil generates heat and conducts heat to the inside of the holder. The data acquisition subsystem collects and records the flow velocity, permeating pressure, confining pressure, inlet and outlet fluid temperatures, and the temperature of the rock's outer surface.

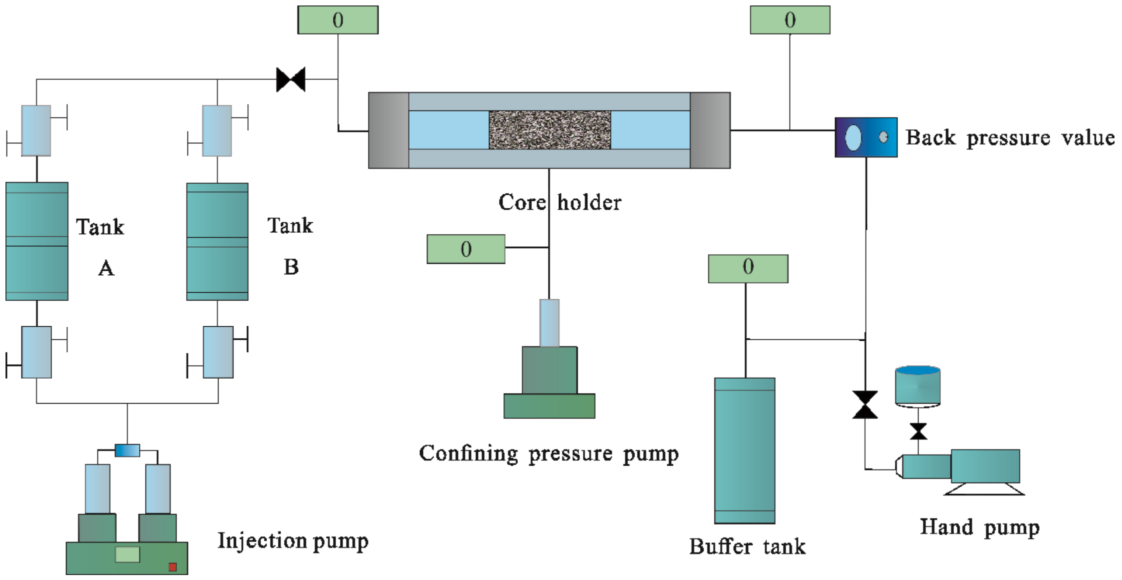
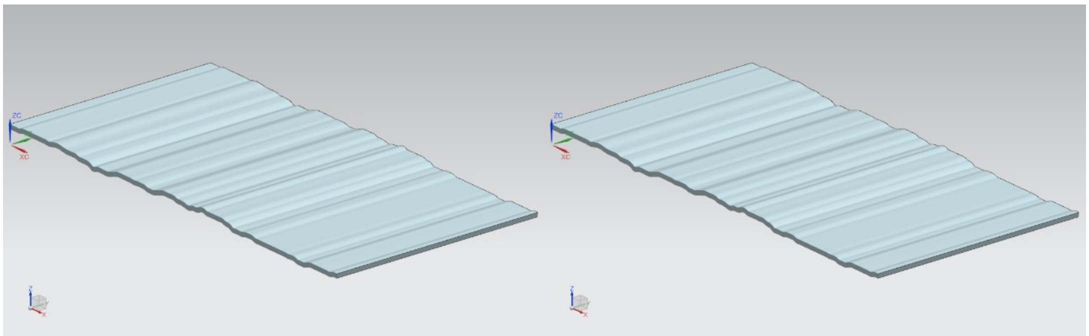
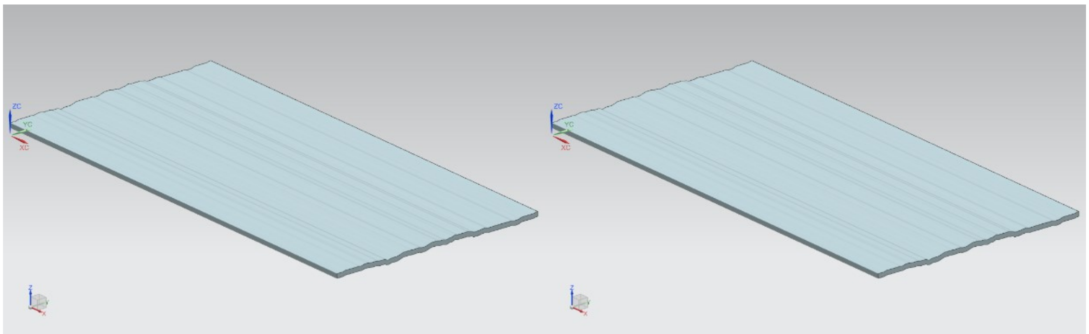


