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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A R T I C L E   I N F O

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- Porous media
- Two-phase flow
- Micro-PIV
- Interface physics
- Fluid velocity field
- Recovery

A B S T R A C T

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 milli-, 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...
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 CO₂ [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/liquid 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 porous models, a confocal microscope can be used to image the 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,
whereas, the transparent prints could provide a minimum feature size of 10 μm. This resulted in a level of smoothing of the grains in the replicated porous media. The model had two inlet ports and one outlet port. The distributor at inlet of the model was designed to achieve a flat invading fluid front. Shape of the posts of the distributor were selected based on the information provided by Vangeloooven et al. [49]. Following the procedure described in more detail by Karadimitriou et al. [50], the designed pattern was fabricated into PDMS with the desired depth for the channels, which was selected as 70 μm by trial and error to minimize the effect of occasional vertical rotation of the trapped globules on the velocity measurements in the x-y plane. The width of channels ranged from 16 to 186 μm. The inlet and outlet ports were then drilled into the model using a sharp needle. Subsequently, the etched PDMS plate was bonded to a flat PDMS plate and then to a glass sheet using a Harrick Plasma machine. The flat PDMS plate was used to make sure that all the sides of the channels were made of one single material, therefore exhibiting similar wetting behavior. The flat glass plate, on the other hand, was used to keep the flexible PDMS plates from bending. Figs. 1 and 2(A) show the designed flow network and the three-dimensional image of the channels and grains of the sandstone model before bonding, respectively. The three-dimensional profiles are obtained using an Olympus LEXT OLS4000 laser measuring microscope.
The porosity of the model was determined by dividing the number of pixels of the pores to that of the whole model and its permeability was measured using the Darcy equation. A pressure gradient was applied to the micro-model using a fixed-head fluid column at the injection port while the production port was open to the atmosphere. Flow rate was determined by accurately measuring the volume of the produced fluid over a specific time period. The porosity and permeability of the Ben-theimer sandstone replica were then determined to be 54% and 3 darcy (D). To study the fluid flow in a more controlled environment, a single channel pore-doublet configuration inspired by those presented by Chatzis and Dullien [4] was designed and fabricated in PDMS using the same procedure as the sandstone model with a depth of 30 μm to have an aspect ratio of close to 1.0 for some of the channels. Fig. 2(B) shows the 3D rendering of a typical pore-doublet configuration utilized in this study. Here the vertical rotation of the globules did not affect our x-y plane velocity measurements. In micro-models made of PDMS, the increase in invading phase flow rate is limited by the level of model’s rigidity. In other words, at very high invading phase flow rates, the significantly increased pore pressure could result in the deformation of channels’ geometry and eventually rupturing of the model or ejection of the tubing from the injection port. Hence, based on the observations made during the experiments, the upper limit of the flow rate was determined to be 0.025 mL/min for experiments performed in single-channel configuration.

2.2. Fluids

Three immiscible fluid pairs were chosen for this study; 5, 50, and 100 centistokes (cSt) silicone oils from Sigma–Aldrich paired with a 21/79 (by volume) mixture of deionized water and glycerol from Fisher Scientifc. The proportion of water and glycerol in the mixture was selected such that the dynamic viscosity of the aqueous mixture (47 centipoise) matched that of the 50 cSt silicone oil (see Table 1). This allowed comparison of imbibition scenarios at which viscosity of the injected fluid (silicone oils) was lower, equal, and higher than that of the defending fluid (water/glycerol mixture), which will be discussed in more detail later in this manuscript.

In cases where a fluid’s velocity field was to be obtained, it was seeded with specific micron-size fluorescent particles. Utilizing a sonication bath, 0.04 vol.% of 1.0 μm orange Fluosphere polystyrene microspheres (540/560) and 0.04 vol.% of 1.0 μm red Fluosphere sulfate (580/605) particles, both from Thermo Fisher Scientific, were dispersed in water/glycerol mixture and silicone oils, respectively, to prepare the final mixtures for the μPIV studies. Surface of these particles are modified to have hydrophilic characteristics by addition of pendant carboxylic acids. In two-phase μPIV experiments, it is preferred to utilize fluid pairs that have similar refractive indices [51,43]. This is required to eliminate the mismatch in the focal planes of the objective lens in each fluid. A significant amount of mismatch in the focal planes causes the image of one of the fluids to become blurry (unfocused) and difficult to analyze. Table 1 lists the refractive indices of the fluids pairs used in this study. As observed, the refractive index of one of the fluids was slightly different than the other values. This, however, did not adversely impact the analysis of the images we generated during the two-phase experiments. Table 1 also lists other properties of the fluids deployed in our flow tests.

Table 2 presents interfacial tension (IFT) values of the fluid pairs with and without dispersed fluorescent particles (seeded and unseeded, respectively). IFT values were measured using the pendant drop method [52] at 20°C and atmospheric pressure. The values of IFT for different unseeded water/glycerol and unseeded silicone oil pairs were 29.2 ± 0.6 dyne/cm, whereas in the case of seeded water/glycerol and unseeded silicone oil pairs, the IFT values were 33.3 ± 1.2 dyne/cm. These values show that the IFTs for the seeded fluid pairs are about 4.0 units greater than those of the unseeded pairs. We believe that the aggregation of particles at the interface of two fluids, the chemical structure of the particles (polystyrene), the additive present in the particle solutions (thimerosal), and the presence of a high density of pendant carboxylic acid molecules on the particles surfaces might have resulted in the increase of IFT.

