Pore-scale analysis of trapped immiscible fluid structures and fluid interfacial areas in oil-wet and water-wet bead packs

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ABSTRACT

The objective of this study is to obtain quantitative evidence of pore-scale immiscible fluid distribution in oil-wet and water-wet porous media using X-ray computed microtomography. Temporal and spatial saturation profiles, as well as surface and interfacial areas, are thoroughly analyzed through cycles of drainage and imbibition using samples with different wetting characteristics but similar pore structures. The population of individual immiscible fluid structures (‘blobs’) was also evaluated. The specific nonwetting phase surface areas of both porous media are found to be in close correlation with the specific solid surface area. On the other hand, the differing wetting strengths of the two porous media affect the curvature of the fluid–fluid interface and thus the specific meniscus interfacial area of the two porous media. Although the magnitude of the specific meniscus interfacial areas is different, they both trend toward a maximum at wetting phase saturations of 0.35–0.55. The differences in wetting characteristics are also apparent in the blob populations. The number of blobs in the oil-wet porous media is three times greater than that of the water-wet porous media at similar saturations; the increase in population is a result of the increase in the amount of smaller blobs inhabiting the smaller pore spaces. The surface areas of individual blobs as a function of the individual blob volumes are found to closely agree with the specific surface area of a sphere at blob volumes below the minimum individual grain volume and with the specific pore space surface area above this volume. These results show how wettability and saturation history influence the distribution of immiscible fluids within the pore space.

Key words: blob, computed microtomography, hysteresis, interfacial area, meniscus, multiphase, pore-scale, wettability

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INTRODUCTION

Multiphase fluid flow and transport in porous media continues to be an important subject because of its application in carbon sequestration, environmental remediation, water resource management, and hydrocarbon recovery. A thorough understanding of multiphase fluid flow and transport in porous media is essential to fluid management and engineering in reservoir and near-surface environments. Characterization of pore space geometry, fluid–fluid and fluid–rock interactions requires quantitative measurements, such as mean distance between solid surfaces, fluid–fluid interfacial areas, fluid–solid interfacial areas, and immiscible fluid structure population statistics. Because of the difficulty in obtaining direct pore-scale measurements, investigators often choose to perform experiments using numerical simulations (Dillard et al. 2001; Dalla et al. 2002; Bryant & Anna 2004), two-dimensional micromodels (Sahloul et al. 2002; Chen et al. 2007), and thermodynamically derived estimations (Bradford & Leij 1997; Grant & Gerhard 2007).

Many investigators have found great success in the utilization of X-ray computed microtomography (CMT) to noninvasively produce three-dimensional images of both
pore space geometry and immiscible fluid distribution within the pore space (Vinegar & Wellington 1987; Coles et al. 1998). Investigations have imaged the pore spaces of natural rocks (Auzerais et al. 1996; Okabe & Blunt 2007), unconsolidated sands and soils (Brusseau et al. 2006, 2008; Constanza-Robinson et al. 2008; Al-Raoush 2009), as well as bead packs (Culligan et al. 2004, 2006; Al-Raoush & Willson 2005; Karpyn et al. 2010).

Computed microtomography images can be processed to construct three-dimensional pore networks that can be used to predict two- and three-phase flow properties (McDougall et al. 2002; Piri & Blunt 2005a,b; Svirsky et al. 2007; Ryazanov et al. 2009). Extraction of pore networks from three-dimensional CMT images, particularly for the characterization of pore throats and pore bodies, has been developed for both matrix and fractures (e.g., Al-Raoush et al. 2003; Jiang et al. 2007; Karpyn & Piri 2007; Piri & Karpyn 2007). CMT images can also be used to model flow and transport properties directly using techniques such as lattice Boltzmann (Wu et al. 2006; Schaap et al. 2007; Boek & Venturoli 2010), moving particle semi-implicit methods (Ovaysi & Piri 2010; Ovaysi & Piri 2011), level-set method (Prodanovic & Bryant 2006), smoothed particle hydrodynamics (Tartakovsky & Meakin 2006), and direct solution of the Stokes equations (Zaretisky et al. 2010). Using CMT to resolve pore space geometry and fluid occupancy for direct applications and comparison with those generated the pore-level models has proven to be an essential step in development and validation of physically based numerical simulators.

