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Full Length Article

Interfacial boundary conditions and residual trapping: A pore-scale investigation of the effects of wetting phase flow rate and viscosity using micro-particle image velocimetry

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ABSTRACT

We introduce a new two-phase and two-fields-of-view micro-Particle-Image-Velocimetry (μPIV) experimental apparatus that is used to conduct systematic studies of pore fluid occupancy and velocity fields under two-phase flow conditions in different micromodels. The apparatus allows simultaneous study of flow fields at the pore- and micromodel-scales. This system is utilized to develop a deeper insight into the distribution of fluids and shear stress at the interface of invading and defending fluids in two Polydimethylsiloxane (PDMS) micromodels: a pore-doublet configuration and a two-dimensional replica of Bentheimer sandstone. We investigate the effect of changes in invading wetting phase flow rate and viscosity and injection of a non-wetting droplet on pore fluid configuration and residual trapping. We discuss how the local perturbations of velocity fields impact displacement of non-wetting phase, the residual trapping, and distributions of the trapped non-wetting phase globules. Furthermore, we map the rotational velocity of the non-wetting fluid within a selected group of trapped globules and discuss how the flow rate of the passing wetting fluid and the momentum transfer across the fluid/fluid interface impacts the stability of the local pore occupancy of the non-wetting phase. The experimental observations provide direct evidence of slip boundary condition at the fluid/fluid interfaces. They show the mechanisms of momentum transfer across the interfaces and their impact on pore-scale displacements and fluid occupancy.

1. Introduction

Micro-models and micro-fluidic devices have long been utilized as effective qualitative and, recently, quantitative tools to develop a better understanding of flow of fluids and fluid/fluid/solid interactions in pores and throats of different porous materials at mili-, micro- and even nano-meter scales. Researchers have successfully fabricated micron-scale features, e.g. pore-doublets [1–5] and two-dimensional porous medium representations [6–22], in which flow of fluids, particles, and solutes are visualized and studied. These representations are often regular connected networks of channels designed to study a specific phenomenon [6,7], replicas of two-dimensional images of actual reservoir rocks [8,9], Hele-Shaw cells [10,11], or very small glass spheres sandwiched between two glass plates [12,13]. Micro-models have to be transparent at least on one side to allow visualization of the fluids and features of the model. Additionally, there are other less common types of micro-models, such as those introduced by Mahmood [14] and Song et al. [15], that are made of crushed cryolite grains, actual rock slabs sandwiched between two glass plates, or an etched calcite crystal that is sealed with a flat glass slide. These models have more fluid visibility limitations when traditional micro-model studies are performed. This limited visibility is because one side of these models is opaque; therefore, the light can only be reflected from the fluids and cannot pass through them. However, when the fluid flow in these models is studied using micro-particle-image-velocimetry (μPIV), such limitations do not exist. Finally, there are studies that have focused on the enhancement of geometrical [23] and geochemical [24] aspects of micro-models. Glass is the most common material used to build micro-models because it is nonreactive to brines, oils, and gases that represent the fluids in hydrocarbon reservoirs [4,16–18,22]. Glass micro-models are mainly made by etching a flow pattern on a piece of glass using hydrofluoric acid (HF) and then thermally bonding it to a flat glass plate. A drawback of etching a glass plate with HF is production of channels with curved walls and bottoms. Therefore, in order to build channels with well-defined cross-sectional shapes and straight sides, a very controlled procedure is needed, or the models should be built using other materials such as silicone and Polydimethylsiloxane (PDMS) by employing manufacturing methods such as photolithography and inductively

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coupled plasma deep reactive ion etching [19–21]. On the other hand, the drawback of using PDMS is its incompatibility with a significant number of oils, particularly crude oils, and its deformability under high pressures. However, PDMS models are very easy and inexpensive to fabricate and can form very well defined channel geometries, i.e., straight walls and flat bottoms. Micro-models can handle conditions ranging from ambient/low pressures and temperatures [4,7,8,10–12,14,15,17,19,21] and inert fluids such as brine, mineral oils, air, and nitrogen [14,21] to high pressures and temperatures [6,13,18,20] and more reactive fluids such as crude oils and CO_2 [12,15]. It is worth noting that water and brine can act as inert [25] or reactive [15] agents in presence of different materials at all pressure and temperature conditions. In recent years, advent of more advanced image acquisition and processing techniques has made the quantitative analysis of fluid flow in rock samples and micro-models possible. There are different quantitative methods to capture images of fluids in pore spaces, analyze them, and extract the physical meaning of the information hidden in each image, such as saturation of each phase, mechanisms of fluid/fluid interactions, and the velocity of fluids at each point in the medium. In this area of research, among the most recent quantitative tools used to capture and analyze images in real rock samples are computed tomography (CT) and μCT imaging [26–31]. For transparent replicas of these rock samples particle-image-velocimetry (PIV) [32,33] and specifically μPIV [34–38] are among the most recent methods. PIV and μPIV track the position of fluorescent particles dispersed in fluids with time; thereby measuring their velocities, which is equal to the velocities of the carrying fluids. This provides pore-scale velocity maps of the flowing fluids in a porous system. In PIV and μPIV, a light source (usually laser) with a specific wavelength illuminates part of the transparent porous medium. Fluorescent particles receive this light and reflect it at a different wavelength towards a recording camera. In order to record only the light received from the particles, the reflected light is passed through some filters before reaching the cameras. More images are then captured at specific time intervals and the positions of the particles are compared in these consecutive snapshots. By dividing single images into smaller divisions called interrogation windows and applying a cross-correlation technique, the distances traveled by the particles are determined. Dividing these distances to the time difference between the two consecutive images, the velocity of fluorescent particles, which is the velocity of the carrying fluid, is measured. The main difference between PIV and μPIV is how the model is illuminated. In PIV, the model is illuminated using a light sheet and the particles that are illuminated by that light participate in measurement of fluid velocity, whereas in μPIV, the focal plane of the objective lens of the microscope acts as the measurement plane [32–36].