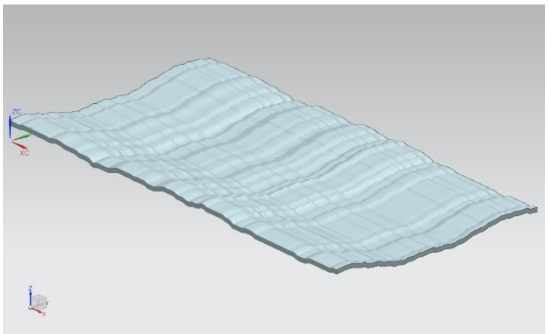
Fig. 1. Experimental system



A: Long side JRC 4-6 B: Long side JRC 10-12



C: Short side JRC 4-6 D: Short side JRC 10-12



E: Long side JRC 4-6; Short side JRC 10-12

Fig. 2 Five surfaces with different morphologies

2.2 Sample preparation

Fracture with five different morphologies were designed. The samples used in the tests consisted of cement mortar and were cylindrical with a length of 100 mm and a diameter of 50 mm. The cement samples were split into two halves with rough surfaces at the beginning of the curing process in order to simulate fractures in the rock. The 3D printing techniques, which have achieved a significant development recently, were used to manufacture specimens with irregular fracture morphology to control the tortuosity of the sample well. Barton (1977) proposed the joint roughness coefficient, which has been widely used in the field of engineering, to reflect the extent of joint surface roughness. We selected two standard typical profiles from the 10 standard typical profiles, and their joint roughness coefficient are 4-6 and 10-12. Five surfaces (Fig.2) with a length and width of 100 mm and 50 mm were produced. The two samples' JRC (A and B) of long side (parallel seepage direction) are 4-6 and 10-12, and their JRC of short side (vertical seepage direction) are 0. Another two samples' JRC (C and D) of short side are 4-6 and 10-12, and their JRC of long side were 0. The last sample' JRC (E) of long side is 4-6, and its JRC of short side is 10-12. We obtained five concrete specimens with a radius and length of 25 and 100 mm, correspondingly. The sample halves perfectly match, as illustrated in Fig. 3.

Fig. 3 The concrete specimens of B (Long side JRC 10-12)

2.3 Experimental procedure

The outer surface temperature of the samples was maintained at 90 °C, and four flow rates (5, 10, 15, and 20 ml/min) were designed in the experiment. First, the specimen was placed in the specimen holder, and then the sealing elements were placed on the ends of the specimen. The confining pressure reached 1 MPa, and the airtightness of the system was checked. The electric heater was installed, and heating was performed until the outer surface temperature of the specimen reached 90 °C. Then, water was injected at setting flow rates of 5, 10, 15, and 20 ml/min through the ISCO pump. The inlet and outlet fluid and rock outer surface temperatures were recorded after reaching a steady state at each flow rate.

3. RESULTS AND DISCUSSION

Heat transfer coefficient is a significant parameter that can describe the characteristics of the heat transfer process of fluid through the fracture surface and can be used to predict hot water production from an enhanced geothermal reservoir. To investigate the heat transfer characteristics of water flowing through samples with different fracture surface roughness, the convective heat transfer coefficient under each experimental condition were calculated. Researchers have developed several equations to calculate the heat transfer coefficient (Zhao and Tso, 1993; Zhao, 2014; Bai et al., 2017). In consideration of our experimental conditions, we used the equation provided by Bai et al. (2017), which assumes that the temperature along the radius of the specimen is a linear function. The form of the equation is:

$$h = \frac{c_{p,w}\rho_w q_v (T_{out} - T_{in})}{dL(T_c - (T_{in} + T_{out})/2)} \quad (1)$$

where h is the heat transfer coefficient (W/(m^2 K)); $c_{p,w}$ is the specific heat capacity at constant pressure of water (J/(kg K)); ρ_w is the density of water (kg/m^3); q_v is the volumetric flow rate (ml/min); T_{out}, T_{in} are the outlet and inlet temperatures of the water (K); d is the diameter of the specimen (m); L is the length of the specimen(m); T_c is the temperature at the outer wall surface of the specimen (K);

