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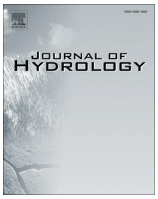

Research papers

Two-phase flow properties in aperture-based fractures under normal deformation conditions: Analytical approach and numerical simulation

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ABSTRACT

A systematic method has been proposed to estimate the two-phase flow properties of horizontal fractures under normal deformation condition. Based on Gaussian aperture distributions and the assumption of local parallel plate model, a simple model was obtained in closed form to predict the capillary pressure-saturation relationships for both wetting and non-wetting phases. Three conceptual models were also developed to characterize the relative permeability behaviors. In order to investigate the effect of normal deformation on two-phase flow properties, the normal deformation could be represented with the maximum void space closure on the basis of penetration model. A rigorous successive random addition (SRA) method was used to generate the aperture-based fractures and a numerical approach based on invasion percolation (IP) model was employed to model capillary-dominated displacements between wetting and non-wetting phases. The proposed models were partially verified by a laboratory dataset and numerical calculations without consideration of deformation. Under large normal deformations, it was found that the macroscopic model is in better agreement with simulated observations. The simulation results demonstrated that the two-phase flow properties including the relationships between capillary pressure, relative permeability and saturation, phase interference, phase structures, residual-saturation-rated parameters and tortuosity factor, were highly sensitive to the spatial correlation of aperture distribution and normal deformation.

1. Introduction

Multiphase flow through rough-walled fractures is significant in many geological applications (Kazemi and Gilman, 1993; Rutqvist et al., 2002; Tsang et al., 2005; Doughty, 2007), such as petroleum reservoirs, geothermal energy development, nuclear waste disposal and geologic storage of carbon dioxide. Constitutive relationships including capillary pressure and relative permeability are essential in modeling multiphase flow and transport process in unsaturated fracture networks or fractured rocks.

Based on the experimental studies of two-phase flow in natural or man-made fractures, the X-model early developed by Romm (1966) indicated that relative permeability is linearly dependent on saturation and the sum of relative permeability is equal to unity. Especially, Wong et al. (2008) also found that the X-model is approximately valid for channel flow patterns when oil-water phases are continuous. However, nonlinear relationships between relative permeability and saturation due to strong phase interference were demonstrated by many other researchers (Merrill, 1975; Persoff et al., 1991; Fourar et al., 1993; Pieters and Graves, 1994; Nicholl and Glass, 1994; Persoff and Pruess, 1995; Fourar and Bories, 1995; Pan et al., 1996; Rangel-German et al., 1998; Bertels et al., 2001). To describe the capillary pressure curves, the Brooks-Corey model was borrowed from porous media by Reitsma and Kueper (1994) and good agreements were shown. The tortuosity of flow structures has been investigated by Nicholl et al. (2000), Chen et al. (2004) and Chen and Horne (2006) according to the distribution of variable apertures.

Simultaneously, several numerical models were proposed to model multiphase flow in rough-walled fractures. These models include standard percolation models (Pruess and Tsang, 1990; Pyrak-Nolte et al., 1990; Mendoza and Sudicky, 1991), a stratified percolation model (Pyrak-Nolte et al., 1992), invasion percolation models (Glass et al., 1998; Amundsen et al., 2009; Ye et al., 2015), continuum model (Murphy and Thomson, 1993;

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Watanabe et al., 2015) and pore network model (Keller et al., 2000; Hughes and Blunt, 2001).

Multiphase flow processes primarily take place in rock fractures, and constitutive relationships are mainly determined by aperture distribution. When the fractures are subjected to stress, the changes of aperture distribution in micro scale may have significant influence on the two-phase flow properties. Recently, Liu et al. (2013) proposed closed-form constitutive relationships between the two-phase properties and fracture-aperture distributions for deformable horizontal fractures subjected to normal stress. Huo et al. (2014) and Huo and Benson (2016) investigated the stress-dependent fracture capillary pressure and relative permeability curves based on experimental measurements. Li et al. (2014) presented a simple and physical model to estimate the relationships between capillary pressure, relative permeability and saturation on water flow in unsaturated rock fractures with normal and shear loading. Watanabe et al. (2015) performed decane-water and nitrogen-water two-phase flow experiments through plentiful real fractures in granite and limestone under confining stress to explore the applicable relative permeability model, it was found that the X-model was also applicable to higher contact angle or bigger aperture condition without capillarity and a new ν-type model modified from Corey model was proposed to describe considerably strong interference between wetting and non-wetting phases.