Table 1

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Density (g/cm³)</th>
<th>Viscosity (centipoise)</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO (5 cSt)</td>
<td>0.913</td>
<td>4.6</td>
<td>1.403</td>
</tr>
<tr>
<td>SO (50 cSt)</td>
<td>0.96</td>
<td>48</td>
<td>1.403</td>
</tr>
<tr>
<td>SO (100 cSt)</td>
<td>0.96</td>
<td>96</td>
<td>1.403</td>
</tr>
<tr>
<td>SWG</td>
<td>1.21</td>
<td>48</td>
<td>1.44 @ 20°C</td>
</tr>
</tbody>
</table>

"SWG" stands for 0.04% seeded water/glycerol (21/79) and “SO” is Silicone oil.

3. Experimental setup

3.1. Experimental setup

The μPIV system utilized in this research consisted of large- and small-FOV modules. The large-FOV module of the system included two 29 Mega-Pixels (MP) CCD cameras with maximum recording speed of 4.5 frames/s (fps) and pixel size of 5.5 μm manufactured by TSI Inc., a 4X Nikon objective lens with a numerical aperture of 0.2, a 532 nm Nd:YAG dual cavity Evergreen laser with 15 Hz pulse repetition rate and 70 mJ energy made by Quantel, and a laser arm that transmitted the laser light to a beam-splitting box. The beam splitting box included a dichroic mirror that directed the laser beam to the fluorescent particles. The setup also included a polarizable liquid-crystal tunable filter, importance of which is discussed later in this document. The cameras for the small-FOV module of the system were Phantom high speed CMOS with 800 fps speed at a resolution of 4 MP and a pixel size of 10 μm. The light for this part of the system was provided by a 527 nm wavelength Nd:YLF dual oscillators Darwin-Duo with 1000 Hz pulse repetition rate and 15 mJ total pulse energy from Quantronix. This part of the system was equipped with 10 × and 40 × objective lenses from Nikon with numerical apertures of 0.3 and 0.6, respectively. The depth of correlation for the large- and small-FOV modules were approximately 30 and 61 μm, respectively. The light from lasers passed through several optical filters and reflected from different optical mirrors to finally reach the cameras through a Nikon Eclipse Ti inverted microscope. One of the cameras in the large-FOV and one in the small-FOV sections were equipped with filters that allowed the capture of the light reflected from only orange fluorescent particles. The other two cameras were supplied with optical filters that passed the light from the red fluorescent particles only. Although there was a little bleeding of orange particles’ reflected light to the red cameras, the images obtained from the two fluids were very well separable. The optical filters in both parts of the system were identical.

The emitted light from the two lasers might interfere with one another. To avoid this problem, a Meadowlark Optics liquid-crystal controller and a polarizable liquid-crystal tunable filter were integrated.
with the setup which blocked the large-FOV laser light from reaching the small-FOV images and vice versa. Finally, the recorded images from both field-of-view modules were processed using the Insight 4G™ software from TSI Inc. Fig. 3 shows the μPIV setup and the locations of optical filters and mirrors.

Fluids were injected into the micro-models using two Harvard Apparatus 11 Elite syringe pumps. Flexible clear Tygon chemical resistant tubing with an internal diameter of 0.0625 in. connected the syringe pumps to the model. Fig. 1 presents a schematic of the flow system.

3.2. Experimental procedure

The single-channel models were first saturated with the wetting phase (50 cSt Silicone oil). The models were then flooded with the non-wetting phase so that only a thin film of the wetting phase remained on the solid surfaces [53–56]. This procedure is used to mimic fluid migration sequence and initial fluid distribution in a real reservoir. Afterwards, the wetting phase was re-injected into the model at different flow rates to investigate the non-wetting phase trapping and production under various flow conditions. The shear stresses were also measured at different flow rates near the fluid/fluid interface within the trapped non-wetting and the invading phases, using Eq. (1).

$$\tau = \frac{\mu \Delta u}{\Delta y}$$

where $\tau$, $\mu$, $u$, and $y$ are the shear stress, the fluid viscosity, the fluid velocity, and the distance of the velocity vector from the interface, respectively.

Flooding experiments were performed in the Bentheimer replica micro-models as well. For the single-phase test, the mixture of glycerol and water was chosen as the flowing fluid, whereas, in the two-phase experiments, the models were first saturated with the wetting phase and subsequently underwent a drainage process at a constant flow rate to establish irreducible wetting phase saturation and a stable fluid configuration. At this stage, images from different parts of the micro-models were acquired for more analysis. After injection of the non-wetting phase was stopped, the wetting phase injection under different scenarios was started. These scenarios consisted of injection of the wetting phase at a constant flow rate, stepwise increases in the flow rate after reaching a stable fluid configuration, and also change of wetting fluid viscosity at a constant flow rate. After reaching all the stable fluid configurations at a constant saturation, images were captured. The images were then analyzed using TSI Inc.’s Insight 4G™ along with ImageJ which is an open-architecture image processing tool. Insight 4G™ was used to perform velocity measurements using the raw images obtained from the μPIV system. Because the range of measured velocities was wide and changed from one experiment to another, the setting parameters in the software were accordingly modified to match the velocity range for a specific test. The most important parameter was the time interval between the two consecutive images ($\Delta t, \mu s$), which was set to smaller values for faster fluid movements and vice versa. On the other hand, ImageJ was used to measure the fluids’ saturations and the remaining non-wetting fluid’s globule sizes.