3.1 The heat transfer characteristics of water flow through sample A and B

The heat transfer coefficient of water flow through sample A and B was calculated using equation (1) and is shown in Fig. 4 for various flow rates. Selecting an appropriate volumetric flow rate is extremely important in fractured EGS system for optimum efficiency and benefit. Four different flow rates of 5, 10, 15, and 20 ml/min were tested in the experiment to illustrate the effect of the flow rate on the convective heat transfer. As shown in Fig. 4, the heat transfer coefficient and the volumetric flow rate are positively correlated. For instance, when the long side' JRC is 4-6, the heat transfer coefficient increases from 53.16 to 289.12 as the volumetric flow rate increase from 5 to 20ml/min. During the experiment, we observed that the outlet temperature of the water remained stable for a short time and then decreased at a volumetric flow rate of 20 ml/min. However, when the volumetric flow rate was 5 ml/min, the outlet temperature remained stable for a longer time. Therefore, a large volumetric flow rate resulted in a greater heat removal rate, whereas a small volumetric flow rate resulted in a more stable outlet temperature of the water. Therefore, these two factors should be balanced when selecting the volumetric flow rate. It is evident that that the heat transfer coefficient differs for the different JRC under the same volumetric flow rates; this indicates that fractures surface roughness has a large influence on the heat transfer characteristics of water flowing through rocks. As shown in Fig. 4, the heat transfer coefficient of sample A is less then that of sample B at every volumetric flow rate. The largest difference between JRCs of 4-6 and 10-12 is observed when the volumetric flow rate is 20 ml/min are up to 23.55 W/ (m2 K). A rougher surface fracture results in greater heat removal during the flow of the fluid through the rock surface. This occurs because the rougher surface provides a lager area to conduct the heat transfer under this experimental condition.

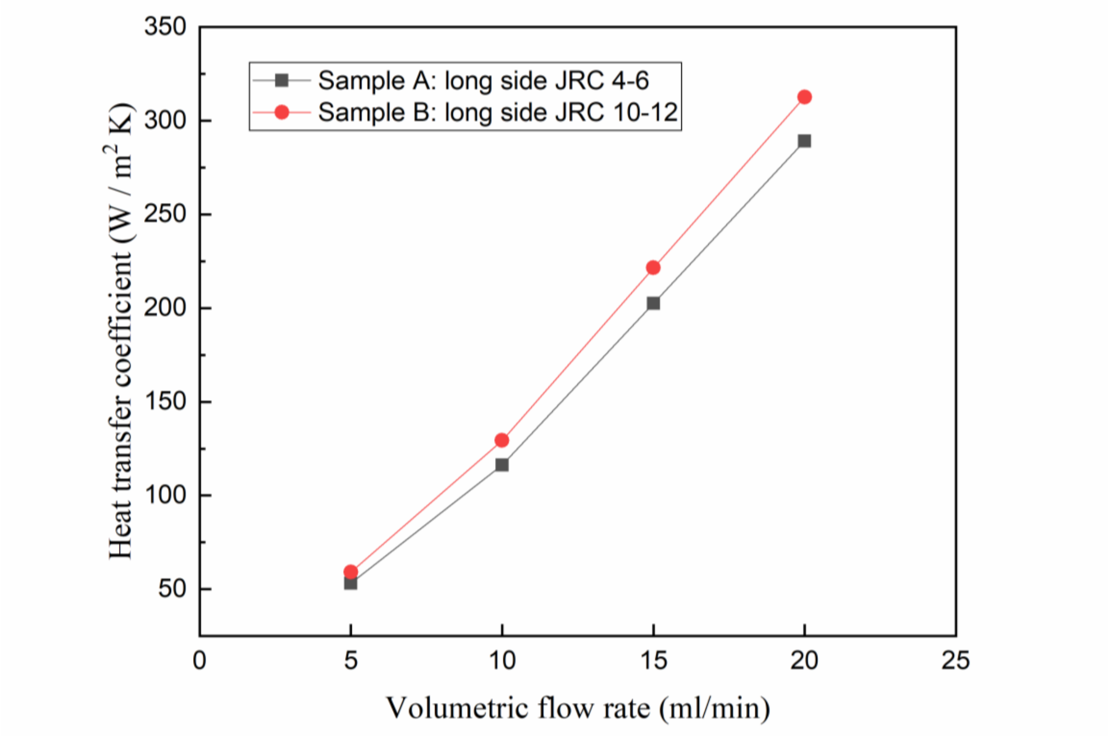


Fig. 4 Heat transfer coefficient for different volumetric flow rates for the sample A and B

3.2The heat transfer characteristics of water flow through sample C and D

When the short side JRC is different, the relationship between heat transfer coefficient and volumetric flow rate is shown in Fig. 5. Compared with the long side rough fracture surface (sample A and B), the influence of volumetric flow rate on the heat transfer coefficient is basically similar. The convective heat transfer coefficient of short side rough fracture surface (sample C and D) is higher than that of the long side rough fracture surface, and the increase is relatively small.