A few researchers have used μPIV to study fluid flow through porous media [39–46]. Perrin et al. [39] showed the applicability of μPIV to porous media research by conducting a single phase flow study in a capillary channel and a Berea sandstone replica etched into silicon. They used an Nd:YAG laser as the light source and a charged coupled device (CCD) camera connected to an epifluorescence inverted microscope to capture the images. Datta et al. [40] also used a single-phase μPIV system consisting of a confocal microscope to directly visualize fluid velocity fluctuations in a three-dimensional synthetic porous medium. They ultimately suggested that although the geometry of the pore space is complicated, the fluid flow through such a medium "is not completely random". This was concluded by calculating the probability density functions of velocity vectors along and transverse to the imposed flow direction. Wang and Wang [41] utilized a single-phase μPIV setup to determine permeability of their two-dimensional porous structure based on velocity measurements in different planes of the model. Their results showed that the calculated permeability based on the center plane velocities was larger than that of the cross section plane velocities. To solve this problem, they recommended calculating the permeability based on the velocity measured over the whole model depth using a scanning μPIV technique. Blois et al. [43], on the other hand, conducted immiscible, two-phase flow experiments on a regular network of pores made of PDMS in order to study liquid–liquid interactions using a two-phase, single-field-of-view μPIV setup. The difference between Blois et al.'s [43] and previously mentioned setups is that the former utilized two cameras and two different fluid tracers with different emission wavelengths which enabled them to perform two-phase velocity measurements. The produced velocity maps using μPIV can be utilized to study fluid/fluid/solid interactions. These maps can also be used to probe the mechanisms involved in trapping, film flow, bifurcation, preferential flow pathways, and confluence in more detail [39,43,44,45,47,48]. Another advantage of deploying the μPIV technique in porous media models is the generation of data required for quantitative validation of pore-scale computational models of fluid flow through porous media [39,46].

In this work, we established a unique two-phase, two-field-of-view (2-FOV) μPIV system in collaboration with TSI Inc., MN, USA. In addition to studying fluid-solid interfaces, this system allows to examine fluid-fluid interactions, which have rarely been applied in flow through porous media research. This setup enables us to simultaneously study fluid movement at the pore scale using the small FOV part of the system, and also across the entire model, using the large FOV module integrated with the apparatus. Images acquired by the large FOV module are used to derive fluid saturations as well. Three Silicone oils with different viscosities were used as the wetting phase, and a mixture of water and glycerol was used as the non-wetting phase. Two-phase flow experiments were performed in designed pore-doublets made from PDMS that allowed the study of velocity fields and shear stress at the fluid/fluid interfaces and the trapping and reconnection mechanisms governing the remaining fluid's distribution and saturation. Furthermore, we built and used PDMS replicas of Bentheimer sandstone. Single-phase tests performed in these porous media models were used to study fluid bifurcation, confluence and stagnation points, which could not be distinguished in a regular micro-model setup with no velocity measurement. Sites where diffusion or dispersion of solutes, contaminants, or particles are more dominant can be easily recognized by determining mobile and immobile fluid locations. In addition to single-phase studies, two-phase drainage and imbibition experiments were performed and fluid interfaces and trapped non-wetting phase distributions along with their velocity fields at the end of each imbibition period were examined in detail. Effects of flow rate change and its history combined with the wetting phase viscosity variation were studied thoroughly on the ultimate recovery and phase distribution. In addition to providing a platform for validation of numerical models of fluid flow in porous media; the information provided here helps in planning and management of oil recovery processes and contaminated soil remediation. To the best of our knowledge, for the first time, this study provides the evolution of velocity fields of the trapped non-wetting globules in a porous system over a sequence of flow rate changes.

In this document, we first introduce the materials used to build the micro-models and the wetting and non-wetting fluids. The experimental setup and procedures are then explained in detail followed by results and discussion. Finally, a set of concluding remarks completes the paper.

2. Micro-models and fluids

2.1. Micro-models

The micro-models utilized in this study were made of PDMS, which is a strongly oil-wet silicone-base organic polymer. Hence, in the experiments performed in this manuscript, the wetting phase was always silicone oil and the non-wetting phase was the water/glycerol mixture. To fabricate the porous model, a pore network was designed using a modified two-dimensional, high-resolution X-ray μCT image of Bentheimer sandstone. The network was then printed on a piece of transparent paper. The μCT image mapped features as small as 2.5 μm,