The displaced fluorescent particles tended to stick to the pore walls and aggregate at the constrictions by time. Visual observation of the model during the flooding tests was the best indicator to detect clogging of the channels. No channel blockage was observed in our tests. There was also a chance of swelling of the models in contact with Silicone oils which would eventually change their configuration [57]. Dangla et al. [57] reported that swelling of PDMS in contact with Silicone oil is negligible for approximately five hours which was always much greater than the duration of our flow tests. No adverse swelling effect was observed in the course of these experiments.

4. Results and discussion

4.1. Single pore system

The single-channel, pore-throat assembly shown in Fig. 2(B) includes two side-by-side pore doublets. This pore configuration allowed trapping of the non-wetting phase during an imbibition process. After saturating the model with the wetting phase (50 cSt Silicone oil), the model was subjected to a drainage process through injection of the non-wetting phase. Subsequently, the wetting phase was introduced into the medium at a flow rate of 0.001 mL/min to trap the non-wetting fluid and reach a stable fluid occupancy in the pore doublets. Introduction of the wetting phase at the above mentioned flow rate results in a viscous dominated flow regime with a capillary number in the order of $10^{-3}$. Two sections of this configuration were then investigated carefully. These sections related to two non-wetting phase globules trapped on the right and left sides of the assembly (Fig. 4).

We first investigated the effect of the wetting phase flow rate on the fluid/liquid interface belonging to the right-hand side globule (Fig. 4). A stepwise increase in wetting phase flow rate from 0.001 to 0.025 mL/min was used in this test. The velocity maps obtained during the experiment showed that increasing viscous forces intensifies the amount of shear stress applied on the trapped non-wetting phase. This translated into the rotation of the trapped non-wetting globule around its own center of mass and producing a greater degree of momentum transfer across the interface. This phenomenon is observed by Roman et al. [46] as well. At higher rates of rotation, globule’s center of rotation moved closer to the interface between the droplet and the invading phase that passed by (Fig. 5). This led to detachment and entrainment of small portions of the above-mentioned globule, while most of the bulk of the trapped fluid remained intact.

Despite the interactions induced by higher flow rates, our...
fluid flow through porous media. However, this finding is in contradiction with the approach used by some scientists in modeling two-phase flow in porous media. For example, Philip [58] disregarded the momentum transfer between the two phases for most practical problems, because of the fact that surfactant is always present in real systems. However, this speculation is not necessarily a valid assumption. Other scientists have also assumed a rigid body motion and existence of a no-slip fluid/fluid and fluid/solid boundary condition during two-phase flow in porous media [59–61].

In this study, slip boundary was detected by comparing velocity vectors of the two phases at their interface. Immediately adjacent to the boundary, at 10 μm intervals, wetting phase velocity values (1.1 × 10⁻⁴ to 1.5 × 10⁻³ m/s) were one-to-two orders of magnitude greater than those of the non-wetting phase (2.1 × 10⁻⁵ to 5.0 × 10⁻⁴ m/s) for different flow rates. These values also showed that although increasing the flow rate of the wetting phase from 0.001 to 0.025 mL/min resulted in a tenfold increase in the velocity of this phase at the interface, its effect on velocity of the non-wetting phase was much less pronounced, which again emphasized on the existence of a slip boundary between the fluids. The type of boundary at the interface of two fluids not only dictates the proper numerical simulation approach for flow of fluids through porous media, but also dictates the effectiveness of trapping and production mechanisms.

Fig. 5 presents the results obtained using the velocity vectors pertaining to the fluids on right side of the pore assembly. This is the location at which the values of shear stress are calculated (see Eq. (1)). The calculated shear stress values are plotted in Fig. 6. This figure shows that the increase in flow rate of the invading phase resulted in an increase in the shear stress at the fluid/fluid interface that in turn heightened the shear stress in the non-wetting phase. It also indicates that the rate by which the shear stress increased with flow rate was less pronounced at the low flow rates (less than 0.005 mL/min) compared to that at higher flow rates (greater than 0.005 mL/min).

In addition to the hydraulically disconnected non-wetting phase on the right side of the pore assembly, another non-wetting phase globule was trapped with a different shape on the left side. After investigating the nature of the boundary condition at the fluid/fluid interface and the effect of flow rate on momentum transfer across it, we focus on how these effects may play a role in mobilizing the trapped globule when (i) flow rate of the wetting phase is increased and (ii) a small quantity of the non-wetting phase is introduced to perturb the velocity and pressure fields in the assembly. As we show later in this section, these perturbations result in the recovery of the trapped non-wetting phase. We probe the mechanisms responsible for this mobilization.

Fig. 7 presents the raw images acquired directly from the μPIV setup along with their relevant redrawn images that show the step-by-step changes in configuration of the trapped non-wetting phase. In these experiments, only the non-wetting phase was tagged with fluorescent particles that illuminated under the laser light. Therefore, the bright and dark spots in Fig. 7 represent the non-wetting and wetting phases, respectively. The difference in brightness between these fluids was used to generate the redrawn images for a better visual illustration of mechanisms.

After the fluid configuration in the pore-doublet was stabilized (Fig. 7(A)), two scenarios for producing the remaining non-wetting phase in the left side of the medium were examined. In the first scenario, the wetting phase injection flow rate was increased. We observed that the higher flow rates, e.g., 0.02 mL/min, generated higher viscous pressure drops that eventually overcame the threshold pressure required to entrain portions of the trapped non-wetting phase toward the production port in a piston-like displacement process. While, in the second scenario, which occurred at a lower flow rate (0.001 mL/min), the invading fluid did not create sufficient viscous pressure drop to help produce any portions of the trapped globule. However, while performing imbibition at a flow rate of 0.001 mL/min, introducing a drop of the non-wetting phase to the pore configuration resulted in

Fig. 4. Pore-doublet model and the trapped non-wetting phase globules during an imbibition process at a flow rate of 0.001 mL/min. Solid features are shown in black and the non-wetting and wetting phases are presented in blue and white, respectively.

