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Visualization of fluid occupancy in a rough fracture using micro-tomography

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Abstract

The purpose of this work is to study the effects of fracture morphology on the distribution and transport of immiscible fluid phases, such as oil and water, through a vertical fracture. An experimental approach, using micro-computed tomography (MCT), was selected to characterize the internal fracture structure and to monitor two immiscible phases. The experiment was performed in Berea sandstone cores with a single longitudinal fracture. The artificially created fracture was oriented parallel to the natural bedding of the rock. The sample was initially vacuum-saturated with water, and oil was later injected through the longitudinal crack. Fluid occupancy in the fracture was mapped under four different flowing conditions: continuous oil injection, continuous water injection, simultaneous injection of oil and water, and a static pseudo-segregated state. Some of the mechanisms observed in this experiment include fluid trapping, preferential flow paths, snapping-off of non-wetting fluid globules, and coalescence and redistribution of globules between dynamic and static conditions. Experimental results indicate that distribution was mainly determined by fracture geometry, saturations, and wetting characteristics of the rock. A strong correspondence between fluid distribution and fracture apertures was found through direct comparison of two- and three-dimensional fracture structures.

Keywords: Open fractures; Oil–water interface; Asperities; Computed tomography; Interfacial tension

1. Introduction

In spite of the importance of fracture geometry on the flow characteristics of fractured formations, fluid flow through fractures is usually studied using oversimplified models. In most cases, fractures are treated as two parallel plates [1,2] because of the inherent difficulty of representing more realistic geometries and the complexity of mechanisms of mass transport in these systems. In fractured porous media, fluid transport is dominated by the properties and geometry of the fracture network. However, in flow simulations of geological systems, flow through fractures is often assumed to occur between parallel plates due to the laborious task of measuring local apertures and accounting for their random variations when modeling fluid flow. Electrical resistor network models have been used to study the effect of path tortuosity on flow through fractures [3], demonstrating a reduction in flow rate with respect to the values predicted by the parallel plate representation, when tortuosity increases. Real fractures have variable apertures, which create roughness and tortuosity for fluids to flow. Thus, actual fracture flow rates are typically less than the ones predicted by the parallel plate model.

Numerous authors [3–7] agree on the complexity involved in describing flow through real fractures and the importance of characterizing roughness and tortuosity to properly describe the effects of fracture structure on the final ability to transport fluids. Experiments using transparent, epoxy replicas, and analog-rough fractures have provided means to describe preferential flow paths [8], entrapped phase dissolution [9], and their dependence on fracture morphology. Numerical models representing fractures with variable apertures have also contributed to current understanding of multi-phase fluid transport through fractures [10–12]. However, the description of immiscible flow in real fractures is still on early development. The motivation of the present experimental work is based on the lack of direct, quantifiable visualization of immiscible fluid phases in a real fracture. A realistic description of the inner structure of a fracture is presented in this work. Water and oil, representing wetting and non-wetting phase, were injected into the fracture to study their interaction with the geometric characteristics of

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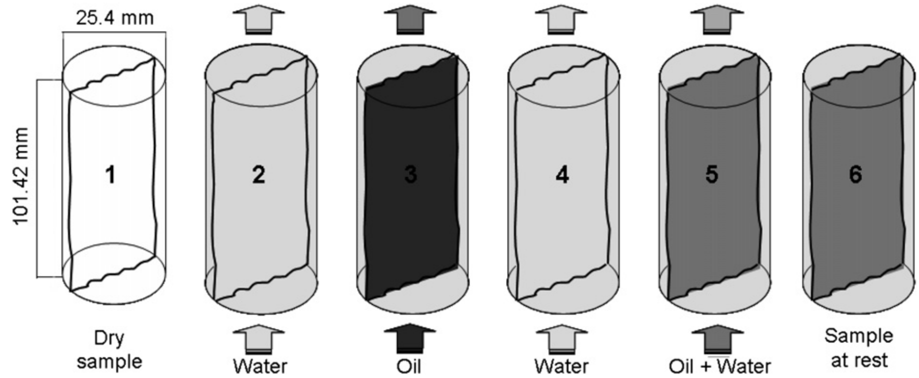

Fig. 1. Schematic of experimental procedure in six stages.

the fracture. Findings from this work have a positive contribution on the description of phase structure and multi-phase fluid conductivity in rough fractures, which could significantly enhance prediction of flow barriers and pathways in numerical modeling.