With the increase of roughness, the heat transfer coefficient of the long side rough fracture surface and the short side rough fracture surface increase, but the increase is different. Fig. 6 shows the increase of heat transfer coefficient of long side rough fracture surface and short side rough fracture surface at different volumetric flow rate when the JRC from 4-6 to 10-12. As shown in fig. 6, the increase of long side rough fracture surface are bigger than that of short side rough fracture surface at every volumetric flow rate, which means the effects of roughness on the heat transfer characteristics in the vertical seepage direction (short side rough fracture) is weaker then that in the parallel seepage direction (long side rough fracture).

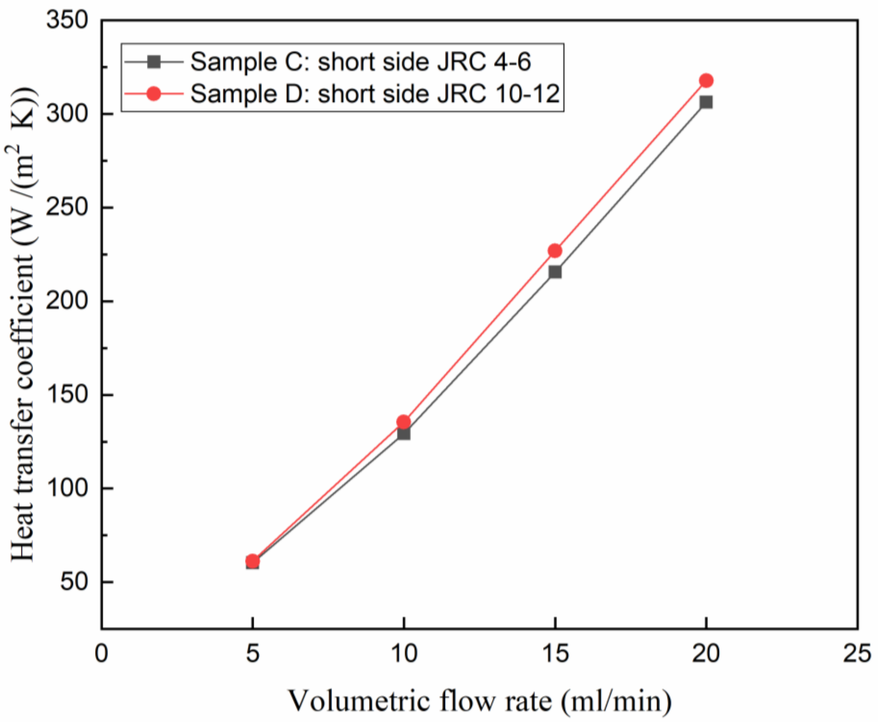


Fig. 5 Heat transfer coefficient for different volumetric flow rates for the sample C and D