Fig. 5. Velocity fields in both invading wetting and trapped non-wetting phases and the center of rotation in the non-wetting droplet at an invading phase flow rate of 0.013 mL/min.

observations (in viscous dominated regime) showed that, not all the energy applied by the passing wetting phase was transferred to the non-wetting phase because of the slip boundary condition and viscous dissipation that existed at the interface of the two fluids. Hence, this phenomenon should be taken into account in mathematical models of
mobilization of a large portion of the trapped non-wetting phase (Fig. 7). We observed that after establishment of the initial condition (Fig. 7(A)), if a drop of non-wetting phase was injected upstream of the pore configuration (Fig. 7(B)), it entered the open pathway (the pore on the right) and while passing through the constriction, it changed the local pressure distribution around the trapped globule, which in turn introduced a pressure shock to the fluid trapped on the left pore-doublet. This shock caused the trapped fluid to start moving and eventually a large portion of it was produced into the production port (Fig. 7(C) to (G)). The pressure shock also affected the right side of the pore-doublet in which the injected non-wetting droplet carried some of the trapped non-wetting fluid along the medium to the production port (Fig. 7(D) to (I)). Therefore, during imbibition process, introducing a non-wetting phase droplet to this pore doublets configuration resulted in production of more than half of the trapped non-wetting phase that was initially in place. Although this seems counter-intuitive, it has a great impact on the distribution of phases in a porous medium, which should be considered in pore-scale numerical models of fluid flow in porous media. Furthermore, previously it was believed that during imbibition the invading fluid passes through some specific open pathways with least resistance to the fluid flow towards the production port; however, considering phenomenon like the one we presented here, wetting fluid pathways could change because of changes imposed to and by non-wetting fluid ganglia movement or ganglion dynamics. Another example of such phenomenon that affects the ganglion distribution is presented by Rucker et al. [62]

4.2. Porous media systems

4.2.1. Single-phase experiments

Single-phase experiments were performed in Bentheimer sandstone replicas to study the effect of size of the pores and throats as well as their connectivity and coordination number (number of throats connected to a pore body) on the fluid velocity magnitude and direction. For this purpose, seeded water/glycerol mixture was used as the flowing phase at a flow rate of 0.003 mL/min. The velocity field was resolved using the large and small FOVs as shown in Fig. 8. In this figure, the larger vectors represent higher fluid velocities, which occur at the narrower channels of the model known as throats. The direction of the arrows indicates the flow direction at each location. As shown in this figure, the large and small FOV modules of the system together provide a very powerful tool to map the velocity field of the flowing fluid within the porous medium. Examples of locations at which fluid bifurcation, confluence, and stagnation were observed are shown in this figure. Stagnant bodies of the fluid were mostly located in the top and bottom sides as well as the corners of the model. The same phenomenon was seen in some of the channels that were perpendicular to the general direction of the flow and also at the fluid/solid interfaces in larger conduits. Locations where the vectors are replaced with dots show the stagnant fluid conditions. Determining where the fluid is stagnant helps in understanding the effect of pore space topology on the size and distribution of stagnant zones. These stagnant fluid bodies are parts of the residing fluid that do not significantly contribute in the general flow field and are not significantly affected by it. However, they participate in different processes such as solute (e.g., chemicals and particles) transport during which these sites store the chemical species and slowly release them to the flow later through, for instance, diffusion [63–65]. Additionally, by gaining an insight into the existence and location of the stagnant wetting fluid bodies in a multiphase flow system, one can utilize techniques such as injection of more viscous fluids (e.g., polymer solutions and gels) that are miscible with the wetting fluid to manipulate the local flow paths in the interest of more effective displacement of the non-wetting phase [25,66–77].

4.2.2. Two-phase experiments

Following the single-phase flow experiment, several drainage (non-wetting fluid displacing the wetting fluid) and imbibition (wetting fluid displacing the non-wetting fluid) tests were performed using different fluid pairs. The first set of these experiments was used to establish the capabilities of the two-phase, two-FOV μPIV apparatus, whereas the second set was aimed at systematically studying the impact of wetting phase flow rate, its flow rate history, and its viscosity on non-wetting phase velocity fields, distribution and recovery.

In the first set of two-phase flow experiments, we conducted two drainage-imbibition cycles at various flow rates. First, the model was saturated with the wetting phase (50 cSt Silicon Oil). It was then drained by injecting several pore volumes of the non-wetting fluid at a flow rate of 0.001 mL/min until a stable pore fluid configuration was reached. Subsequently, a forced imbibition with a flow rate of 0.001 mL/min was started until the fluid configuration stabilized again. Fig. 9 depicts the velocity fields of the two fluids after the forced imbibition was performed. The same procedure was employed for the second test at drainage and imbibition flow rates of 0.01 mL/min (Fig. 10). In the following paragraphs, we discuss the pore-level phenomena we observed during these flow tests that directly impacted the local trapping of the non-wetting fluid.
Trapping of the non-wetting phase globules in dead-end pores is very common; e.g. the trapping observed in the pore-doublet assembly (see Section 4.1). However, as shown in Figs. 9 and 10, during imbibition, the defending phase was not trapped in dead-end pores. Fig. 9(B) and (C) show that the non-wetting phase was disconnected primarily because it was by-passed by the invading phase. In other words, although the invading phase was displacing the bulk of the non-wetting fluid toward the production port, the exerted pressure was not sufficient to exceed the local capillary pressure required for displacement of the non-wetting phase from sites surrounded by the narrower pathways. On the other hand, Fig. 10 demonstrates that the entrapment of non-wetting phase occurs because the configuration of the grains helps direct the flow of the invading phase through the neighboring sites leaving the non-wetting fluid stranded. Furthermore, the shear stress inserted by the invading phase at the lower side of the non-wetting droplet was not enough to mobilize it. By examining the velocity values of both fluids at their interface (Fig. 10(B) and (C)), the slip boundary condition that was observed in the single channel assembly, was also seen in this configuration at the interface of the two fluids. Here, wetting phase velocity was in the range of 0.006–0.009 m/s whereas non-wetting phase velocity was equal to or smaller than 0.0005 m/s.

