Measurement of the Pore-Scale Velocity Distributions in a Two-Dimensional Porous Medium

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(Dated:

Abstract

We investigate the fluid dynamics in two-dimensional micromodels that represent natural complex porous media using micro-Particle Image Velocimetry (micro-PIV). The pore-scale velocity distributions are measured for single-phase flow and are in very good agreement with direct numerical simulations. Our validated and optimized Micro-PIV system is then used to investigate immiscible two-phase flow properties in porous media. Complex interface dynamics are reported at the pore scale. For the first time, we are able to quantify the velocity of dissipative recirculations during two-phase flow.
A good understanding of the physics that governs multiphase flow in porous media is of great importance for a wide range of applications, including oil recovery, geological CO$_2$ sequestration [1], fuel cells [2], nuclear safety devices [3] or separation processes in chemical engineering [4]. Immiscible two-phase displacements depend on the physical and chemical properties of both the injected and displaced fluids, the hydrodynamic forces, and the physical and chemical properties of the porous medium [5]. The modeling of multiphase flow in porous media is challenging due to the multiscale nature of transport mechanisms. On the one hand, macroscopic behaviors influence the local pore-scale velocities. On the other hand, pore-scale events affect the large-scale behaviors considerably, including the nature and degree of phase entrapment as well as the pressure gradient. In fact, the consequences of local processes, such as interfacial jumps, or contact-line dynamics, remain largely unexplored and not well understood [6]. To develop rigorous pore-level models, it is necessary to provide reliable measurements of the spatial and temporal fluid dynamics over a wide range of experimental conditions. In this work, we have conducted experiments in two-dimensional (2D) etched-silicon micromodels of realistic pore patterns that provide direct observations of the pore level not directly available using sand columns or consolidated rock cores [7]. Extrapolation of micromodel results to 3D systems must be performed carefully of course; nevertheless, micromodels are an excellent tool to understand subsurface flow processes [8]. To assess the microdynamics of two-phase flow in porous media, we used Particle Image Velocimetry technique using micron-sized particles (micro-PIV) to obtain instantaneous velocity measurements [9].

Initial efforts towards the micro-PIV technique in porous media are described in recent studies [10–13]. Chen [10] reported a spatial resolution of $12\mu m \times 6\mu m$ in a high-porosity etched-silicon micromodel of $20\mu m$ pore throats. Sen et al. [11] measured the velocity field of single phase flow in a 3D glass micromodel of 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. [13, 14] investigated two-phase flow in a 2D micromodel made of cylinders of $300\mu m$ diameter with pore throats of $40\mu m$, with a vector resolution of $5\mu m$. Notably, this technique was applied in simplified porous media made of cylinders or glass spheres and has not been validated using reference experiments of known velocity profiles, or by comparing the results with reference data. It is well known that velocimetry measurements may produce results that are not representative of the actual properties of the flow [15], and that they must be validated before they can be
used with confidence. Yet, to the best of our knowledge, a quantitative validation of micro-PIV measurements in complex porous media has not been published. Moreover, micro-PIV systems generally use complex and expensive optical systems Blois et al. [14].

In this work, we performed micro-PIV measurements in micromodels using simple optical equipment with efficient image acquisition and processing. The pore-scale velocity distributions are obtained in the case of a fully saturated porous medium with a typical pore size of 5-40\( \mu \)m at a resolution of 1.27\( \mu \)m \( \times \) 1.27\( \mu \)m vector grid. The micro-PIV measurements are in very good agreement with direct numerical simulations of single-phase flows, for which the modeling is nowadays well established and therefore serves as a reference. The experimental setup is then used with confidence to investigate the dynamics of immiscible two-phase flow in porous media.

