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Fractal analysis of single-phase water and polymer solution flow at high rates in open and horizontally displaced rough fractures

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ABSTRACT

A study on the percolation characteristics of single-phase flow in rough fractures at high rates representing hydraulic fracturing conditions is presented. Two-dimensional transparent models of fractures obtained from different rock types (granite, marble and limestone) were reproduced by molding. To represent typical hydraulic fracturing fluids, water and polymeric solutions were injected at a constant flow rate. The inlet pressure was continuously monitored to correlate the permeability changes due to surface roughness of fractures. The fluid distributions were also mapped using the images acquired through the experiments. The surface roughness was quantified using three fractal methods (variogram, power spectral density, and triangular prism) and the ratio of total and planar areas, and these parameters were correlated to the percent wetted areas and pressure drop (i.e., permeability). This exercise was performed on joint type and horizontally displaced (sheared) model fractures.

The percentage of planar flow wetted area representing invasion percolation and pressure drop changed remarkably with rock types. Both parameters were controlled by grain size and the surface roughness of fractures. Increasing degree of the roughness caused a decrease in permeability and area wetted by fluid. Models generated from bigger grain size rocks showed more channeling and a lower percentage of fluid wetted areas as well as lower pressure drop (higher permeability). The variogram fractal dimension showed better agreements among other methods for both fluid (water and polymeric solution) and fracture types (joint and horizontally displaced).

1. Introduction

Flow of Newtonian and non-Newtonian fluids in fractures is commonly encountered in different industrial applications including hydraulic fracturing. The distribution of these fluids carrying proppants is critically important to create and maintain the conductivity of the fractures. The common approach followed by practitioners in estimating the conductivity capacity is the assumption of two parallel smooth plates (smooth surfaces) to represent the fracture and applying Darcy's law:

$$Q = -\frac{kA}{\mu}\frac{\Delta P}{L} \tag{1}$$

where Q is the flow rate, L is the length of fracture, ΔP is the pressure drop through the length of the fracture, A is the cross sectional area, k is permeability, and μ is the fluid viscosity.

If the fracture surface is considered as a smooth planar area, the permeability of fracture (k_f) is defined according to the parallel plate model as follows [1]:

$$k_f = \frac{b^2}{12} \tag{2}$$

where b is the aperture of the fracture; i.e., the distance between two plates. Since the relation of flow rate with pressure drop in a length of fracture is given by Darcy's law:

$$Q = -\frac{k_f A}{\mu}\frac{\Delta P}{L} \tag{3}$$

Then, flow through fracture with fracture permeability in a cross-sectional area of A=Wb is defined according to cubic law as:

$$Q = -\frac{Wb^3\Delta P}{12\mu L} \tag{4}$$

where b and W are the average aperture and the width of the fracture.

The flat plate model is inadequate for predicting permeability in fractures as the change of the aperture width results in inconsistent

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values of permeability.[2] With a decrease in the wavelength of the fracture wall due to roughness the overall aperture decreases, which yields a decrease in the permeability of fracture.[3,4] It was reported by Tsang[5] that the predicted value of flow rate for a real rough fracture using the parallel plate assumption can be three or more orders of magnitude higher than the actual value of that fracture. Similarly, Brown[6] showed that with the assumption of smooth fracture surfaces, the flow rate predicted by cubic law can be 70–90% higher than realistic (rough) representation of surface fractures. In fact, when fluid flows in smooth fractures, the velocity profiles are ideally parabolic; this is not the case in the presence of surface roughness.

Oron and Berkowitz[7] and Berkowitz[8] questioned the validity of cubic law. Berkowitz[8] remarked the adequacy of cubic law for rough rock fractures to be an open question due to the difficulty in obtaining reliable data of aperture. The cubic law in Eq. (4) derived by the Darcy's law exhibits a linearly proportional relationship between the flow rate and pressure drop for a flow through two parallel smooth plates. But, the presence of surface roughness can cause the formation of different flow regimes in real fractures. Linear relation between the flow rate and pressure drop was observed in some laboratory flow tests performed on rough fractures.[9,10] On the other hand, the commonly reported flow regimes in the literature have usually been the non-linear types for rough fractures. For instance, cubic[11] and quadratic[11,12] relationships were reported from the results of both experiments and simulations. Qian et al.[13] defined an empirical exponential function. Similarly, the characteristics of flow were also non-Darcian in the experimental works of Chen et al.[14] and Qian et al.[15] The geometrical model proposed by Javadi et al.[16] suggested a polynomial expression, similar to the Forchheimer law. Therefore, flow in rough fracture surfaces cannot sufficiently be characterized by cubic law (Eq. (4)). Additional physical and theoretical parameters such as distribution of asperities should be incorporated into cubic law.[17]