As mentioned earlier, we also performed a second set of two-phase experiments. These included drainage flow tests at an identical flow rate to generate the same initial condition for the imbibition tests; followed by imbibition test(s) at different flow rate combinations and wetting fluid viscosities. In the following section, we provide a detailed discussion of the results. Using Eq. (2) [78], the capillary numbers ($N_C$) for all the tests performed under this section were calculated and are listed in Table 3:

$$N_C = \frac{V \mu_w}{\sigma_{nw-w}} \left( \frac{\mu_w}{\mu_{nw}} \right)^{0.4}$$

where $V$ is the Darcy velocity of the wetting phase ($\text{m/s}$), $\mu_w$ and $\mu_{nw}$ are the wetting and non-wetting fluid viscosities (Pa.s), and $\sigma_{nw-w}$ is the interfacial tension (N/m). We used Abrams’ definition of capillary number [78] because he included the effect of fluids viscosities in his equation which leads to a more accurate definition for Capillary number. The capillary number values listed in Table 3 show that the flow regime in
all the flooding tests performed in this study is likely to be viscous dominated, which is generally experienced near the production and injection wells.

For presentation purposes, this group of tests was divided into five subsets. In the first three subsets, the porous medium was first saturated with the wetting phase (50 cSt silicone oil). This was followed by a drainage at a flow rate of 0.01 mL/min to establish a stable fluid configuration and the initial wetting phase saturation (0.10 ± 0.02). In the first subset, forced imbibition was then initiated at a flow rate of 0.005 mL/min. After the fluid configuration was stabilized with a constant fluid saturation, the flow rate was instantly increased to 0.01 mL/min, and eventually, when the fluid configuration was stable again at a second constant saturation, the flow rate was once again increased to 0.02 mL/min. The injection at this final flow rate was continued until the last stable fluid configuration was achieved. Following the initial preparation for the second subset, the wetting fluid was initially introduced at a flow rate of 0.01 mL/min until the fluid configuration was constant and then its flow rate was increased to the final value of 0.02 mL/min. For the third subset, forced imbibition was performed at a constant flow rate of 0.02 mL/min. In the fourth and fifth subsets, after fully saturating the model with the 5 and 100 cSt silicon oils, respectively; the initial wetting phase saturations were established by non-wetting phase injection. The imbibition tests were then commenced at a flow rate of 0.01 mL/min. These five subsets cover three flow rate increase sequences as well as three wetting fluid viscosities. These experiments allowed us to investigate the effect of the above-mentioned parameters on the final recovery of the non-wetting fluid and distribution of residual saturation in the pore space. Table 4 summarizes fluid pairs used in all the subsets and their corresponding non-wetting fluid saturations at the end of each step. It is worth mentioning that the saturation values for each test were measured utilizing a MATLAB® code that counted the number of pixels of different phases (i.e., solid and fluids) based on the color of each phase. As mentioned before, the initial wetting phase saturation was 0.10 ± 0.02 in all the subsets.

A closer examination of Table 4 shows that changes in wetting phase flow rate and viscosity significantly impacted the residual non-wetting fluid saturation. The comparison between different steps of the first and second subsets showed that as the flow rate of the wetting phase during imbibition was increased, the saturation of the trapped fluid increased.
non-wetting fluid was reduced considerably. For example, in the first subset, increasing the imbibition flow rate from 0.005 mL/min to 0.01 mL/min and finally to 0.02 mL/min, resulted in non-wetting phase saturations of 0.37, 0.29, and 0.24, respectively. Furthermore, the residual saturation values for the first three subsets did not show considerable sensitivity to the imbibition flow rate history. For instance, although the forced imbibition flow rate of 0.01 mL/min was the second flow rate of the first subset and the first flow rate of the second subset, the stable remaining non-wetting phase saturation for both cases were 0.29. This was also observed at the imbibition flow rate of 0.02 mL/min. At this flow rate, regardless of the imbibition flow rate history, the final saturation of the remaining non-wetting fluid was 0.25 ± 0.01. We believe this is partly due to the fact that the flow experiments were conducted under viscous-dominated displacement regime. This is based on the fact that in a capillary dominated regime, increasing wetting phase flow rate after the first imbibition cycle has a minor impact on the remaining non-wetting phase saturation [79]. However, in viscous dominated imbibition cycles, an increase in the wetting phase flow rate after the first imbibition cycle has a minor impact on the remaining non-wetting phase saturation [79].

Furthermore, changes in wetting fluid viscosity also affected the residual saturation as it can be seen from the data listed in Table 4. The results show that decreasing the wetting phase viscosity resulted in an increase in the residual non-wetting fluid saturation at an identical flow rate. This is because of a decrease in the viscous pressure drop of the wetting fluid that impacts the pore-scale displacement sequence. This consequently produces different remaining non-wetting phase saturations.