One of the important characteristics defining fluid distributions is fluid–fluid interfacial area. Fluid–fluid interfacial area measurements have received much attention in the literature (Bradford & Leij 1997; Vivek et al. 2003; Culligan et al. 2004, 2006; Chen et al. 2007; Constanza-Robinson et al. 2008; Al-Raoush 2009; Brusseau et al. 2009), as it is an important parameter influencing mass, momentum, and energy transfer between fluid phases. It is also believed that capillary pressure – saturation hysteresis is because of the projection of a capillary pressure – saturation – fluid–fluid interfacial area functional surface onto the two-dimensional plane of capillary pressure versus saturation (Hassanzadeh & Gray 1993). Porter et al. (2009) went on to show that a capillary pressure – saturation – fluid–fluid interfacial area functional surface adequately captures the capillary pressure – saturation hysteresis displayed by a succession of scanning curves produced by a lattice-Boltzmann simulation, thus eliminating capillary pressure – saturation hysteresis with the inclusion of fluid–fluid interfacial area. Constanza-Robinson et al. (2008) and Brusseau et al. (2009) both imaged two-phase immiscible fluid distributions in sand and bead packs using CMT and developed empirical linear functions relating the specific nonwetting phase surface area to the saturation. Constanza-Robinson et al. (2008) developed a linear function relating the specific nonwetting phase surface area to the saturation using the specific solid surface area of the porous medium, which can be approximated in the case of spherical grains by the porosity and mean grain diameter. Brusseau et al. (2009) also developed an empirical linear function relating specific nonwetting phase surface area to saturation based on the median grain diameter of the porous medium. These empirical relationships can provide an estimate of specific nonwetting phase surface areas for all saturations with easily obtainable measurements of a porous medium, such as porosity and mean grain diameter.

Al-Raoush (2009) used CMT images to perform a nonaqueous-phase-liquid (NAPL) blob size and shape frequency analysis of 100%, 50%, 25%, and 0% by weight NAPL-wet to water-wet bead packs. With an increasing fraction of NAPL-wet beads, the NAPL blobs grew smaller and shorter; with increasing NAPL-wet solid surfaces, more of the blobs were truncated by NAPL-wet surfaces. The blobs of the 100% NAPL-wet bead packs had larger meniscus interfacial area to volume ratios owing to their smaller size. This investigation suggests wettability can have a strong impact on interfacial areas, particularly the specific wetting phase surface area. The distribution of fluids and their interfaces affect relative permeability curves, which are a result of pore space geometry, saturation history, interfacial tension, and wettability. Idealized relative permeability curves and illustrations of fluid distribution in the pore space of porous media with varying wettability are presented in Fig. 1.

The investigation presented here uses a synthetic porous system, a bead pack, in lieu of a natural core to limit heterogeneity in grain surface properties and pore space geometry. The beads used are oil-wet acrylic beads; a previous experiment, which provides a raw image data set for direct comparison to the results of this investigation, used water-wet silica beads (Karpyn et al. 2010). Natural porous media such as sands and outcrop sandstones are normally water-wet, while carbonates from oil-bearing formations are commonly oil-wet or of mixed wettability. The acrylic bead pack here is representative of medium grained porous system rendered oil-wet by the deposition of heavier components of oil (e.g., Asphaltenes) on grain surfaces. Previous investigations of immiscible fluid distribution in bead/sand packs utilizing CMT used cores of lengths 70–100 mm and inner diameters of 3.50–7.00 mm (Auzerais et al. 1996; Culligan et al. 2004, 2006; Al-Raoush & Willson 2005; Brusseau et al. 2006, 2008; Okabe & Blunt 2007; Al-Raoush 2009; Brusseau et al. 2009). In this investigation, and that of Karpyn et al. (2010), a core holder of considerably larger dimensions (102 mm long and 25.4 mm in diameter) than those of the above investigations is utilized. Bead size is comparable to those reported in previous experiments, providing a much lower
bead diameter to core holder diameter ratio, and thus a greater uninterrupted pore space, while maintaining enough image resolution to define curved interfaces. Also, the bead pack used in this investigation was scanned in its entirety, while previous investigations using CMT only scanned the middle 4–10 mm of the core. By scanning the entire bead pack, fluid distribution throughout the bead pack including the extent of systematic boundary effects can be investigated. More importantly, it provides a very large data set from which to sample immiscible fluid structure population statistics at residual and irreducible saturations. Results from this work provide direct measurements of porosity, saturation, meniscus associated oil–water interfacial areas, and fluid–bead interfacial areas, as well as insight into pore-scale displacement mechanisms responsible for observed fluid occupancies. An analysis of blob population statistics is included to complete the description of immiscible fluid distribution. We also describe these fluid distribution measurements in the context of the pore space geometry. It is expected that these results will be used for the construction, calibration, and validation of representative pore-scale models.