The experimental apparatus simply includes 2D etched-silicon micromodels covered by a glass plate connected to a syringe pump that are placed under an optical microscope for flow visualization [16]. The micromodels contain an etched pore network pattern of 50mm \( \times \) 50mm. Two micromodel patterns are employed: the first represents solid circles homogeneously distributed with a diameter of 40\( \mu \)m and 10\( \mu \)m pore throat and the second consists of a 1:1 realization of pore sizes and pore shapes drawn from a sandstone thin section with grain sizes ranging from 30 to 200\( \mu \)m. The micromodels contain two microchannels of 500\( \mu \)m width along the edges of the porous medium that allow fluid to enter and exit the porous medium at any point along its side [16]. During micro-PIV measurements, a 2D plane of viewable particles is created by the objective lens of the microscope[17]. The thickness of the focal plane of our objectives is on the order of the thickness of our micromodel (\( \approx \) 10\( \mu \)m). Thus, velocities are measured for only one focal plane and the micromodel is considered 2D. A video camera is used to record sequences of images at a speed of 30 frames per second.

We perform single phase flow experiments using water, the imposed flow rates range from 5.10^{-4} to 1.10^{-2}mL/min. We use Carboxylate Modified Latex microparticles with a diameter of 1\( \mu \)m (Polybead Carboxylate Microsphere, Polysciences) to seed the water. The particles are hydrophilic and negatively charged to avoid particle aggregation and binding to the pore walls that are water-wet. They are also near neutrally buoyant to avoid sedimentation.

We also perform drainage two-phase experiments. In that case, n-heptane is used as the non-wetting displacing fluid that forces a 65% water/35% glycerin mixture to drain from the porous medium. The viscosity of the wetting fluid is \( \mu_w = 2.7cP \) and \( \mu_{nw} = 0.417cP \).
Figure 1. Homogeneous pattern micromodel: interface between the porous matrix and the outlet channel. A: One of the original images acquired with the camera. B: Image after image processing. C: Velocity vectors from micro-PIV, arrow: flow direction.

for the non-wetting fluid, which leads to a viscosity ratio \( M = \frac{\mu_{nw}}{\mu_w} = 0.15 \). The ratio of density is \( \frac{\rho_{nw}}{\rho_w} = 0.6 \). The Capillary number is \( Ca \approx 1 \times 10^{-6} \) and Reynolds number is \( Re \approx 10^{-5} - 10^{-2} \). This range of parameters is representative of a CO\(_2\)/brine system in subsurface aquifer conditions [18]. With the use of these analog fluids, we expect behavior similar to supercritical CO\(_2\) and brine.

Before micro-PIV measurements, image pre-processing is performed using MATLAB® to detect the grains, remove the background, and make the particles brighter. From an original image sequence acquired with a standard microscope light source, the image processing workflow leads to a final image sequence that contains only information related to the moving particles (Figure 1, B).

Finally, we perform micro-PIV measurements with PIVlab a tool for MATLAB® [19]. The principle of PIV is to record two images of the flow of particles shortly after one another. Images are subdivided into many small interrogation windows. The displacements of interrogation windows between the two images are determined through spatial cross-correlation. Velocity is found by dividing the particle displacements by the time between images. The process is repeated for all regions in the flow to obtain the instantaneous velocity field [20]. Usually the displacement vectors are obtained by averaging at least 100 image pair measurements [17]. The parameters for the PIV analysis, the optical system, and the particles have been carefully chosen to ensure high-quality micro-PIV experiment [17].
To validate the velocity measurements from micro-PIV, we compared the experimental data with 2D direct numerical simulations of the single-phase flow through the different geometries under consideration in the case of fully saturated micromodels. The simulations are run using the simulation toolbox OpenFOAM®. To reduce the computational effort, we only consider the smallest pattern, which is repeated all over the micromodel. This repeating feature is represented using periodic boundary conditions. Our simulations are 2D solving Stokes equations averaged over the thickness, i.e. adding an Hele-Shaw correction term to consider 3D effects [21]. In order to facilitate the comparison between experiment and simulation, velocity fields are normalized by the maximum value in the displayed domain. Note that even though larger domains have been computed for the simulation, only smaller parts are shown to enhance the visualization.

In Figure 1 (C), we present the velocity vectors obtained in the homogenous pattern when looking at the interface between the porous matrix and outlet channel. The fluid is water seeded with micro-particles flowing through the micromodel with a flow imposed at 45°. The ratio between the maximal velocity in the channel and the maximal velocity in the porous medium is 2.05 for the experiments and 1.99 for the simulations, which leads to 3% relative error. We show the micro-PIV measurements for single-phase flow through the sandstone pattern on Figure 2 for the greatest magnification we have used. We analyzed the normalized velocity magnitude and displacements along the $x$ and $y$ directions. We see clearly that the flow patterns from both the experiments and simulations are quite similar. This is also true for the homogeneous pattern [16]. The resolution (Figure 2, right) is one vector each 1.27µm. Importantly, the spatial resolution and accuracy are both good.