In addition to the above-mentioned results, we analyzed the images acquired at the end of each imbibition test to study the size distribution of the trapped non-wetting phase globules and their dependence on the invading fluid flow rate and viscosity. To this end, we first measured the globules’ surface areas using ImageJ software. The volume of each globule was then calculated by multiplying the measured area by the depth of the channels of the porous medium. The results are presented in two forms, namely, the trapped non-wetting globule volume frequency and their cumulative contribution to the non-wetting fluid saturation. Fig. 11 shows the trapped globule volume distribution for all the imbibition flow rates of the first subset. As presented in this figure, the higher is the flow rate, the greater becomes the frequency of the smaller globules. Higher flow rates produced higher capillary numbers, viscous pressure drops, and shear stresses. This in some cases resulted in entrainment of a portion of the globules to the production port and splitting some others into smaller droplets. This is why at flow rates of
0.01 and 0.02 mL/min, no globules larger than $2.0 \times 10^6 \mu m^3$ and $1.0 \times 10^6 \mu m^3$, respectively, were observed. However, both of these globule sizes could be found at the end of the imbibition test with a flow rate of 0.005 mL/min. Furthermore, the number of remaining non-wetting phase globules smaller than $5.0 \times 10^5 \mu m^3$ was almost twice at the highest flow rate compared to those of the two lower flow rates.

During imbibition, the effect of invading fluid’s viscosity on the distribution of the remaining non-wetting globules is illustrated in Fig. 12. This figure shows that the higher is the viscosity of the invading fluid, the greater becomes the frequency of the smaller globules of the remaining defending fluid. Here, again a higher viscous pressure drop caused the larger non-wetting globules to be broken into smaller ones. For imbibition tests with wetting fluid viscosities of 50 cSt and 100 cSt, no residual non-wetting globules larger than $2.0 \times 10^6 \mu m^3$ and $1.0 \times 10^6 \mu m^3$, respectively, were observed.

Fig. 13 shows that, although the residual non-wetting phase saturations due to flow rate of 0.02 mL/min in the 1st, 2nd, and 3rd subsets were similar, their globule size distributions were different. Comparing

![Fig. 10. Velocity fields of wetting and non-wetting phases after forced imbibition at a flow rate of 0.01 mL/min. Velocity legend on the left is for both wetting and non-wetting phases. Velocity legend on the right is for the non-wetting phase only.](image-url)

Table 3

<table>
<thead>
<tr>
<th>Fluid pair</th>
<th>Flow rate (mL/min.)</th>
<th>$N_C$</th>
<th>$N_C$/porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWG/ Silicon Oil (5 cSt)</td>
<td>0.01</td>
<td>$4.7 \times 10^{-5}$</td>
<td>$8.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>SWG/ Silicon Oil (50 cSt)</td>
<td>0.005</td>
<td>$6.5 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>SWG/ Silicon Oil (50 cSt)</td>
<td>0.01</td>
<td>$1.3 \times 10^{-3}$</td>
<td>$2.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>SWG/ Silicon Oil (50 cSt)</td>
<td>0.02</td>
<td>$2.6 \times 10^{-3}$</td>
<td>$4.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>SWG/ Silicon Oil (100 cSt)</td>
<td>0.01</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$6.6 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

“SWG” stands for 0.04% seeded water/glycerol (21/79).

Table 4

<table>
<thead>
<tr>
<th>Subset</th>
<th>Fluid Pair</th>
<th>Q (mL/min.)</th>
<th>NW Sat. (fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>SWG/SO (50 cSt)</td>
<td>0.005</td>
<td>0.37</td>
</tr>
<tr>
<td>2nd</td>
<td>SWG/SO (50 cSt)</td>
<td>– –</td>
<td>0.01</td>
</tr>
<tr>
<td>3rd</td>
<td>SWG/SO (50 cSt)</td>
<td>– –</td>
<td>– –</td>
</tr>
<tr>
<td>4th</td>
<td>SWG/SO (5 cSt)</td>
<td>– –</td>
<td>0.01</td>
</tr>
<tr>
<td>5th</td>
<td>SWG/SO (100 cSt)</td>
<td>– –</td>
<td>0.01</td>
</tr>
</tbody>
</table>

“SWG” stands for 0.04% seeded water/glycerol (21/79), “SO” is Silicone oil, “Q” is flow rate (mL/min.) and “NW Sat.” is non-wetting phase saturation (fraction).
the frequencies of the globules sizes show that the effect of changing flow rate from 0.01 mL/min to 0.02 mL/min (in the 1st and 2nd subsets) was different compared to that in the 3rd subset during which the flow rate was instantly increased from zero to 0.02 mL/min. This figure also shows that a greater stepwise increase in flow rate results in the production of a larger number of small non-wetting globules. After performing the imbibition at a flow rate of 0.01 mL/min in the 1st and 2nd subsets, the trapped non-wetting phase, that had already experienced entrainment and globule split, was again affected by an increase in flow rate. However, because the non-wetting globules were already trapped, the effect of change of flow rate in these cases was less than that of the third subset in which there was a connected non-wetting phase cluster present before the wetting phase flow rate was instantly increased from zero to 0.02 mL/min. This was why no globules larger than $5.0 \times 10^5 \mu m^3$ were present at the end of the imbibition in the third subset. Assuming perfect cylindrical globules, a globule of the volume $5.0 \times 10^5 \mu m^3$ has a diameter of 94 $\mu m$. Note that the pore and throats of the porous medium model range from 16 to 186 $\mu m$.

