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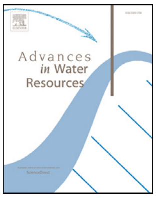

Fluid trapping during capillary displacement in fractures

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ABSTRACT

The spatial distribution of fluid phases and the geometry of fluid–fluid interfaces resulting from immiscible displacement in fractures cast decisive influence on a range of macroscopic flow parameters. Most importantly, these are the relative permeabilities of the fluids as well as the macroscopic irreducible saturations. They also influence parameters for component (solute) transport, as it usually occurs through one of the fluid phase only. Here, we present a numerical investigation on the critical role of aperture variation and spatial correlation on fluid trapping and the morphology of fluid phase distributions in a geological fracture. We consider drainage in the capillary dominated regime. The correlation scale, that is, the scale over which the two facing fracture walls are matched, varies among the investigated geometries between $L/256$ and L (self-affine fields), L being the domain/fracture length. The aperture variability is quantified by the coefficient of variation (δ), ranging among the various geometries from 0.05 to 0.25. We use an invasion percolation based model which has been shown to properly reproduce displacement patterns observed in previous experiments. We present a quantitative analysis of the size distribution of trapped fluid clusters. We show that when the in-plane curvature is considered, the amount of trapped fluid mass first increases with increasing correlation scale L_c and then decreases as L_c further increases from some intermediate scale towards the domain length scale L. The in-plane curvature contributes to smoothening the invasion front and to dampening the entrapment of fluid clusters of a certain size range that depends on the combination of random aperture standard deviation and spatial correlation.

1. Introduction

Many important subsurface engineering applications, such as the geological storage of CO_2, nuclear waste disposal, and geothermal exploitation, involve fractured media and give rise to two-phase flow phenomena in fractures. While understanding the two-phase flow behavior at the scale of fracture networks is important for practical applications, modeling at such a scale requires fundamental knowledge of the behavior at the single-fracture scale. Of particular importance is the fluid trapping process during immiscible displacement in the open fracture. The present study focuses on characterizing fluid trapping and examining its controlling parameters.

The general problem of fluid trapping in geological media is central for engineering situations such as petroleum recovery and CO_2 sequestration. In the former situation, the trapping of oil or gas in the pore space should be minimized to achieve the recovery efficiency of the reservoir. In the latter, on the contrary, trapping of supercritical CO_2 in the pore space by various mechanisms is desired as it improves storage capacity and safety. Recently there has been extensive investigation of fluid displacement and trapping in porous material, including both pore-scale numerical modeling [7,18,23,36] and experimental studies (e.g., [3,4,12,22,28,40]) thanks to the advances in high-resolution imaging techniques (e.g., X-ray computed tomography). But, fluid trapping in fractures has received relatively little attention in the recent literature, although many of the above modeling and experimental methodologies can be applied to the fractured setting.

Natural rock fractures have rough surfaces and variable apertures. The aperture distribution is one of the primary parameters that influence the hydraulic properties of a fracture, both for single and multiphase flow processes. Considerable effort has been devoted to the characterization and measurement of fracture wall topographies and of the resulting fracture aperture fields. Different approaches for aperture measurement have been developed, including surface profilometry (e.g., [1,11,38]), X-ray computed tomography (e.g., [27]) and nuclear magnetic resonance imaging (e.g., [15]). The high resolution measurement of aperture fields together with modern visualization

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techniques has allowed for fundamental investigations of fluid displacement in single fractures. Those measurements and the subsequent analyses of surface topographies of natural fractures have established that these topographies are self-affine (e.g., [8,10]. Besides, the two walls of a fracture have topographies that are essentially identical at length scales larger than a typical mismatch (or correlation) length L_c, and uncorrelated with each other at scales smaller than L_c [10]. Consequently, the resulting aperture field is self-affine at scales smaller than L_c, and exhibit essentially no fluctuations at scales larger than L_c [10,34].

Such a representation of fracture apertures, based on geostatistical parameters (e.g., mean aperture, standard deviation, and correlation length) quantifying the aperture distribution, has been used in several studies involving fluid flow in fractures [5,9,32–34,47]. It has also proven useful to understand the effect of variable apertures on single-phase flow and transport [26,29].

Configurations of immiscible two-phase flow in individual variable aperture fractures have also been addressed [6,16,21]. Such flows are controlled by the interplay between capillary, gravitational, viscous and inertia forces [14]. Understanding that interplay and its impact on the flow regimes and the resulting fluid phase configurations is a prerequisite to studying fluid trapping. Loggia et al. [30] showed that under the influence of buoyancy two-phase flow regimes range from tortuous fingers and random clusters to piston-like displacement with trapping, depending on different combinations of the dimensionless Bond numbers and capillary numbers, which compare buoyancy to capillary forces and viscous to capillary forces, respectively. However, the fracture geometries, flow conditions and regimes explored in these experiments are still limited in comparison to the wide spectrum of behaviors that can occur. On the other hand, insights from investigating fluid trapping as a function of the medium geometry and flow conditions for a given system could allow for an a posteriori characterization of the flow regimes, from the mere knowledge of the trapped cluster geometry. Trapping of the defending fluid during immiscible displacement affects the flow structure of the invading phase behind the front. The amount of trapped phase fluid and its spatial distribution within the fracture affects the relative permeability of the other fluid phase and the fluid–fluid interfacial area. In order to estimate the interfacial area, the characteristics of the trapped phase, i.e., the morphology and topology of the trapped phase clusters, need to be known [19]. Interfacial area is an important parameter for the interphase mass transfer processes that are critical, e.g., to contaminant remediation problems [13,43,45].