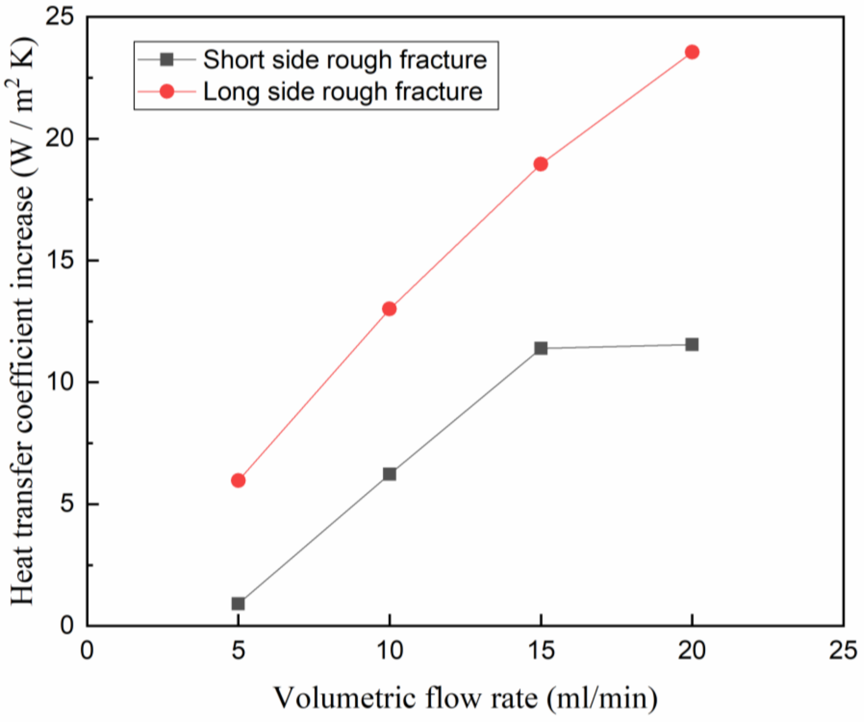


Fig. 6 Heat transfer coefficient increase for different volumetric flow rate

3.3 The heat transfer characteristics of water flow through sample E

Fig. 7 shows the relationship between heat transfer coefficient and volumetric flow rate for sample E. Compared with the sample A, B, C and D, the influence of volumetric flow rate on the heat transfer coefficient is similar. As the volumetric flow rate increases, the heat transfer coefficient increases. However, when the volumetric flow rate is 5 and 10 ml/min, the heat transfer coefficient of sample E is smaller than that of sample A, B, C and D. When the volumetric flow rate is 15 and 20 ml/min, the heat transfer coefficient of sample E and sample A, B, C, and D have little difference. It is possible that the dominant path is easily formed due to the tortuosity of the fracture surface, resulting in a smaller heat transfer coefficient.

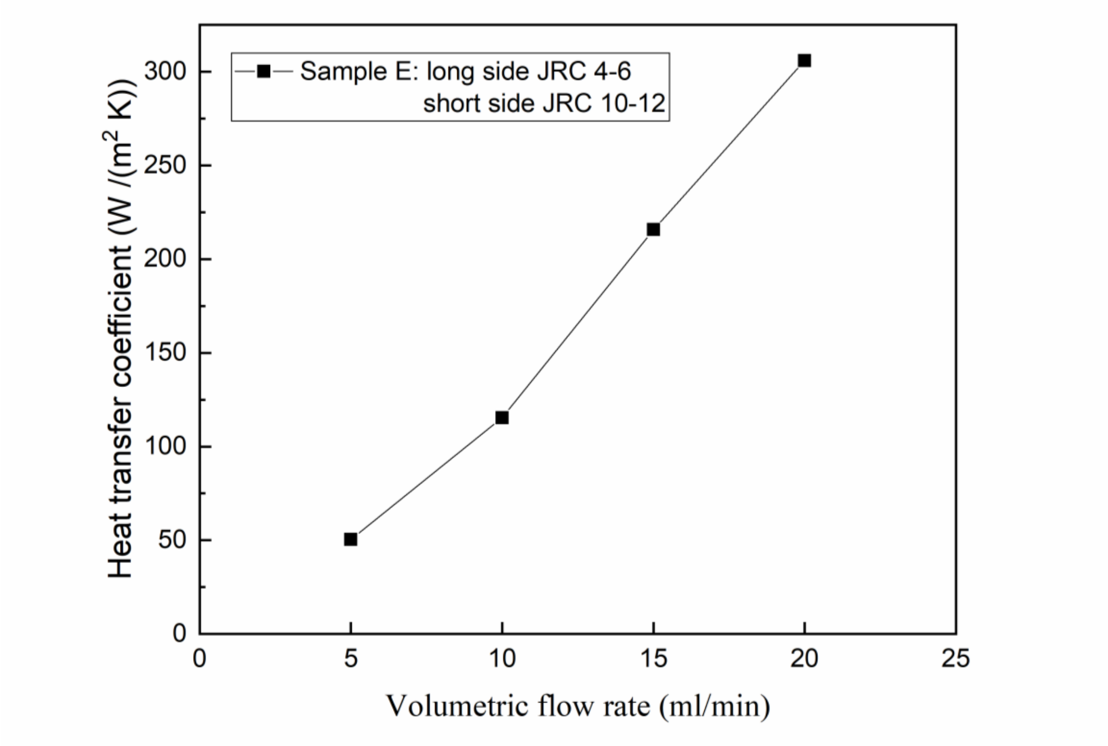


Fig. 7 Heat transfer coefficient for different volumetric flow rates for the sample E

4. CONCLUSIONS

We conducted an experimental study of the heat transfer of water flow through five rough fractures with different JRC to determine the effect of the fracture surface roughness on the heat transfer characteristics. The effects of the volumetric flow rate, the JRC, and the JRC with different side on the heat transfer characteristics of water flow through a rough fracture were determined. The following conclusion were drawn:

(1) A larger volumetric flow rate resulted in a greater heat removal rate in all five samples.

(2) A rougher surface with JRC bigger result in greater heat removal in sample A, B, C and D.

(3) The effects of roughness on the heat transfer characteristics in the vertical seepage direction (short side rough fracture) is weaker than that in the parallel seepage direction (long side rough fracture).

(4) When two sides of the sample are rough, the heat transfer coefficient are smaller compared to sample only one side is rough due to the formation of dominant path.

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