The cumulative contribution of the globules to the total remaining non-wetting fluid saturation at the end of each imbibition is shown in Figs. 14–16. The cumulative contribution curves were generated by dividing the volume of all the globules equal or smaller than a specific size, by the total volume of the remaining non-wetting phase. The data for the first subset is presented in Fig. 14. As presented in this figure, the slope of the curve representing the imbibition flow rate of 0.02 mL/min is the greatest, which emphasizes that at this flow rate, the cumulative contribution of smaller trapped non-wetting phase globules to the final saturation was much more than the other two imbibition flow rates. However, the cumulative contribution of smallest globules to the non-wetting phase saturation were almost the same for the two lower imbibition flow rates of 0.005 and 0.01 mL/min.

The effect of imbibition flow rate history on the cumulative contribution of the trapped non-wetting phase globules to the residual saturation is shown in Fig. 15. Two sets of flow rates with equal wetting fluid viscosities are included in this figure. It is worth noting that the curves representing equal flow rates showed a considerable difference. One of the reasons for this difference was the magnitude of flow rate change in each experiment. For the tests conducted at a flow rate of 0.01 mL/min, the increase in flow rate in the first subset was only 0.005 mL/min (from 0.005 to 0.01 mL/min), while in the second subset it was 0.01 mL/min. A greater stepwise increase in the wetting phase flow rate resulted in a higher number of larger globules splitting into smaller ones. This was why the contribution of the smaller globules at a flow rate of 0.01 mL/min was higher in the second subset and its contribution curve had a larger slope at small values of globule size than that of the curve for the first subset. This was observed in the tests with a flow rate of 0.02 mL/min as well. On the other hand, examination of the first and second subsets at the flow rate of 0.02 mL/min show that although the flow rates and their final step increase were the same, the curves representing these two cases did not follow the same trend. This might be attributed to the imbibition flow rate history before they reached the flow rate of 0.01 mL/min. In the first subset, the flow rate...
was increased by 0.005 mL/min, while for the second subset, the increase was larger, i.e., from zero to 0.01 mL/min. Therefore, in the latter case, before a change of flow rate from 0.01 to 0.02 mL/min could affect the size of the globules, they had already been under a greater pressure gradient than those in the first subset, and hence they split into a greater number of smaller globules. Furthermore, in the first subset, before the flow rate was increased to 0.01 mL/min, some of the globules had already been trapped under an imbibition flow rate of 0.005 mL/min, which made them less susceptible to displacement by the invading wetting phase than the connected clusters of the non-wetting phase. Similar trends have also been reported by Khishvand et al. [80] for imbibition tests conducted in Bentheimer sandstone and Gambier limestone core samples. Datta et al. [56] also performed similar analyses. They used a confocal microscope to investigate globule formation and mobilization under different conditions in a sintered glass bead pack. Both studies concluded that for small capillary numbers the configurations of the trapped globules did not change with flow rate. However, if capillary number increased, Datta et al. [56] reported that
the larger globules become mobilized and produced without significant break-up, while Khishvand et al. [80] noted globule break-up in their naturally-occurring porous media. This difference might be because of the significant differences in pore space topologies between glass bead packs vs. natural rock samples. Our observations were consistent with those reported by Khishvand et al. [80].

The effect of change in invading viscosity on the cumulative contribution of the non-wetting globules to its residual saturation, while all the other parameters including the invading phase flow rate were kept constant, is shown in Fig. 16. The results show that higher was the viscosity of the wetting fluid, the greater became the viscous pressure drop acting on the residing non-wetting globules, which ultimately caused them to split into smaller droplets. Examining the slope of the curves of each test shows that the number of smaller globules contributing to the total remaining non-wetting saturation increased with increasing the viscosity of the invading fluid.

Figs. 17–20 present visual tools to support the discussion on the effect of flow rate and viscosity on the trapped non-wetting globules size distributions. Additionally, these images provide the velocity fields in some of the globules. We observed that the remaining non-wetting phase globules experienced rotation due to the shear stress exerted on their outer surface by the passing wetting fluid. Here, the greater was the shear stress, the faster became the globules rotation. This also showed the locations at which the passing fluid had a higher velocity. In these experiments, because of the complexities of the flow field, not all sections of a single globule produced detectable velocity vectors and this was why the velocity vectors at the interface of the two fluids were shown only for some of the trapped clusters. In Figs. 17–19, the non-wetting globule distribution of the 1st subset and the velocity fields of some of the clusters are presented for three different flow rates of 0.005, 0.01, and 0.02 mL/min. In these images, the sub-figures (A) and (B) illustrate the alterations in the shapes and velocity fields within the same trapped non-wetting globules at the identical locations for all the flow rates, while the sub-figure (C) shows the changes for only two of the flow rates. The trapped cluster in sub-figure (A) remained intact for the first two flow rates, however as the flow rate was increased to 0.02 mL/min, it split into several smaller globules. As the velocity field in one corner of this globule shows, its rotation speed increased from $1.5 \times 10^{-3}$ m/s to about $2.4 \times 10^{-3}$ m/s when flow rate was changed from 0.005 mL/min to 0.01 mL/min. At the flow rate of 0.2 mL/min, the rotation velocity of one of the smaller globules that were less exposed to the passing wetting phase remained at a value close to $2.4 \times 10^{-5}$ m/s (Fig. 19(A)). However, although the velocity field of the non-wetting globule shown in sub-figure (B) evolved with the changes in flow rate, its configuration remained almost identical for all the three flow rates. As the imbibition flow rate increased from 0.005 to 0.01 mL/min, the rotation velocity of the globule shown in sub-figure (B) increased. On the other hand, increasing the imbibition flow rate from 0.01 to 0.02 mL/min caused a reverse effect, meaning, a decrease in the rotation velocity of the above-mentioned trapped globule. Here, as the imbibition flow rate increased from 0.01 to 0.02 mL/min, the globules redistributed such that the wetting fluid had more access to the previously invaded pores in the porous medium; therefore the flow rate of the wetting fluid passing through the neighboring pore of the mentioned trapped globule decreased, which in turn caused a decrease in the exerted shear stress and the rotation velocity of the globule in sub-figures (B). This effect was also observed in the neighboring trapped globule shown in sub-figure (C). In this case, when the flow rate increased from 0.01 to 0.02 mL/min, the rotation velocity of the trapped

