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Research Paper

Effects of surface roughness on the heat transfer characteristics of water flow through a single granite fracture

Yuanyuan He [a,b], Bing Bai [a,*], Shaobin Hu [a], Xiaochun Li [a]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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A B S T R A C T

The understanding of flow and heat transfer in a rough fracture is not sufficient at present due to the complexity of quantifying fracture geometry and the lack of experimental work. This paper adopted fractal dimension D and profile waviness Ra to characterize surface roughness and investigated the effects of surface roughness on the heat transfer characteristics of water flow through a single granite fracture by combining the experimental and numerical modeling approaches. It is found that the local heat transfer coefficient distribution mainly depends on the fracture surface roughness, followed by aperture and flow rate.

1. Introduction

Geothermal energy, which is clean, renewable and widespread, has become the focus of research and development all over the world, and considerable attention has been given to exploiting and utilizing the Enhanced Geothermal System (EGS), which is dominated by hot dry rock (HDR) 3–10 km underground. However, the permeability of hot dry rock with few natural fractures is extremely low. Generally, artificial stimulation is used to create interconnected pathways for working fluid circulation and heat transmission. Thus, it is of great significance to have an accurate understanding of the heat transfer characteristics of water flowing through fracture channels for hot dry rock geothermal energy extraction. But yet, among EGS studies, prediction of the heat transfer between rock masses and water flow through artificially extended fracture encounters considerable challenges due to limited knowledge of the detailed nature of flow and experimental work.

Artificial extension fracture surfaces are usually irregular and rough and even contain contact asperities. In addition, the order of magnitude of fracture apertures is only at the micron level under high pressure; thus, it is difficult to measure the fluid temperature and inner surface temperature at various points along the flow direction. The parallel plate model is traditionally used to simplify the actual rough fracture surface, and many empirical equations can be observed in the literature, which may lead to a certain degree of error. For example, Tsang [1]and Brown [2] suggest that 1–2 order of magnitude error for flow estimation may result if real fractures are modeled using parallel plate theory. Zhao [3] found that the traditional equations of heat convection overestimate heat transmission in rock fractures based on the experimental results obtained from laboratory study of hydrothermal properties of rock fractures by heating the rock and forcing water through the rock fractures, which suggests that fracture geometry and surface roughness play a dominant role in water- rock heat transfer. Ranjith [4]found that fracture surface roughness is one of the main factors that determines the Reynolds number, which is used to describe the state of flow according to experimental data. Zhao [5] noted that water temperature increased non-linearly along the fracture plane, so Zhao and Tso [6] underestimated the temperature of water and the average heat transfer coefficient. Afterwards, Zhao et al. [7] simulated flow and transport processes in two different fracture networks to investigate the influences of local surface roughness of fractures on fluid flow and solute transport processes at the macroscopic scales of fracture networks. And then Luo et al. [8] considered two empirical models relating hydraulic apertures to mechanical apertures based on his work and found that fracture surface roughness can affect the fluid flow and heat transfer processes in fracture networks to various extents. Therefore, the effects of fracture surface roughness on the heat transfer characteristics of water flowing through a fractured rock

* Corresponding author.
E-mail address: bai_bing2@126.com (B. Bai).

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are worth studying. As a result, describing the fracture surface roughness becomes an important challenge. The simplest and very first method proposed in the literature for this purpose is the joint roughness coefficient (JRC) introduced by Barton [9] in 1973. Based on the observations on artificially produced rough joints, Barton developed ten typical profiles with different roughness and assigned coefficients from 2 to 20 to describe them. However, this led to artificial estimate error by comparing to the 10 standard profiles when determining the JRC value because the natural fracture surface morphology is variable [10]. Li and Huang [11] used relative waviness and elongation to evaluate JRC based on Barton's standard roughness rating profile curves and some undulating shape of practical rock joints, and the standard roughness rating profile curves were classified as flat, wavy and serrated. However, it is still difficult to quantify the JRC because of the contradiction among the three categories. Some researchers [12–15] proposed fractal dimensions, spectral analysis and wavelet analysis to characterize fracture surface roughness; however, most methods are complicated and difficult to apply in practice. Interestingly, numerous works of Turcotte et al. revealed that many geological phenomena are scale invariant [16] and fractal concepts can be applied to geological problems in a variety of ways such as frequency-size distribution and continuous distribution [17]; Xie and Pariseau [18] demonstrated that fractal dimension D is a measurement of joint roughness coefficient, and the greater D means the greater JRC. To measure the fractal dimensions, Babadagli et al. [19] mapped the rough surfaces of fractures using the fully computer-controlled surface scanning device and calculated the fractal dimension (D) of each surface using 2D datasets through variogram analysis [20,21]. Xie and Pariseau [18] proposed an h-L method to calculate the fractal dimensions, which is defined as follows:

