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Simulation of two-phase flow in horizontal fracture networks with numerical manifold method

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ABSTRACT

The paper presents simulation of two-phase flow in discrete fracture networks with numerical manifold method (NMM). Each phase of fluids is considered to be confined within the assumed discrete interfaces in the present method. The homogeneous model is modified to approach the mixed fluids. A new mathematical cover formation for fracture intersection is proposed to satisfy the mass conservation. NMM simulations of two-phase flow in a single fracture, intersection, and fracture network are illustrated graphically and validated by the analytical method or the finite element method. Results show that the motion status of discrete interface significantly depends on the ratio of mobility of two fluids rather than the value of the mobility. The variation of fluid velocity in each fracture segment and the driven fluid content are also influenced by the ratio of mobility. The advantages of NMM in the simulation of two-phase flow in a fracture network are demonstrated in the present study, which can be further developed for practical engineering applications.

1. Introduction

Natural rock mass consists of intrinsic discontinuities forming a discrete fracture network, which generally acts as potential path for fluid flow. Understanding of the behavior fluid flow and its effect on the rock mass is of significance in hydro-geological and energy engineering. Many relevant researches are reported, such as tracking non-aqueous phase liquids (NAPLs) migration (Slough et al., 1999a,b), nuclear waste management in subsurface (Thunvik and Braester, 1990; Berger and Braester, 2000), and enhanced oil recovery in fractured reservoirs, etc. (Wanfang et al., 1997; Joonaki and Ghanaatian, 2013). Due to the intrinsic heterogeneous characteristic of rock mass and the interaction with fluids, simulation of two-phase flow in a fractured rock medium is very challenging (Pruess and Tsang, 1990; Reichenberger et al., 2006; Hoteit and Firoozabadi, 2008; Huang et al., 2014). There are three prevailing fundamental models for the representation of single- or two-phase flow in heterogeneous fractured media, i.e., (1) Equivalent continuum model, (2) Dual-continuum model, and (3) Discrete fracture model (Wanfang et al., 1997; Li et al., 2014).

The equivalent continuum model represents the rock mass with a fracture network as a porosity media, in which the permeability of the intact rock mass is generally neglected. The effective parameters, such as equivalent permeability and effective porosity, are assumed to characterize the hydraulic property of the fractured domain (Long et al., 1985). The dual continuum model is relatively more accurate by assuming both the rock matrix and fracture network as porosities. These two porosities overlaps with each other in the geometric model with their respective different seepage governing equations. The governing equations are connected through a transfer function in the mathematical model (Huang et al., 2014; Li et al., 2014). These two aforementioned continuum models are not very efficient to analyze the transient seepage problems due to the striking contrast of the hydraulic properties between the fractures and the rock matrix. And how to effectively represent the transfer function is yet to be explored for dual continuum model (Lim and Aziz, 1995).

The discrete fracture model (DFM) describes the fractures explicitly. It is widely used for simulations of single-, two- and multi-phase flow in fractured media (Murphy and Thomson, 1993; Maryška et al., 2004; Baghbanan and Jing, 2007; Benedetto et al., 2014; Liu et al., 2016). The fractures can be treated similarly as the matrixes when they stretch through the rock matrix and are distributed sparsely (Hughes and Blunt, 2001). Otherwise, the so called "reduced-dimension method" is applied, in which the fracture networks in an *n* dimension domain has been simplified by an

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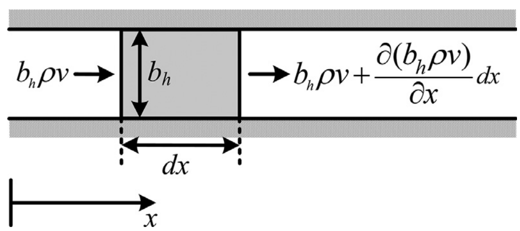

Fig. 1. Schematic illustration of the fluid flow in a saturated fracture.

$n-1$ dimensional mesh geometrically (Juanes et al., 2002; Karimi-Fard et al., 2004; Hoteit and Firoozabadi, 2005; Martin et al., 2005). The permeability of the rock matrix can be considered in this method (Kim and Deo, 2000; Belayneh et al., 2006). On the other hand, in order to simulate fluid flow in the densely fractured rock masses, it is can be assumed that fluid flows within the connected fracture networks only if the permeability of rock matrix is much smaller than that of the fracture network (Chen and You, 1987; Braester and Thunvik, 1988; Hoteit and Firoozabadi, 2009).

Based on these three models, many computational methods have been proposed to solve the two-phase flow in the fractured media, e.g., finite element method (FEM) (Kim and Deo, 2000; Karimi-Fard and Firoozabadi, 2003), finite difference method (FDM) (Slough et al., 1999a,b), finite volume method (FVM) (Granet et al., 2001; Monteagudo and Firoozabadi, 2004), and hybrid method (Hoteit and Firoozabadi, 2008; Huang et al., 2014), etc. A review of these methods for the two-phase flow in the fracture network has been performed by Hoteit and Firoozabadi (2008). However, the discrete interface between two fluids generally leads to the moving boundaries, pressure, and saturation discontinuities. Mesh is required to conform to or adapt to the interface of fluids based on these traditional numerical method. Thus, re-meshing the moving interface between the fluids highly increases the computational intensity. To overcome this inefficiency, numerical manifold method (NMM) is introduced and developed to simulate the two-phase flow in fracture networks.

