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Influence of void space on microscopic behavior of fluid flow in rock joints

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ABSTRACT

Advanced microfluidic technology was used to examine the microscopic viscous and inertial effects evolution of water flow in rock joints. The influence of void space on fluid flow behaviour in rock joints under different flow velocities was experimentally investigated at the micro scale. Using advanced fabrication technology of microfluidic device, micro flow channels of semicircular, triangular, rectangular and pentagonal cavities were fabricated to simulate different void space of rock joints, respectively. Using the fluorescence labelling approach, the trajectory of water flow was captured by the microscope digital camera when it passed over the cavity under different flow velocities. The flow tests show that the flow trajectory deviated towards the inside of the cavity at low flow velocities. With the increase in flow velocity, this degree of flow trajectory deviation decreased until there was no trajectory deviation for flow in the straight parallel channel. The flow trajectory deviation initially reduced from the void corner near the entrance. At the same time, a small eddy appeared near the void corner of the entrance. The size and intensity of the eddy increased with the flow velocity until it occupied the whole cavity domain. The gradual reduction of flow trajectory near the straight parallel channel and the growth of eddy inside the cavity reflect the evolution of microscopic viscous and inertial forces under different flow velocities. The eddy formed inside the cavity does not contribute to the total flow flux, but the running of the eddy consumes flow energy. This amount of pressure loss due to voids could contribute to the nonlinear deviation of fracture fluid flow from Darcy's law. This study contributes to the fundamental understanding of non-Darcy's flow occurrence in rock joints at the micro scale.

1. Introduction

Fluid flow through rock joints commonly occurs in the underground environment. It is a significant topic in long wall mining, coal bed methane extraction and underground geo-sequestration of greenhouse gas as well [1–3]. Over the past decades, substantial research efforts have been performed on either fluid dynamics or coupled hydro-mechanical behaviour of this coupling phenomenon attributable to engineering concerns of hydrogeology in the fields of geotechnical and mining engineering [4,5]. Nowadays the study is continuing to improve the confidence level of description due to the complexity of this process, which mainly results from the aperture variation and flow path tortuosity [6,7].

So far, numerical and experimental studies on hydro-mechanical behavior of rock fractures have been extensively performed using the cubic law of constant or spatially-varied aperture [8–10]. In coupled hydro-mechanical behavior, the confining stress and associated shear displacement have a significant influence on fracture flow characteristics. For example, increased shear displacement makes the fracture hydraulically anisotropic [11]. This coupled hydro-mechanical behaviour is beyond the aim of this study and is not discussed further here.

The motion of fluid in rock joints obeys the basic rules of fluid mechanics. For example, the principle of linear momentum conservation (i.e., Navier–Stokes Equations), at the micro scale, can describe the fluid motion well in rock joints as shown in Eq. (1):

$$\rho\left(\frac{\partial U}{\partial t}+U\cdot\nabla U\right)=-\nabla p+\mu\nabla^2U+F \tag{1}$$

where ρ is the fluid density; U the velocity vector of flowing fluid; t the time; ∇ the pressure gradient; μ the dynamic viscosity of fluid; and F the body force vector. However, the nonlinearity of Eq. (1), largely reduces the computation efficiency in real application. Moreover, the flow boundary (bonded joint wall) in geological engineering is invisible and its precise mathematical description

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is difficult. To facilitate engineering prediction, macroscopic governing equations for joint flow have been empirically developed, such as linear Darcy's law and Forchheimer equation, which are expressed by Eqs. (2) and (3), respectively:

$$-\nabla p = \frac{\mu}{k_0 A} Q \tag{2}$$

$$-\nabla p = \frac{\mu}{k_0 A} Q + bQ^2 \tag{3}$$

where k_0 is the permeability; A the cross-sectional area of flow perpendicular to the flow direction; Q the volumetric flow rate; and b a model constant accounting for the nonlinear deviation effect. Even though, Eqs. (2) and (3) were proposed empirically, and their theoretical validity has been proved using various approximate mathematical techniques, such as averaging method [12,13].

With regard to flow regime transition, Zimmerman et al., based on laboratory and numerical experiments, observed that, macroscopically, a weak inertial regime occurs for Reynolds number ranging from 1 to 10, which can be expressed by a cubic-typed Forchheimer equation; while a strong inertial regime occurs for Reynolds number larger than 10, which can be expressed by Eq. (3) [14]. Zhang and Nemcik experimentally examined the fluid flow regimes in mated and non-mated rock joints of different joint roughness coefficients (JRC), and quantified the dependence of nonlinear coefficients b of the Forchheimer Eq. (3) on the confining normal stress [15].