2. Experimental method and materials

A cylindrical sample of Berea sandstone was artificially fractured using a triaxial, servocontrolled, hydraulic press. Normal stress was gradually increased on the sample up to the point of failure. After splitting the sample, the two exposed surfaces were ill-matched with a slight shift of 1 mm along the longitudinal axis. This shift accentuated aperture changes inside the fracture. Both ends of the cylindrical core were saw cut and ground parallel. The exterior of the sample was wrapped with Teflon to prevent confining fluids from entering the rock. Confining fluid was injected into the annulus between the sample and the walls of the core holder, providing an equally distributed confining pressure of about 0.2 MPa. Confining pressure prevents fluids bypassing through the rock walls and gives physical stability in the radial direction.

Micro-computed tomography (MCT) was used to characterize the fracture's inner structure and to map fluid occupancy under dynamic and static conditions. The MCT scanner consists of an X-ray source, a detector, a translation system, and a computer that controls motion, data acquisition, and reconstruction. The X-ray source produces cone-shaped beams that allow the collection of volumetric data. The system produces 1024×1024 pixels per image and enables a maximum resolution of 5–10 μm. Previous experimental work using X-ray CT for the characterization of natural fractures report pixel resolutions that range from 0.27 mm $\times$ 0.27 mm to 1.40 mm $\times$ 1.40 mm [13–15]. In some cases [14,15], CT data are coupled with imaging and calibration algorithms to refine aperture measurements. To overcome the difficulty of measuring fracture apertures with accuracy, the specified voxel resolution in the present experiment was set at 0.027344 mm $\times$ 0.027344 mm $\times$ 0.032548 mm, where 0.032548 mm indicates the slice thickness. A total of 3116 slices were necessary to scan the entire core (3116×0.032548 mm $= 101.42$-mm-long core).

The two fluid phases used were oil and water. The oil phase was a mixture of silicone oil and 30% by weight of n-decane, for a resulting approximate viscosity of 5.0 cp and a density of 0.89 g/cm^3 at 25 °C. Water was tagged with 15% by weight of sodium iodide (NaI) in order to increase its CT registration, thus increasing the contrast between the two phases. The viscosity of tagged water was approximately 1.2 cp and its density was 1.11 g/cm^3.

A schematic representation of the experimental procedure and scanning sequence is presented in Fig. 1. The dry sample was scanned for a period of about 5 h to obtain a three-dimensional map of the fracture (stage 1 in Fig. 1). These MCT images were used for detailed characterization of the fracture's inner structure, including aperture distribution, topography, volumetric calculations, and determination of contact area. In stage 2 of Fig. 1, the sample was vacuum saturated with tagged water. The difference between the volume required to saturate the sample and the volume of the fracture allows estimation of effective sample porosity. The following two stages of the experiment, stages 3 and 4 in Fig. 1, consisted of displacing fluids in the fracture through consecutive injection of oil and water. In both cases, the sample was scanned from bottom to top. During continuous oil injection, fluids in the fracture reached irreducible water saturation (Swirr). The distribution of fluids at residual oil saturation was obtained from continuous water injection (stage 4). The terms irreducible water and residual oil saturations are used in the context of the duration of the current experiments. Continued injection may in fact reveal slightly smaller residual and irreducible saturations. Preferential flow paths, developed during the simultaneous injection of wetting and non-wetting phases (water and oil), were observed during stage 5 of the experimental procedure. In stage 6, oil and water were allowed to spontaneously segregate for a period of 12 h. Fluid exchange between the rock matrix and the fracture was considered negligible. The strong wetting affinity of water to the rock prevented oil from invading the matrix at low injection pressure. The two ends of the fracture were open, which also facilitated fluid flow through the fracture only.

3. Results and discussion

3.1. Visualization of fracture geometry

A three-dimensional reconstruction of the MCT data from the dry scans is presented in Fig. 2 top. The sample was