$$D = \frac{\log 4}{\log[2(1+\cos(\arctan(2\mathrm{h}/\mathrm{L})))]} \tag{1}$$

$$h = \frac{1}{M}\sum_{i=1}^{M} h_i, \quad L = \frac{1}{M}\sum_{i=1}^{M} L_i$$

where L and h are the average base length and height of "high-order" asperities of a joint, respectively. A similar definition was also given in the following expression by Askari and Ahmadi [22]:

$$D = \frac{\log 4}{\log[4\cos(\arctan(2\mathrm{h}/\mathrm{L}))]} \tag{2}$$

However, it is difficult to identify the so-called "high-order" asperities of a profile and perform manual measurement of their base length and height. Thus, a proper method to describe the fracture surface roughness is required. Many researchers obtained relationship between JRC and fractal dimension by computer regression, Li and Zhang [23] summarized these empirical equations proposed to estimate the joint roughness coefficient (JRC) of a rock fracture based on its fractal dimensions (D) and found that great variation exists among the previously proposed equations because of the lack of data points used to derive these equations. Additionally, different methods may yield different D values for a given profile [24], which is really confusing. So they repeated what the previous researchers had done and examined a larger population of 112 rock joint profiles. To avoid subjectivity involved in identifying the "high-order" asperities, they proposed an updated h-L method: construct the least-square line on the trend-removed profile; segment the profile by the intersection points; and measure the base length (L) and the extreme peak or valley (h) for each segment. The averages of h and L for a rock joint profile can then be used in the formula (1) to calculate the fractal dimension. As a parameter independent of scale effects, fractal dimension is an important bridge to connect entire morphology with local features [25], so it can be a useful method to describe the surface roughness. Owing to the fact that Bai et al. [26] has investigated the distribution characteristics of local heat transfer coefficients along the fracture by successfully combining the experimental and numerical modeling approaches, this paper aims at exploring the effects of surface roughness on the heat transfer characteristics of water flow through a single granite fracture based on the same methods.

2. Derivation of the local heat transfer coefficient

Heat transfer coefficient is an important parameter to indicate the heat transfer characteristics of working fluid flowing through fractured rock. The average heat transfer coefficient h can be obtained on the basis of energy conservation because the heat absorbed by water in the whole fracture pathway equals the heat transfer by convection between the water and the inner surface of the fracture [27], so:

$$h = \frac{c_{p,w}\rho_w u d\delta(T_2 - T_1)}{A\left(T_i - \frac{T_1+T_2}{2}\right)} \tag{3}$$

where h is the average heat transfer coefficient (units of $\mathrm{W/(m^2\,K)}$); $c_{p,w}$ is the specific heat capacity of water at constant pressure, taken to be $4200\,\mathrm{J/(kg\,K)}$; ρ_w is the density of water, taken to be $1000\,\mathrm{kg/m^3}$; u is the flow rate of water along the flow direction in m/s; d is the diameter of the cylindrical rock specimen in m; δ is the fracture aperture in m; T_1, T_2 are the inlet and outlet temperature of the water, respectively, in units of K; A is the heat convection area; T_i is the inner surface temperature of the fracture;.

Because the order of magnitude of fracture aperture is only at the micron level under high pressure, it is difficult to measure the fluid temperature and inner surface temperature at various points along the flow direction. Fortunately, according to the work of Bai et al. [26], numerical modeling is an alternative way to obtain these values. If t_1, t_2 are the temperatures of two adjacent points of the inner surface of the fracture along the flow direction and x_1, x_2 are the x-coordinates of the two points, respectively, then the local heat transfer coefficient h′ can be evaluated as follows:

$$h' = \frac{c_{p,w}\rho_w u\delta(t_2 - t_1)}{2(x_2 - x_1)\left(T_i - \frac{t_1+t_2}{2}\right)} \tag{4}$$

3. Experiment

3.1. Rock sample

A cylindrical rock sample with a diameter of 50 mm and a length of 100 mm was cored from a granite block. It was then split into two halves by the Brazilian method. Fig. 1 shows the cylindrical granite specimen before and after the Brazilian split. Adhesive was applied to the lateral sides of the fracture to prevent fluid leakage. Mechanical and thermo-physical properties of the granite block, along with geometric parameters of the granite specimen with a single fracture, were measured and are listed in Table 1.

3.2. Fracture surface morphology

To determine the surface condition of the fracture, a laser scanning microscope (Olympus *R* LEXT OLS4100) was used to perform a non-contact 3D scan of the coarse fracture surfaces. Then, the coordinates of 19,900 points of the upper half of the fracture were obtained. The 3D view of the fracture surface is shown in Fig. 2 by importing the coordinates (x, y, z) of every point to Tecplot.