**MATERIALS AND METHODS**

**Core holder design**

The core holder was specifically designed for a series of low pressure experiments (~1 atm) (Karpyn et al. 2010). The assembly is capable of producing a 25.4 mm in diameter granular pack of lengths up to 102 mm. The assembly is composed of a polycarbonate sleeve capped by stainless steel end plugs. Each end plug has two ports, a main flow port and an auxiliary port; in the investigation presented here only the main flow port was used. Between the end plugs and the bead pack are spacers, flow distributors, and screens. The polycarbonate annular 20- to 25-mm-long spacers act to separate the flow distributors from the end plugs. The cylindrical polycarbonate flow distributors contain a uniform collection of 2-mm-diameter channels that act to distribute and straighten the flow in and out of the bead pack. As the average bead diameter is much smaller than the channels of the flow distributor, a nylon screen with openings of 0.001 mm is placed between the bead pack and the flow distributor, thus keeping the beads from being displaced and entering the flow distributors.

The core assembly has two ends, a static end and a dynamic end. The assembly of the static end allows for support against which beads were compressed by the dynamic end. Once the beads are in place, the dynamic end of the core holder is assembled; as it is tightened, a slight mechanical axial compression is imparted on the bead pack. This compression ensures the immobilization of the beads without bead deformation. Once the bead pack is assembled, flooding of fluids can occur from either end of the core, and the core can be used at any orientation. Throughout this investigation, the dynamic end is oriented directly vertically above the static end.

**Experimental installation**

The experimental set-up contains four main parts; a fluid reservoir, a fluid flooding system, a core, and the X-ray CMT scanner (Fig. 2). The immiscible fluids (brine and kerosene) were mixed vigorously and kept in the same fluid reservoir to minimize mass transfer between fluids during the flooding process. A hydrostatic flooding system was built to allow control on small pressure heads throughout the experiment. From the reservoir, fluids are pumped to a
pressure head maintenance tank that contains three-quarter valves along its bottom. These valves allow for the maintenance of fluid level which in turn provides a consistent inlet pressure of injected fluids. The difference in height between this fluid level and the outlet provides a measure of overall pressure difference across the bead pack, core holder, and connecting tubing. The pressure head maintenance tank is translated vertically by a crank-driven system, providing different inlet heights and thus different inlet pressures. The flow-rates are maintained by manually increasing/decreasing the height of the pressure head maintenance tank. Pump-based fluid injection is not consistent, but rather a succession of impulses; this system eliminates these impulses. During the course of fluid injections, the flow-rates were maintained within 15% of the average flow-rate. The core is placed on a rotating mount between the source and detector of the X-ray CMT scanner where it can be imaged.

Materials

The oil-wet beads used in this investigation are acrylic beads purchased from Lucite Diakon. These beads were sieved to provide a bead diameter range of 0.425–0.600 mm. The resulting bead pack had a length of 87.753 mm and a diameter of 25.4 mm. Two immiscible fluids were used, kerosene, the wetting phase, and brine, the nonwetting phase. The kerosene phase has a surface tension with air of 26.69 mN m⁻¹, density of 0.797 g cm⁻³, and a viscosity of 2.43 cP. The brine used was a 6% by weight NaI solution, and the NaI was dissolved by vigorous mixing in deionized water. The brine has a surface tension with air of 78.00 mN m⁻¹, density of 1.061 g cm⁻³, and an approximate viscosity of 1.0 cP. NaI was chosen over other salts as it supplies the greater contrast with the kerosene in the CMT images; iodide attenuates X-rays much more than kerosene or acrylic beads because of its high atomic number. Experimental measurements of contact angles were taken using the Washburn method and a Kruss FL12 cell (Mora et al. 2010). The contact angle through the wetting phase for the acrylic beads used was 19.0°, representing a strongly oil-wet porous medium. However, as is discussed in the results section, we believe during the presaturation stage of the experimental procedure these beads became more weakly oil-wet.