For porous media, Dybbs and Edwards experimentally studied the flow regimes in porous media and concluded that the steady nonlinear flow was induced by the formation of a hydrodynamic boundary layer near the solid–liquid interface and an inertial core in the centre of the pores [16]. Hassanizadeh and Gray mathematically argued that the growth of microscopic viscous forces is the source of flow nonlinearity, which dominates over macroscopic viscous and inertial forces [17]. This was supported by joint work of Ruth and Ma [18]. Chaudhary et al. numerically studied the water flow through porous media and attributed nonlinear deviation from Darcy's law to the growth of eddies inside the pore [19]. Detailed review of flow transition from viscous via cross viscous-inertial to inertial patterns in porous media can be referred to Hlushkou and Tallarek [20].

For rock joints, some numerical computational attempts have been made to identify the source of nonlinear flow. Based on CFD simulations, Panfilov et al. concluded that the nonlinear flow can be induced by cross viscous-inertial effect at low Reynolds number, and identified that quadratic termed deviation, i.e., Eq. (3), is triggered by the pure inertial effect of eddies formed inside locally-varied cavities at higher Reynolds number and partially by an inertia-viscous cross effect [21]. Panfilov and Fourar further found that the inducement of cross inertia-viscous forces on nonlinear flow, which was identified as a source of nonlinear flow at weak inertial regime in periodic flow channels, disappears in non-periodic flow channel structures [22]. Even though numerical attempts to identify the source of flow nonlinearity have been made, laboratory studies of the influence of the irregular joint wall and the flow velocity on flow patterns, at the micro scale, have not been reported.

In this study, the fluid flow behaviour in rock joints was experimentally investigated at the micro scale by fabricating channels with different void shapes, trying to bridge the gap identified above. The micro-behaviour of fluid flow was examined based on the advanced fabrication technology of microfluidic channel device [23,24]. Fluorescence labelling methods were used to capture detailed motion trajectory of water when it passed over spatially-varied channel walls.

2. Methodology

With the fluorescence labelling approach, the micro-behaviour of water flow over four different flow channels was investigated using a microfluidic flow testing system. In this section, the fabrication of flow channels and testing process are briefly described.

2.1. Flow channel fabrication

For successful study of water flow over rough walled channels, the fabrication of microfluidic channel device is of key importance. In this study, polydimethylsiloxane (PDMS) was used to fabricate the channel structure in light of its convenience of chemical inertness and cost effectiveness. Two glass plates were used as the confinement of the patterned channel. The fabrication process consists of four main steps in time sequence, involving PDMS layer coating, channel patterning, confined glass processing and bonding (Fig. 1).

Initially, the first layer of PDMS is coated on the bottom glass, which acts as the transferring layer in the bonding stage. This PDMS layer is covered by a thin layer of Teflon, and then another thin layer of PDMS is coated over the Teflon, which is used for channel patterning and serves as the bonding medium at the bonding stage. The channel is patterned in a CO_2 laser cutter (Universal Laser Systems, Model VLS3.50 of dimension of 609 mm × 302 mm). Before the patterning, the flow structure was firstly designed with AutoCAD commercial software (Fig. 2) and sent to the laser cutter. Following the design, the laser moves to complete the patterning. Before bonding the two halves of the flow channel together, the glass needs to be processed in advance, which involves inlet and outlet hole drilling with DREMEL 220, glass wash in acetone, rinse in distilled water and drying in nitrogen flow in time sequence for cleaning purpose. At last, the top and bottom halves of the channel are bonded together to finalise the fabrication (Fig. 1). The detailed fabrication process can be obtained in references [23,24].

Four different flow channels were designed to simulate micro behaviour of water flow over non-planar walls at different flow velocities, as illustrated in Fig. 2. The width of the straight part of micro-channel is 50 μm, which is measured along the direction parallel to the plane of the glass; and the aperture of the channel is 70 μm, i. e., the thickness of the PDMS layer for channel fabrication or the vertical distance of two confined glass plates. Other geometrical dimensions of flow channel are schematically shown in Fig. 2.

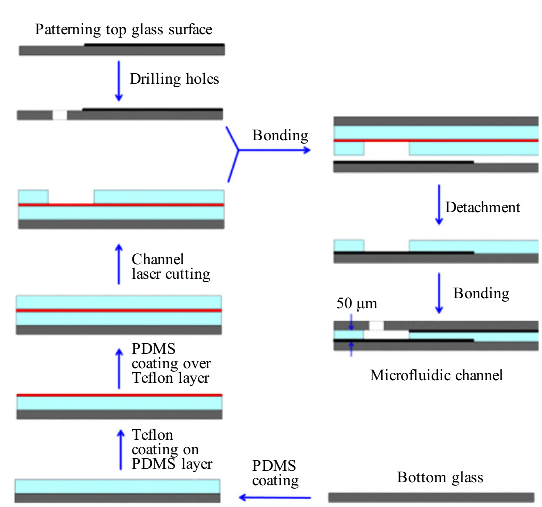

Fig. 1. Fabrication process of microfluidic flow channel [25].