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Fluid friction and heat transfer through a single rough fracture in granitic rock under confining pressure☆

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ABSTRACT

To better understand flow and heat transfer in the fractured rock in enhanced geothermal systems (EGS), experiments were conducted to investigate the single-phase convective heat transfer and pressure drop of water flowing through a single fracture in a cylindrical granite rock. Dimensionless correlations for the Poiseuille number (Po) and the average Nusselt number (Nu) with the Reynolds number (Re) were obtained from the experimental data. It was found that the experimental results significantly deviated from those of rectangular macrochannel flows, and the flow friction is raised and the heat transfer is weakened significantly due to the large relative roughness. As confining pressure is applied, reduction of the aperture raises both Po and Nu. A roughness–viscosity model (RVM) was employed to account for the effects of the surface condition, and a satisfactory agreement between the numerical results based on RVM and the experimental data was achieved.

1. Introduction

The ability to provide reliable low-carbon power makes geothermal energy one of the promising renewable energy options to meet the growing energy demand through replacing fossil fuels [1]. However, the limited availability of naturally occurring hydrothermal systems that have both sufficient permeability and in-situ fluids for commercial geothermal energy applications, severely limits its deployment. Alternatively, enhanced geothermal systems (EGS) offer a solution to utilize a much larger fraction of deep geothermal resources [1]. To harness those hot dry rock (HDR) resources, hydraulic stimulation is required to create interconnected fractures for lower flow resistance. Among the studies of EGS, prediction of the artificially fractured reservoir performance encounters considerable challenges due to limited knowledge of the detailed nature of flow and heat transfer in the fractured rocks [2].

Regarding the hydraulic behavior of water flowing through rock fractures, many laboratory studies have been conducted on rocks with a single fracture. Theories for laminar flows through ideal parallel plates demonstrate that the Poiseuille number (Po), which is the product of the Reynolds number (Re) and the friction factor (f), is determined solely by the cross-sectional dimension of the channel [3]. Accordingly, the widely employed cubic law which indicates a linear relationship between the ratio of flow rate to hydraulic gradient and the cube of fracture aperture was derived [4]. Accurate predictions of flow rates can be achieved using the hydraulic aperture, a fitting parameter which is calculated from the measured flow rates and hydraulic gradients [4]. However, fracture surface roughness and aperture variation make the application of the cubic law unsuccessful when, as is often the case in EGS, the experimental data is insufficient to form the basis for fitting a hydraulic aperture [5]. Therefore, it is necessary to carry out fundamental investigations to further study the physics of water flowing through a fracture with an emphasis on the effects of fracture surface conditions, and to obtain an empirical relations between the flow rate and the pressure drop over the rough fracture for predicting the flow.

In addition, heat transfer in rock fractures is also of great significance to EGS as thermal energy is extracted through the fluid–rock heat exchange. An understanding of convective heat transfer between the rock fracture surfaces and the circulating fluid plays a key role in estimating heat recovery in fractured rocks. In large-scale reservoir simulations that explicitly represent fractures, the heat transfer coefficient is a critical parameter as it determines the heat exchange between the circulating fluid and the rocks, and the resultant production of hot water. However, only limited experimental data pertaining to heat convection in rock fractures has been reported [6,7]. A series of experiments to study heat convection in rock fractures under various flow velocities was conducted by Zhao and Tso [6,7], and the heat transfer coefficient was correlated with velocity. Moreover, as suggested by the results, the fracture surface roughness plays a dominant role in heat transfer. Therefore, additional efforts should be directed towards exploring

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Nomenclature

A	coefficient in Eq. (10)
A_c	cross-section area, m^2
H/W	height-to-width ratio
L	fracture length, m
L_h^+	non-dimensional heating length
Nu	Nusselt number
P	fluid pressure, Pa
P_c	confining pressure, Pa
Po	Poisueille number
Q	volumetric flow rate, m^3/s
R_a	fracture roughness, m
Re	Reynolds number
Re_k	roughness Reynolds number
R_h	hydraulic radius, m
b	fracture width, m
c_p	specific heat, J/kg·°C
f	friction factor
h	heat transfer coefficient, W/m^2
l	shortest distance from the point to the central line of the fracture, m
q	heat transfer rate, W
T	fluid temperature, °C
$\overline{T_i}$	fracture surface temperature, °C
T_o	rock outer surface temperature, °C
T_1	fluid inlet temperature, °C
T_2	fluid outlet temperature, °C
u	velocity, m/s
$u_{\mathrm{ave}}(=Q/\delta/b)$	average velocity, m/s
u_k	velocity at the top of the roughness element, m/s
$u^+(=u(y)/u_{\mathrm{ave}})$	non-dimensional velocity
w	total uncertainty
y,z	Cartesian coordinates, m
y^+	non-dimensional distance from the fracture surface
ΔP	pressure drop, Pa·s
ΔT	mean temperature difference, °C
μ_{eff}	effective viscosity, Pa·s
μ_{f}	fluid viscosity, Pa·s
M_r	roughness viscosity, Pa·s
λ_r	rock thermal conductivity, W/m·K
λ_w	water thermal conductivity, W/m·K
ρ	density, kg/m^3
δ	fracture aperture, m

