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Particle velocimetry analysis of immiscible two-phase flow in micromodels

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ABSTRACT

We perform micro-PIV measurements in micromodels using very simple optical equipment combined with efficient image acquisition and processing. The pore-scale velocity distributions are obtained for single-phase flow in porous media with a typical pore size of 5–40 µm at a resolution of 1.8 µm × 1.8 µm vector grid. Because the application of micro-PIV in micromodels is not standard, extensive effort is invested into validation of the experimental technique. The micro-PIV measurements are in very good agreement with numerical simulations of single-phase flows, for which the modeling is well established once the detailed pore geometry is specified and therefore serves as a reference. The experimental setup is then used with confidence to investigate the dynamics of immiscible two-phase flow in micromodels that represent natural complex porous media (e.g., sandstone). For unstable immiscible two-phase flow experiments, micro-PIV measurements indicate that the flow is highly oscillatory long before the arrival of the invading interface. The dynamics are accompanied with abrupt changes of velocity magnitude and flow direction, and interfacial jumps. Following the passage of the front, dissipative events, such as eddies within the aqueous phase, are observed in the micro-PIV results. These observations of complex interface dynamics at the pore scale motivate further measurement of multiphase fluid movement at the sub-pore scale and requisite modeling.

1. Introduction

Detailed understanding of the underlying physics of immiscible two-phase flow in porous media is of great importance in many areas of applied science and engineering including hydro-geology [62], reservoir engineering [18], and CO_2 sequestration [52]. Interest also extends to manufactured porous materials such as fuel cells [31], nuclear safety devices [59], and distillation columns [63]. For example, a fundamental understanding of the displacement mechanisms of a more viscous fluid by a less viscous fluid is critical to optimal hydrocarbon recovery and subsurface storage of CO_2 [72]. In large-scale subsurface flow processes, the behavior is a strong function of the physical and chemical properties of both the injected and resident fluids (viscosity, interfacial tension, density, solubility) and to the porous medium itself (pore size, permeability distribution, wettability of the solid surface, and so on). The competition between the capillary, gravity and viscous forces can lead to highly unstable flow resulting in fingering. These instabilities are the least understood and least predictable phenomena in porous media physics [13].

Previous studies of unstable two-phase flow at the core-scale [7] have demonstrated that these processes are not described adequately by the standard two-phase extension of Darcy's law [43]. This is not surprising given that this Darcy-based approach relies on very strong assumptions, including scale separation between the local events and the large-scale phenomena as well as that the shear stress exerted at the non-wetting/wetting fluid interface has no impact on the large-scale behavior [71]. More importantly, the standard multiphase approach assumes that the fluid–fluid interface is locally stable at the pore-scale [40]. Observation of immiscible two-phase flows in porous media often includes complex mechanisms that span multiple length and time scales. On the one hand, macroscopic phenomena influence the local velocities; on the other hand, pore-scale interfacial events affect the large-scale patterns considerably. It is well established that the interface between two immiscible fluids is transported by abrupt jumps, the so-called Haines jumps [25]. Over the last several decades, it has been demonstrated that these rapid pore-scale events are essential and that they account for a significant fraction of the energy dissipation in the system [42]. Moreover, it has been shown experimentally [11,41] and numerically [6,23] that these jumps reach velocities that are orders of magnitude larger than the mean injection velocities. It has been suggested that such inertial effects that accompany the jumps, completely dictate the invasion patterns [23], and thus, the emerging large-scale behaviors. The origins

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and consequences of these local interfacial processes on large-scale flow in complex porous media remain largely unexplored.

Despite recent great improvements in computational fluid dynamics (CFD) techniques, it is still challenging to model accurately the dynamics of the interface between two immiscible fluids in the pore space at low capillary numbers. For example, interface capturing techniques, such as the Volume of Fluid [26], or Level Set [65] methods, still suffer from spurious currents introduced during the computation of the curvature of the interface. In capillary driven flows, these 'parasitic' velocities can become more important than the physical interface dynamics and lead to completely unphysical invasion patterns. Some authors have applied filtering techniques to minimize the impact of spurious currents [24,30,49]. As demonstrated by the recent experimental work of Moebius and Or [41] and emphasized here, the interface motion is highly complex and one has to be sure that such filtering techniques do not lead to wrong conclusions about the physics associated with multiphase flow. Another challenging aspect of the numerical modeling of two-phase flow in porous media concerns the representation of the contact-line dynamics at the solid walls. The scales associated with such contact lines are measured in nanometers, which is extremely expensive in CFD simulations. Instead, a cut-off size is usually employed, and the real contact angle formed by the two-phases and the solid is up-scaled to the numerical simulation scale [19]. It has been shown that the velocity of the interface near the contact line depends significantly on the model describing the contact angle [34,64]. Accurate measurements of multiphase flow in complex natural porous media are needed to compare these multiphase pore-scale simulators with reference data.