Quasi-static displacement in horizontal fractures is dominated by capillary forces, so that in models viscous forces and gravity can be ignored. The capillary number, which compares viscous to capillary forces, has to be much smaller than 1 in this case. Invasion percolation (IP) models have been widely recognized as a physically-sound approach for modeling such slow displacements in rough-walled fractures (see experimental and theoretical studies, e.g., [2,17,20,24,31,35,44]). In these models, a proper calculation of the capillary pressure between the wetting and non-wetting fluids is crucial when simulating fluid invasion, especially if one focuses on characterizing phase distribution and structures. According to the Young–Laplace equation, capillary pressure depends on the interfacial tension and the mean curvature of the fluid–fluid interface. For the fracture geometry, the mean curvature can be calculated using its two principal components, one of them being defined in a vertical plane, the other, which we shall denote in-plane curvature, being defined in the fracture plane. Displacement in the capillary regime is controlled by the competition between the effects of (i) the aperture variability along the fracture plane, which tends to roughen the interface, and (ii) the in-plane curvature, which tends to smoothen it [21]. To calculate the local in-plane curvatures, Glass et al. [20] proposed to use an empirical length scale (which the authors set to half of the correlation length, defined in terms of the autocorrelation or variogram of the aperture field) and an average angle extracted from the local fluid-fluid interface. Similar approaches have been used by Neuweiler et al. [35] and Ferer et al. [17] who treated the empirical length scale as a fitting parameter to be determined by trial and error based on a comparison with physical experiments, which is difficult to be generalized. To overcome those limitations of the above mentioned approaches, Yang et al. [42] developed a generalized method based on a purely geometric definition of the curvature radius, in consistency with the Laplace equation. They estimated the local in-plane curvature radius through a procedure that adaptively fits a circle to the fluid-fluid interface. The in-plane curvature is estimated as the inverse of the radius of the best fitted circle. This approach was validated against experimental data and shown to be advantageous over previous approaches (see 42). Another recent study [46] investigated the effect of aperture field geometry on relative permeabilities; however, the IP model used by Ye et al. [46] took neither in-plane curvature, nor the trapping of the defending fluid, into account.

To our knowledge, the effect of the aperture field geometrical (geostatistical) parameters on fluid displacement and trapping is still not fully understood. The purpose of this study is thus to quantitatively characterize the trapping of the defending wetting fluid during drainage, under various aperture field geometries. We focus on trapped wetting phase saturation and on the distributions of sizes for trapped fluid clusters. The aperture fields investigated span a range of geometries, from uncorrelated fields to fully self-affine fields.

2. Method

In this section, we will first present the method to generate realistic aperture fields, followed by the description of the model which is based on invasion percolation including the effect of in-plane curvature. Then, we describe the simulation scenario of nonwetting phase invasion and the parametric study design.

2.1. Fracture aperture fields

To describe the topography fracture wall surfaces, we follow Brown [10] to define a power spectrum for surface roughness of the form

$$G(\xi_x, \xi_y) \propto \left[\xi_x{}^2 + (\xi_y/a)^2\right]^{-(1/2+H)} \tag{1}$$

where ξ_x and ξ_y are the wave numbers in the x and y dimensions, H is the Hurst exponent, in the range of $0.5 < H < 1$ with a typical value of $H = 0.8$ [8], and a the anisotropy factor. In this study, we assume isotropy in fracture surface roughness by assigning $a = 1$. We use an inverse fast Fourier transform (iFFT) method to generate fracture wall surfaces.

Fracture apertures correspond to the gap between the two facing rough surfaces, whose average planes are parallel to each other. Experimental work by Brown et al. [11] has shown that at large wave numbers (short wave lengths) the power spectrum of fracture aperture fields has the power law behavior typical of self-affinity and described in Eq. (1), and therefore characterized by the corresponding Hurst exponent, but that at small wave numbers (long wave lengths) the spectrum density approaches a constant value. We define a mismatch (or cutoff) wave number (spatial frequency), ξ_c (respectively, a mismatch length scale, L_c), below (respectively, above) which the spectrum density flattens out. To ensure the two surfaces to be matched at small wave numbers (i.e., long wave lengths), we generate the two surfaces with phase spectra that are identical below the cutoff wave number ξ_c. The resulting random aperture fields are self-affine at scales smaller than L_c, and exhibit hardly any heterogeneities at scales larger than L_c. A more detailed description of the procedure for generating the fracture surfaces and aperture fields can be found in Brown [10].

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