the relation between the surface conditions and the heat transfer characteristics in the fracture. Due to the poor current understanding of the relationship between heat transfer coefficient and fluid velocity, fracture geometry and thermal properties of the fluid, the heat transfer coefficient is usually assumed to take a constant value [8,9]. Thus, investigation of the forced convection through a rough fracture in terms of the fracture surface conditions and fluid thermal properties is also significant for more accurate simulation models.

The objective of this study is to investigate flow and heat transfer in a fractured granitic rock. Relations for dimensionless parameters are obtained based on the measured data for different rock temperatures and confining pressures. To demonstrate the influence of fracture surface, the relative roughness is quantified by measuring the roughness and the fracture aperture. In view of the small dimension of the aperture, a roughness–viscosity model (RVM) for microchannel flows is applied to predict hydraulic and heat transfer performance, and numerical predictions which compare reasonably well with the experimental results are obtained.

2. Experiment

To simulate the subsurface conditions of granite rocks in EGS, high temperatures were attained for the granite rock in the experiment, and confining pressures (P_c) were applied and varied to change the fracture aperture reflecting the thermo–hydro–mechanical effects in EGS. Fluid–rock heat exchange took place as cold water was pumped through the fracture which was created under tensile stress. To acquire the surface roughness and the average aperture of the fracture, non-contact laser scanning was used for measurement.

2.1. Rock sample preparation

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 under tensile stress by sharp wedges loaded in a uniaxial compressive apparatus (Fig. 1), which is a standard procedure known as the Brazilian method. Adhesive was applied to the lateral sides of the fracture to prevent fluid leakage. Mechanical and thermophysical properties of the granite block, along with geometric parameters measured by a digital caliper are listed in Table 1.

2.2. Surface topology measurement

A Laser Scanning Microscope (Olympus® LEXT OLS4100) was used to perform non-contact 3D scan of the rough fracture surfaces. The aperture variation was determined by the asperity heights of both surfaces, and an average value of 135 μm was determined. The wavy topology requires a suitable cutoff value for roughness analysis: a large value would include the waviness and a small one would isolate the waviness. The standard value of 0.8 mm for the cutoff wavelength was chosen and the average surface roughness (R_a) was derived as 20 μm. Accordingly, the relative roughness ($R_a/2R_h$) is 0.148 without confining pressures.

2.3. Experimental apparatus and procedure

Fig. 2 shows the experimental apparatus. It consists of five parts: (1) high-pressure cell; (2) water supply unit; (3) temperature and pressure loading unit; (4) sensor unit; (5) data-acquisition unit. The fractured rock wrapped with a thermal shrinkable sleeve was immersed in anti-wear hydraulic oil that fills the high-pressure triaxial cell. Deionized water was pumped to the test section through a Teledyne® Isco syringe pump. An electric heater with temperature control was wrapped around the cell. A pressure loading unit was connected to the cell to apply P_c through oil. The water flow rate and the pressure were recorded automatically by the pump with 0.5% of full-scale accuracy. Pt100 sensors with an accuracy of 0.5 °C and a response time of 50 ms were

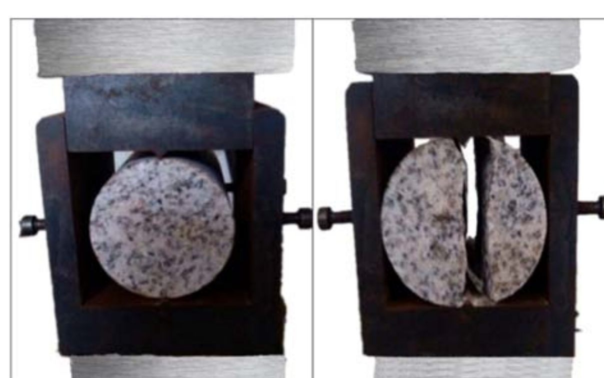

Fig. 1. The cylindrical rock before and after the Brazilian split.