Nevertheless, most of constitutive relationships for two-phase flow properties in variable-aperture fractures are often borrowed or simply modified from the porous media. For instance, three relative permeability models commonly used are given in Table 1, where k_{rw} is the wetting phase relative permeability, k_{rnw} is the non-wetting phase relative permeability, S_{w} is the wetting phase saturation, μ_{r} is the viscosity ratio between wetting and non-wetting phases, S_{wr} is the residual wetting phase saturation and S_{nwr} is the residual non-wetting phase saturation. These models established based on simple conceptual model for two-phase flow in porous media are questionable for variable-aperture fractures and no single relationship is valid for all type of subsurface fractures. Therefore, the development of constitutive relationships for two-phase flow characteristics for subsurface fractures is still a considerable challenge, especially with stressed or deformable condition. To our knowledge, a systematic approach to quantify the relationships between constitutive relationship and aperture structure for deformable fractures is lacking in the literature. The primary objectives of this study are (1) to develop appropriate constitutive relationships for two-phase flow in aperture-based fractures and evaluate the validity of these models using data from two-phase flow experiments in synthetic and natural fractures from the literature, and (2) to propose an efficient numerical method for assessing the deformation-dependent two-phase flow behavior and investigating the quantitative relationships between self-affine fractal nature of fracture surfaces and characteristic parameters of constitutive relationships.

In this study, we address the development of the relationships between two-phase flow properties and normal deformation in horizontal rough-walled fractures, with consideration of spatial correlation of aperture distribution and tortuosity of flow path. This study is organized as follows. In Section 2, closed-form functions for the capillary pressure and relative permeability of wetting and non-wetting phases are developed, and comparisons between the proposed model and experimental data are presented. In Section 3, on the basis of fractal characteristics, penetration model and invasion percolation model, a comprehensive numerical method is proposed to calculate the relationships between capillary pressure, relative permeability and saturation for deformable fractures. In Section 4, the theoretical predictions for capillary pressure and relative permeability curves are compared with numerical simulations, and the effect of spatial correlation for two-phase flow properties is also investigated.

2. Two phase properties for individual fractures

2.1. Capillary pressure

During the slow immiscible fluid displacements in horizontal, rough-walled rock fractures, the two-phase flow movements are mainly determined by the capillarity where viscous forces and gravity are negligible with respect to capillary forces. When wetting phase is separated from a non-wetting phase by an interface, a pressure difference named capillary pressure P_{c} exists across the interface between two immiscible fluids under the quasi-static condition, and is related to the interfacial tension or surface tension and curvature of the fluid-fluid interface, which can be expressed by general Young-Laplace equation:

$$P_{\mathrm{c}} = P_{\mathrm{nw}} - P_{\mathrm{w}} = T_s\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{1}$$

where P_{nw} and P_{w} are the non-wetting and wetting phase pressures, respectively, T_{s} is the interfacial tension or surface tension, R_1 and R_2 are the principal radii of curvature of the interface. As shown in Fig. 1, R_1 is the radius of in-plane curvature (Fig. 1(a)) and represents the shape of interface curve within the fracture plane, while R_2 is perpendicular to the fracture plane (Fig. 1(b)) and can be determined by local aperture b, contact angle (CA) α and convergence angle β as

$$R_2 = \frac{b}{2\cos(\alpha + \beta)} \tag{2}$$

The CA of wetting phase is given by $0^\circ < \alpha < 90^\circ$ and that of non-wetting phase $90^\circ < \alpha < 180^\circ$.

With the assumptions that the fracture walls are locally composed of two parallel plates with constant aperture b (shown in Fig. 2), and the in-plane interface is flat and thus $R_1 = \infty$ and $\beta = 0$, R_2 can be calculated as $R_2 = b/2\cos\alpha$, and the effect of in-plane curvature $1/R_1$ is negligible in comparison with the aperture-induced curvature $1/R_2$. Hence, the local capillary force balance between the two-phase interfaces yields the following simplified equation:

Table 1
Traditional relative permeability models.

Type	Function
X model (Romm, 1966)	$k_{\mathrm{wr}} = S_{\mathrm{w}}$ $k_{\mathrm{nwr}} = 1 - S_{\mathrm{w}}$
Viscous coupling (VC) model (Fourar et al., 1993)	$k_{\mathrm{wr}} = \frac{S_{\mathrm{w}}^2}{2}(3 - S_{\mathrm{w}})$ $k_{\mathrm{nwr}} = (1 - S_{\mathrm{w}})^3 + \frac{3}{2}\mu_r S_{\mathrm{w}}(1 - S_{\mathrm{w}})(2 - S_{\mathrm{w}})$
Corey model (Corey, 1954)	$k_{\mathrm{wr}} = \left(\frac{S_{\mathrm{w}} - S_{\mathrm{wr}}}{1 - S_{\mathrm{wr}} - S_{\mathrm{nwr}}}\right)^4$ $k_{\mathrm{nwr}} = \left(1 - \frac{S_{\mathrm{w}} - S_{\mathrm{wr}}}{1 - S_{\mathrm{wr}} - S_{\mathrm{nwr}}}\right)^2\left[1 - \left(\frac{S_{\mathrm{w}} - S_{\mathrm{wr}}}{1 - S_{\mathrm{wr}} - S_{\mathrm{nwr}}}\right)^2\right]$