Experimental procedure

A summary of the experimental procedure can be found in Fig. 3, beginning with vacuum conditions of 1.57 Pa. The dry bead pack is then scanned using CMT and presaturated with brine, which allows the volumetric calculation of sample porosity. The porosity was found to be 0.421, corresponding to a pore volume of 18.8 cc. After presaturation, brine was flooded from the bottom of the core at flow rates ranging from 4.0 to 9.4 cc min⁻¹, from which absolute permeability was found to be 1.58 × 10⁻¹¹ m². Following brine injection and consecutive imbibition–drainage cycles, the bead pack was scanned.

During the first imbibition (I1), as summarized in Fig. 3, kerosene (wetting phase) flooding took place from the top of the bead pack. The kerosene flood was stopped after residual brine saturation was reached. Residual saturation is considered to be reached when no more of the phase being displaced appears at the outlet for more than two pore volumes. Following I1, brine was flooded from the bottom of the bead pack the first drainage (D1). After the first drainage, the bead pack underwent its second imbibition (I2), carried out in the same manner as the first one. These two imbibition cycles allowed the comparison of fluid distributions that resulted from kerosene flooding in the absence of initial wetting phase (I1) and kerosene flooding in the presence of the initial wetting phase (I2).

The second drainage (D2) followed the second imbibition and became the initial conditions for a third imbibition. The bead pack was not scanned after the second drainage, as it was believed the second drainage would result in a fluid distribution similar to that of first drainage, a supposition later supported by the results. The third imbibition (I3) was carried out at a faster flooding rate and scanned to analyze the effect of flooding rate on the resulting fluid distribution. In summary, this experimental procedure resulted in three-dimensional images of a dry bead pack, a presaturated bead pack, a first imbibition, a first drainage, a second imbibition, and a third imbibition.

Imaging technique

The bead pack and resulting immiscible fluid distributions are imaged using CMT. X-ray CMT imaging is a noninvasive imaging technique that produces a three-dimensional grid of voxels – much like pixels for a two-dimensional image – each of which contain an integer value CMT registration number. CMT registration numbers are relative values of X-ray attenuation and are a function of the density.
and apparent atomic number (average atomic mass) of the material. This three-dimensional grid of CMT registration numbers can be viewed as a three-dimensional image. Further image processing identifies the phase occupying each voxel. The X-ray CMT system used in this investigation is composed of four main parts, the X-ray source, a rotating mount, a detector, and a computer that controls motion and data acquisition. In this investigation, the CMT system was tuned to a voxel resolution of 0.0259 \times 0.0259 \times 0.0274 mm, where 0.0274 mm represents the height of the voxel or the thickness of the slice. Each three-dimensional rendering of the entire core sample contains slightly more than 2.3 billion voxels.

**Image processing**

Raw image data were processed using Avizo Fire 6.2 and in-house subroutines. The CMT images were first filtered using a 3 \times 3 \times 3 kernel median filter to reduce image noise. The filtered images were then segmented into the phases present. Image segmentation was accomplished by simple thresholding, that is, all voxels that contain a CMT registration number equal to or below a CMT registration number threshold are segmented from the voxels with CMT registration numbers above this threshold. First, the pore space is segmented from the bead space using the presaturation images to ensure any bubbles in the beads are not misidentified as pore space. To fully segment our three-phase (bead, kerosene, and brine) system using simple thresholding, the bead space was subtracted from the three-phase images to produce images with only two phases present (kerosene and brine), which were subsequently segmented using simple thresholding. The threshold value used to segment pore space from bead space was determined from an outside measurement of porosity by finding the threshold value that resulted in a porosity equal to the measured value. The determination of the threshold value for the segmentation of the fluids was different, as we did not have an independent measurement of saturation. Instead, a linear relationship between the mean CMT registration numbers of an imaged volume and the saturation of the volume was assumed. The linear relationship was calibrated with only two points, one from the presaturation scan \((S_w = 1.0)\) and one from a scan taken with a bead pack presaturated with oil \((S_w = 0.0)\). The saturation of a imaged volume was thus determined by the mean of its CMT mean registration number, and a threshold value was found that matched this saturation. However, because our linear function is calibrated with only two points, this value was considered to be an estimate. Thus, threshold values were determined visually within a small window of this value for each segmented image volume. The difference in results from using different threshold values within this window was negligible.