NMM is able to model both the continuum and a discontinuous medium simultaneously based on a finite cover system with independent mathematical and physical covers. The NMM cover system is free from the model geometries, which dispense the necessity of re-meshing due to evolution of the discontinuity. Thus, the NMM innovative dual cover system overcome the inconvenience of the interface element assumption that is required in a conventional numerical method. In this way, the NMM can model continuum, transition of a continuum to a discontinuous medium, as well as a discontinuous medium including the geometric discontinuities (Shi, 1991, 2013) and material discontinuities (An et al., 2011; Wu et al., 2017) in a unified manner. A review of the NMM can be found in Shi (1991, 2013). NMM was initially proposed to solve rock mechanics problems, such as stability of rock structures (Ma et al., 2010; Ning et al., 2011), failure propagation in rock masses (Ma et al., 2009; Zhang and Zhang, 2012; Zheng et al., 2014; Zheng and Xu, 2014; Yang et al., 2016; Wong and Wu, 2014; Zhang et al., 2017), hydraulic fracture simulating (Wu and Wong, 2014; Zhang et al., 2015), and stress wave propagation across rock masses (Fan et al., 2013; Zhao et al., 2014; Zhou et al., 2017). Recently, the NMM has also been explored and developed to analyze the seepage flow in porous and fractured media. Zheng et al. (2015) adopted the NMM to solve unconfined seepage flow in porous media. A new second-order numerical manifold method was proposed and used to analyze free surface flow in inner drains by Wang et al. (2016). Hu et al. (2016, 2017) further developed a new NMM model for analysis of fluid flow and coupling process of hydro-mechanical in fractured media with non-conforming mesh. On the other hand, application of NMM to two-phase flow in fractures and fracture network has not been reported.

This paper presents a numerical manifold method simulation of two-phase flow in fracture networks. Detailed derivation are presented for the development of NMM for the two-phase flow in a fracture network, such as deleting of isolated and dead fractures, the proposed mathematical covers for fractured intersections, derivation of NMM discrete equation, and updating of time step. Exemplification of the developed NMM for study of the two-phase flow in a single fracture, single intersections, and fracture networks is then implemented. The NMM simulation results are verified by those from the FEM or analytical method.

2. Two-phase flow in a fracture

2.1. Governing equations

The fluids flowing in a facture are separated by discrete interfaces in the present study. Therefore, in each fluid domain, the fluid flow can be represented as a single-phase flow following mass conservation and momentum (Darcy's law) equations. Single-phase fluid flow in a fracture has been extensively studied (Witherspoon et al., 1980; Li et al., 2016). Fig. 1 is the schematic illustration of a single-phase flow in a single fracture, where b_h is the hydraulic aperture, dx is the length of small control volume in the direction of x, and ρ is the fluid density. Therefore, the mass conservation can be expressed as

$$b_h \rho v \cdot \delta t - \left[b_h \rho v + \frac{\partial (b_h \rho v)}{\partial x} dx \right] \cdot \delta t = \frac{\partial (b_h \rho dx)}{\partial t} \cdot \delta t \tag{1}$$

where δ_t is the time interval, v denotes the average flow velocity in a fracture, which can be described using the below cubic law

$$v = -\frac{b_h^2}{12\mu} \frac{\partial p}{\partial x} = -\frac{k}{\mu} \frac{\partial p}{\partial x} \tag{2}$$

where x is the local coordinate for the fracture, p is fluid pressure, μ is the fluid dynamic viscosity, k is fluid permeability as $k = b_h^2/12$.

Actually, the surface of fracture in a rock mass is not absolutely smooth and parallel. In order to use the cubic law to describe fluids flow in rough fractures, the method that treating a rough fracture as a pair of smooth and parallel plates is often adopted. The corresponding aperture of the smooth and parallel fracture is 'hydraulic aperture' or 'equivalent hydraulic aperture'. Since it is difficult to obtain the hydraulic aperture, efforts have been devoted to calculate the appropriate hydraulic aperture for a rough fracture. Previously proposed methods were summarized and compared in the research of Li et al. (2016) in detail. Moreover, it is also suggested that the hydraulic aperture could be calculated using the geometric mean aperture (Konzuk and Keuper 2004; Babadagli 2006; Walsh et al., 2008). For example, Morgan and Aral (2015) took the average of the geometric aperture of a wedge-shaped fracture as its hydraulic aperture to study the fluids flow in a single fracture.

The present study is mainly focused on the development of numerical manifold method for two-phase flow simulation in discrete fracture networks. Therefore, the cubic law with constant hydraulic apertures is directly utilized.

For compressible fluid, the fluid compressibility β can be expressed under isothermal condition as

$$\beta = \frac{\partial \rho}{\rho \partial p} \tag{3}$$

Combining (1), (2) and (3), the governing equation for single-phase flow in a single fracture is then derived as

$$\beta \frac{\partial p}{\partial t} - \beta \frac{k}{\mu} \left(\frac{\partial p}{\partial x} \right)^2 - \frac{k}{\mu} \frac{\partial^2 p}{\partial x^2} = 0 \tag{4}$$