Experiments in simplified two-dimensional porous media, *i.e.,* micromodels that provide direct observations at the pore level [14] are used to develop a detailed understanding of the flow dynamics in complex pore spaces. In these experiments, a silicon wafer is generally used, in which the image of the pore network is etched to a certain depth and bonded to a glass plate to form the micromodel [51]. Reference experimental studies in micromodels of the displacement mechanisms of one fluid by another were performed by Lenormand et al. [36,37] in rectangular ducts. For drainage displacements, *i.e.* a non-wetting fluid such as oil displacing a wetting fluid such as water, they identified three major flow regimes (viscous fingering, capillary fingering, and stable displacement) according to the capillary number and viscosity ratio [35]. These early works have been extended to micromodels of realistic pore patterns, which are particularly interesting to understand subsurface flow processes. The current micromodels can represent pore throats as narrow as several micrometers. Extrapolation of micromodel results to 3D systems must be performed carefully of course; nevertheless, micromodels are an excellent tool for visualizing fluid movements in complex pore geometries [15].

In order to focus on the dynamics of two-phase flows in micromodels, the Particle Image Velocimetry (PIV) technique is used here to obtain instantaneous velocity measurements. This optical method of flow visualization is based on the detection of tracer particles in the flow field. The motion of the seeded particles is used to calculate the velocity field. This technique allows for quantitative comparisons between experimental and numerical data. In the context of microfluidics, in 1998, Santiago et al. [58] introduced micro-Particle Image Velocimetry (micro-PIV) that uses a microscope, micron-sized particles, and a CCD camera to record high-resolution particle-image fields, where the velocity field is calculated by cross-correlating the acquired images [39]. Micro-PIV systems generally use complex and expensive optical systems, including a laser, tracer fluorescing particles, an epifluorescent microscope, a high-speed camera for observation, and optical filters to block the non-fluorescent light disturbances. A recent study has shown the use of two cameras to image the two-immiscible fluids separately using spectral separation [11].

Problems and difficulties faced by performing micro-PIV measurements are numerous, and they must be dealt with using particular attention. Notably, the micro-particles should follow, but not disturb, the flow field [39]. Moreover, light originating from the channel walls and other disturbances have to be blocked, or removed, in order to collect only the light originating from the tracer particles. Moreover, micro-PIV experiments suffer from low particle image concentration and errors due to Brownian motion [39]. Thus, it is essential to choose carefully all the parameters for a micro-PIV measurement: illumination, seeding, optics, implementation of the PIV algorithms, and so on. It is well known that velocimetry measurements may produce results that are not representative of the actual properties of the flow [53], and that they must be validated before they can be used with confidence. The quality of PIV measurements is closely connected to how it is implemented and the data is processed and analyzed. For the study of flow in complex natural porous media, however, it is difficult to satisfy the "ideal" conditions for the implementation of the technique. For these reasons, validation of our approach is emphasized in this paper. Velocimetry measurements were validated by confirming the parabolic Poiseuille flow profile within a square capillary [21], but there are no convincing validation exercises for the more complex pore geometries and velocity distributions of interest in natural porous formations where there is converging and diverging pore space and networks of pore space with variable connectivity among different pores.

There have been several recent studies related to the micro-PIV technique in porous media [11,12,16,21,60]. Chen [16] reported a vector grid of $12\,\mu m \times 6\,\mu m$ in a high-porosity etched-silicon micromodel, the grains are $40\,\mu m$-diameter cylinders arranged with a spacing of $60\,\mu m$ from center to center. Sen et al. [60] measured the velocity field of single phase flow in a 3D glass bead micromodel for pore sizes ranging from 10 to $50\,\mu m$ with velocity vectors distributed onto a grid of $11\,\mu m \times 11\,\mu m$. Blois et al. [11] investigated two-phase flow in a 2D micromodel made of cylinders of $300\,\mu m$ diameter, and they measured the velocity distribution at the interface of both phases. They were able to obtain a vector grid of $5\,\mu m \times 5\,\mu m$ for pore sizes of 40 to $180\,\mu m$. Notably, these micro-PIV measurements have not been validated by comparing the results with reference data or calculations for the micromodel under study. Moreover, to the best of our knowledge, micro-PIV measurements in more complex geometries such the pore networks or realistic porous media replica have not been published yet.

In this work, we performed micro-PIV measurements in micromodels using simple optical equipment with efficient image acquisition and processing. The experimental setup and the simulation work-flow are described in Section 2. In Section 3, we present the pore-scale velocity distributions obtained in the case of a fully saturated porous medium with a typical pore size of 5–40 μm. Extensive comparisons among experimental and simulated results are presented to establish the accuracy and robustness of the experimental method. In Section 4, we use the experimental setup with confidence to investigate the dynamics of immiscible two-phase flow in porous media.

2. Material and methods

In this section, we introduce our experimental framework and the micro-PIV methodology we developed to measure the local velocity distributions. Then, we present the numerical procedure used to obtain reference solutions in the case of fully saturated micromodels.

2.1. Experimental setup

2.1.1. Micromodel

The experimental apparatus includes 2D etched micromodels connected to a syringe pump and placed under a microscope for