Results obtained in the case of a fully saturated porous medium at steady state validate our micro-PIV work-flow. Let us note, however, that in micro-PIV measurements, the finite depth of field results in an underestimation of the velocity profile [22, 23]. We verified that this concern do not affect our results, especially because we concentrated on the velocity distributions normalized by the maximal value on the domain under study. This fact is confirmed by the comparison with direct numerical simulations. To the best of our knowledge, it is the first time that micro-PIV measurements are quantitatively validated to investigate the dynamics at the pore scale with order 1µm resolution and accuracy. Then, we use this technique with confidence to investigate two-phase flow mechanisms in the micromodels of interest.
After the single-phase validation step, drainage experiments have been conducted to demonstrate the extension to two-phase flow. The wetting fluid is seeded with microparticles and a UV-dye is added in order to differentiate organic and aqueous phases. The micromodel is first saturated with the wetting phase. Then, we inject the non-wetting phase at constant flow rate \(2.5 \times 10^{-3}\text{mL/min}\). Once the second phase enters the micromodel, we record movies at different locations in the micromodel for different magnifications. Because the non-wetting phase is not seeded with microparticles, we do not image flow patterns within that phase.

Our first observation is that the flow organization is dramatically altered compared with the single-phase case. In Figure 3, we present the velocity distributions for a single phase flow (left) obtained numerically and, for a two-phase flow experiment in the same pore area and with the same imposed flow direction (right). The flow directions and intensities are clearly perturbed compared to single-phase flow. Figure 4 shows the first (left, up) and the last (left, bottom) image of a sequence of images recorded during the drainage. The grains are black, the water phase is green with black particles and the non-wetting phase appears white (see movie [16]). At the beginning of this sequence the area under study is saturated with water. At this moment, we see clearly that the particles flow back and forth in the pore areas, even before the passage of the interface. The oil-phase enters the area by a fast interfacial jump 14 seconds after the start of the recording, at the top left corner (point 1, Figure 4). Twenty seconds later, the oil phase enters the porous area by the bottom
edges of the image (point 2, Figure 4). At the end, we have areas with water (as in point 3, Figure 4) and areas filled with oil. We look then at the displacement along $x$ and $y$ as a function of time for each of these three positions, Figure 4 (right). We clearly see the perturbations induced by the advancing non-wetting phase. When the non-wetting phase enters the first area, the wetting phase is pushed and we observe its significant acceleration. After the passage of the interface in this area, because the oil phase is not seeded, we can no longer see particles and so the plotted data stop abruptly for position 1 (Figure 4, plot data for position 1). Then, large perturbations are recorded at the second location (Figure 4, position 2). After the passage of the interface, there are still some perturbations and they become smaller, as can be seen at the third location [24].

Figure 4 (middle) shows the streamlines computed from the PIV measurements at the end of the same experiment, i.e., from $t = 45$ to $t = 60$s. We focused on the wetting phase that is entrapped surrounded by either solid walls, or the oil. The non-wetting phase (gray) and the grains (black) are differentiated from the wetting phase because no velocity is measured by micro-PIV. Interestingly, the wetting phase shows a recirculating motion until the end of the recording, i.e., at least 20 seconds. The trapped phase is not immobile, contrary to what is usually assumed. This driven cavity flow is due to the shear stress resulting from the non-wetting phase that is still flowing. These observations may have consequences in the modeling of CO$_2$ sequestration processes. For instance, the pore-to-pore methodology based on micro-CT images of trapped CO$_2$ combined with direct numerical simulations proposed by Andrew et al. [25] to predict the re-mobilization mechanisms of the ganglia might be improved by considering the shear stress at the fluids interfaces. Furthermore, it is generally assumed that in conventional porous media of low permeability the viscous driven effects of a fluid on the other are negligible at large scale [26]. These observed recirculations suggest, however, that in case of many clusters of entrapped water, the viscous dissipation terms in the multiphase extension of Darcy’s Law [27, 28] may not be negligible as it is usually accepted [26]. Moreover, this phenomenon may have implications for multicomponent mass transport by enhancing mixing, or accelerating reactions such as dissolution mechanisms. These recirculations are not an isolated phenomenon and have been observed over the entire micromodel.
Figure 3. Velocity magnitude distribution and velocity vectors for a single phase flow (left) and of the wetting phase during a drainage experiment (right) at the time of the arrival of the interface just upstream of area. Arrow: imposed flow direction for both cases.