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**Fig. 16.** Effect of the invading phase viscosity on the cumulative contribution of the globules to the total remaining non-wetting fluid.

**Fig. 17.** Distribution of the remaining non-wetting globules and their velocity fields, first subset, imbibition flow rate: 0.005 mL/min (black: grain, grey: non-wetting phase, white: wetting phase).
globule decreased from $1.8 \times 10^{-5}$ to $1.4 \times 10^{-5}$ m/s. A close inspection of Figs. 17–19 reveal that although one might expect that the neighboring trapped globules might have similar rotation velocities, owing to the complicated nature of the connectivity of the pores and throats and their size distributions, this does not always occur (see, for instance, Fig. 18(C) and (D)). These results along with those presented in the section dedicated to single-phase experiments show the importance of a porous medium topology and its role in fluids distribution and behavior.

Study of the velocity fields of the sample non-wetting globules in imbibition tests with different invading fluid viscosities (5 cSt, 50 cSt and 100 cSt) and identical flow rates of 0.01 mL/min show that invading fluid viscosity did not have a pronounced impact on the velocity fields of the globules (see for example Fig. 20). In other words, no detectable trend was observed in the velocity fields of the globules with changes in viscosity of the invading fluid. The study of velocity field in the trapped non-wetting phase globules also helped us to understand the nature of the transport that was more likely to take place in each location of the porous system. The sites at which the rotation velocity of the non-wetting phase was higher were those with a greater chances of permitting dispersive transport across the fluid/fluid interface (Fig. 20(D)), while those with a lower rotation velocity were more prone to transport dominated by diffusion across the interface (Fig. 20(C)).

5. Conclusions

A unique two-phase, two-fields-of-view (FOV) $\mu$PIV system was developed and utilized to map velocity fields of two fluids at the pore- and micromodel-scales, simultaneously. The experimental observations provided evidences of existence of slip boundary condition and significance of viscous dissipation at the fluid/fluid interfaces in porous media. They showed the nature of momentum transfer across the interfaces and their impact on pore-scale displacements and fluid occupancy. Study of fluids’ interfaces in a pore-doublet configuration showed that the rate by which the shear stress increased with flow rate was less pronounced at the lower flow rates and not all the energy exerted by the passing wetting phase was transferred to the non-wetting phase.
phase because of the slip boundary condition at their interface. The observations showed that at higher flow rates, there is a higher probability of producing the trapped non-wetting fluid globules. However, at lower flow rates, at which the trapped non-wetting fluid could not be mobilized, perturbations of the local velocity and pressure fields by introduction of a droplet of non-wetting phase into the pore-doublet could result in production of the trapped non-wetting fluid. Probing velocity field in single-phase flow tests in a two-dimensional PDMS replicate of Bentheimer sandstone resulted in identification of points of confluence and bifurcation as well as stagnant bodies of fluid. The data significantly improve our understanding of the characteristics of the local flow fields that can directly impact fluid/fluid and fluid/solid interactions and mass transfer under multiphase flow conditions. Additionally, capabilities of the µPIV system to produce unique two-phase two-FOV velocity fields for flooding tests at different invading fluid flow rates was presented. These results showed that the defending phase could get trapped with vastly different configurations because of the pore-scale morphology of the medium and its effect on the local capillary pressures. Distributions of trapped globules’ volumes and their contributions to the final residual non-wetting phase saturation under different flow rates, flow rate histories, and invading fluid viscosities were systematically investigated. It was shown that under a viscous-dominated flow regime, although the flow rate history did not produce a significant impact on the final saturation of the non-wetting phase, it did affect its globule size distribution and their cumulative contribution to the residual saturation. The trapping history after each imbibition test and the magnitude of the increase in flow rate at each step were the main reasons for the changes in non-wetting fluid distribution. The higher was the imbibition flow rate, the greater became the frequency of smaller trapped globules. When the flow rate was increased in greater number of steps to reach to a specific final value, the small globules’ contribution to the final non-wetting saturation was decreased. Furthermore, increasing the viscosity of the invading fluid elevated the contribution of the small globules to the final non-wetting saturation. Velocity fields of the trapped non-wetting globules were utilized to probe the influence of the trapped fluid globules’ distribution on the micromodel-scale flow patterns. Careful investigations of single trapped globules at different invading flow rates during imbibition.

Fig. 19. Distribution of the remaining non-wetting globules and their velocity fields, first subset, imbibition flow rate: 0.02 mL/min (black: grain, grey: non-wetting phase, white: wetting phase).
showed that due to the changes in the distribution of the non-wetting globules throughout the porous medium, the velocity of the invading fluid in some of the channels could reduce when its flow rate was increased. The results presented in this document not only studies parameters affecting fluid flow in a replicate of an oil reservoir rock, but also can be extended to flow of contaminations and water in underground fresh water resources and flow of fluids in biological porous structures like the skin.

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