Adjacent rough walls of a fracture may perfectly match and thoroughly contact each other forming a tightly closed joint type fracture.[18] The normal (or vertical) displacement of such a horizontal single fracture in the direction that is perpendicular to the mean fracture plane without any horizontal (shear) displacement may cause the formation of a constant aperture field within the fracture. On the other hand, any horizontal (or shear) offset of such a fracture with or without normal opening may result in mismatching fracture walls and thus variable aperture structure. Roughness can be neglected for large fracture openings, in which case the parallel plate model may be relevant to flow whereas for a small opening less than roughness, aperture fluctuations are controlled by the height distribution of the.[19]

The resistance of fluid to flow through variable openings caused by surface roughness leads to diverted flow around asperities in contact and to take a tortuous flow path.[20] Tortuous flow path is controlled by the hydraulic aperture, which decreases with increasing surface roughness and, eventually, affects the permeability of fracture.[5,21,22] Variation of surface roughness depends on rock type and its material grain size.[23–25] Meanwhile, mismatching of two surfaces is formed as a result of shear displacement, which leads to redistribution of asperities (variable aperture structure) and increase in heterogeneity.[26–29] Then, aperture distribution broadens with increasing mismatching and this results in a more challenging type flow and thereby an increase in fracture connectivity.[3,30] Horizontal (shear) displacement of a fracture induces an anisotropic aperture field that is significantly larger in the direction perpendicular to the movement, and this causes long flow channels to form in that direction through which a higher effective permeability occurs.[28,31] All these observations were also supported by visualization studies.[25,32–35] These studies verify that surface roughness is a significant parameter and can lead to a considerable difference from the parallel smooth plate model. The main problem is to quantify these effects for a wide range of rock, fracture and fluid types to eventually incorporate the roughness effect into the flow equations.

In our earlier studies, the roughness effect was qualitatively and quantitatively analyzed for single phase flow in deformable (dilating) fractures[25] and multiphase flow.[24,25] These studies were conducted at the flow conditions applicable to natural flow or water-gas injection to enhance oil/gas recovery. Therefore, the injection rates were relatively low. The objective of this paper is to examine the flow of Newtonian and non-Newtonian fluids at much higher rates that are applicable to hydraulic fracturing conditions. This type of high rate application is particularly important for distributing the proppant injected throughout the fracture as uniformly as possible to maintain hydraulic conductivity during the production stage.

Di Federico[36] derived a governing equation for non-Newtonian power law fluid flow taking the tortuosity effect into account. For one-dimensional idealized fractures, his approach demonstrated that fracture permeability decreases with increasing flow tortuosity and neglecting tortuosity leads to an overestimation of fracture permeability. The recommendation Di Federico[36] made was further experimental work, especially on a real fracture with variable aperture structure to validate his prediction. In his review paper, Lavrov[37] pointed out that current knowledge and understanding of non-Newtonian fluid flow in realistic self-affine rough fractures is by far weaker than that of Newtonian fluid flows in fractured and porous media despite its practical importance to be invaluable for optimization of technologies in drilling and oil production. In this study, the laboratory experiments of Newtonian and non-Newtonian fluid flow were carried out in joint type and horizontally displaced (sheared) model fractures representing different roughness characteristics (granite, marble, and limestone) and quantitative analyses were performed using fractal properties of fracture surfaces. The quantitative and visual data of fluid flow were collected from the experiments performed on the joint and horizontally displaced (sheared) fractures by injecting water and polymer solution. The degree of roughness was described by several fractal methods (variogram analysis, power spectral density analysis, and triangular prism surface area method) and using the ratio between total and planar areas of the surfaces. Then, correlations between the roughness parameters and wetted areas and fracture permeability were sought for Newtonian and non-Newtonian fluids flowing in joint and horizontally displaced (sheared) fractures.

2. Experimental methodology

2.1. Sample preparation

Seven lithologically different rock types were used in this study to present a wide range of fracture roughness types. Thin sections were prepared from these rock samples and inspected under polarized microscope using point counting technique for exact nomenclature and petrographic description based on the composition of constituent minerals, textural properties, and granularity (grain size). Minimum, maximum, and average sizes of the grains were directly measured on these thin sections under polarized microscope. Brief petrographic descriptions and granularities obtained are presented in Table 1. Sample images taken from the thin sections under polarized microscope are visualized in Fig. 1a. We could not perform this inspection process for the sample Fr1 as it is quite difficult to prepare a thin section from this sample due to its crumbling nature when cutting. Thus, only a macroscopic description was made for this sample.

Seven rock samples of different kinds (granite, marble, and limestone) with dimensions 20×20×20 cm were fractured under tension (modified Brazilian test). Then, single fracture models square in shape with a side length of 20 cm were produced by a series molding and casting processes of the created rock fractures (Fig. 1b). To visualize the experiments, the upper part was made of transparent polyurethane while the lower part was manufactured using a non-transparent rubber. One model's (Fr.4s) both sides were made of solid transparent polyurethane as an exception. The details of the procedure followed to prepare fracture models are provided in Develi and Babadagli.[25]