From Figure 4 it is also interesting to notice that the large perturbations appear at the same time at different locations in the micromodel. One might posit that this is a result of a system that is largely incompressible. In fact, these back and forth movements only occur at the vicinity of the interface between the fluids [16]. We have checked that this phenomenon is reproducible and not induced by the syringe pump. As reported previously by Blois et al. [13], this behavior suggests that pressure instabilities and their propagation further downstream are induced by the Haines jumps and perturb the wetting phase. Haines jumps have been directly visualized in our experiments (see movie Roman et al. [16]) and we observed that the structure of the flow is perturbed before the actual passage of the interface. Moreover, these instabilities continue during the entire passage of the interface. It is likely a consequence of the Haines jumps: for a given time the interface is quasistatic while pushed by the non-wetting phase. Since the pressure in the non-wetting phase keeps increasing due to the injection, the particles slightly move forward. Then, at one point, the pressure locally overpasses the threshold defined by the Young-Laplace law [29] and the non-wetting phase suddenly passes through a throat, invades a pore and we can see the acceleration of the particles in the wetting phase. The pressure is immediately relaxed all along the interface, resulting in a backward movement. This pressure instability may be propagated several pores downstream. On the other hand, the paths taken by the non-wetting phase redistribute the flow within the wetting fluid switching direction and magnitude. This also
Figure 4. Two-phase flow experiment. Top left: first image $t = 0$ (arrow: flow direction), bottom left: last image $t = 60s$ of the sequence, middle: plotted streamlines for $t = 45 - 60s$. Right: displacement along $x$ ($U_x$, blue) and $y$ ($U_y$, red) as a function of time for the positions 1, 2 and 3 depicted on left images.

leads to flow instabilities when the wetting phase is pushed into different directions by the surrounding interface. These phenomena emphasize the importance of taking into account mechanisms related to local pressure and macroscopic effects linked with the topology of the non-wetting fluid [29].

We have developed a micro-PIV system that allows for a better understanding and characterization of the microdynamics of complex flows. Micro-PIV measurements in micromodels have been validated by comparing experimental and simulation data in the case of single-phase flow. To the best of our knowledge, it is the first time that such measurements are performed in micromodels with pore throat sizes less than 10 microns and with a vector resolution of roughly $1\mu m$. In addition, micro-PIV measurements are performed using very simple equipment which includes: a standard camera, an optical microscope and polymer particles. Thus, these measurements are easily reproducible in any lab. We now investigate two-phase flow mechanisms in micromodels with high accuracy. Our first efforts show that we are able to analyze the velocities for unstable immiscible two-phase flows. The micro-PIV
measurements during a drainage experiment have already shown unusual behaviors. In particular, we have shown that for an unfavorable mobility ratio, the flow patterns are highly perturbed by local and macroscopical effects. In addition, for the first time, we were able to quantify the velocity of dissipative recirculations during two-phase flow. These results are potentially important for accurate numerical representation of processes such as CO\textsubscript{2} injection into saline aquifers and mixing of CO\textsubscript{2} with the resident brine. The observation of these dissipative events opens new lines of research and deserves further experiments and modeling to understand fully their behavior and to characterize their consequences at the different scales.

**ACKNOWLEDGMENTS**

The authors acknowledge the Petroleum Institute of Abu Dhabi for funding this research. It is a pleasure to acknowledge W. Thielicke and E. J. Stammuis for developing and releasing the PIVlab package, and W. Thielicke for assistance with PIVlab.


[24] Details of the measures of unstable velocity distributions are in Supporting Information [16].


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