Each three-dimensional reconstruction of the imaged core contains a substantial amount of data, and therefore, post-processing for detailed volume and surface measurements can be computationally expensive. For that reason, several

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**Fig. 3.** Experimental procedure indicating fluid and direction of flooding, as well as average flow rate \((Q)\) and total flooding volume \((V)\). Radiation symbols represent postcycle computed microtomography scanning. I. Vacuum dried bead pack. II. Pre-saturation, brine flooding, and determination of absolute permeability. III. First imbibition of bead pack fully saturated with nonwetting phase at low flow rate from 100% brine saturation. IV. First drainage at low flow rate. V. Second imbibition of bead pack partially saturated with nonwetting phase at low flow rate. VI. Second drainage at low flow rate. VII. Third imbibition of bead pack partially saturated with nonwetting phase at high flow rate.
regions of interest or subsamples were extracted from the main 3D image sets for detailed image processing and characteristic measurements. Representative Elementary Volume (REV) analysis was conducted for porosity, saturation, and specific meniscus interfacial area resulting in an REV size on the order of 80 \times 80 \times 80 \text{ voxel} (2.072 \times 2.072 \times 2.196 \text{ mm}^3). A larger subsample size was then chosen to provide a large population of separate nonwetting blobs. These subsamples are 400 \times 400 \times 400 \text{ voxel} (10.36 \times 10.36 \times 10.98 \text{ mm}^3) in size, distributed throughout the core, for each flooding cycle and two bead packs, acrylic and glass. The glass bead experiment from which subsamples were extracted is presented in Karpyn et al. (2010). A combined total of 64 subsamples were taken from all flooding cycles and both bead packs (13 from first imbibition – acrylic beads, 19 from first drainage – acrylic beads, eight from second imbibition – acrylic beads, eight from third imbibition – acrylic beads, eight from first drainage – glass beads, and eight from first imbibition – glass beads). Subsampling also allows close examination of regions that exhibit different saturation conditions within the same set and across data sets. Table 1 presents a summary of measurements obtained from each subsample and their corresponding indexing and location. Table 2 presents a list of symbols used. Subsamples with the same indexing correspond to the same \( x \), \( y \), and \( z \) location. Reported measurements are discussed in following sections.

Figure 4 shows three-dimensional displays of trapped nonwetting blobs found in subsamples of equivalent saturation history from the glass and acrylic bead packs. Note the difference in the appearance of the nonwetting phase blobs for the two bead packs. The blobs in the glass bead pack appear smoother and less disconnected than the blobs in the acrylic bead pack. Blobs with volumes \(< 4.6 \times 10^{-3} \text{ mm}^3\) were filtered out, because they are near the limit of CMT resolution, become indiscernible from image noise, and do not contribute significantly to residual saturations.

**Image data set of glass bead pack**

The results of this investigation are analyzed and compared with a previous investigation conducted with the same core holder design, experimental installation, and imaging technique (Karpyn et al. 2010). In the previous investigation, the beads used were made of glass, a strongly water-wet material with a contact angle of 17°, as measured through the water phase using the Washburn method. The bead diameter range was also 0.425–0.600 mm. The purpose of comparing the existing glass bead data set with the present acrylic data set is to investigate the effect of wettability on fluid distribution, and the dependence of interfacial areas and fluid distribution on such wettability. Although wettability is the primary contrast between these two experiments, there are other differences worthy of mention. The glass bead data set has voxel resolutions of 0.0260 \times 0.0260 \times 0.0292 \text{ mm}^3, compared with 0.0259 \times 0.0259 \times 0.0274 \text{ mm}^3 for the acrylic set. Karpyn et al. (2010) calculated surface areas by summing the interfaces between segmented voxels; here, the surface areas are calculated using a modified marching cubes algorithm. The glass bead pack investigation used ceramic flow distributors and perforated thin steel plates, in place of the polycarbonate distributors and nylon screens used in this investigation. The glass bead investigation involved only a single drainage (kerosene flooding) and imbibition (brine flooding) cycle, with an 8% by weight NaI solution. The flood sequences are also different; the glass bead pack underwent a drainage first, while the acrylic bead pack underwent imbibition first. The image segmentation was performed using simple thresholding, but the threshold value was determined in a different manner. The threshold values were calculated by assuming all segmented voxels have a CMT registration number equal to the mean CMT registration number of the phase occupying the voxel, and the mean CMT registration number of this segmented image is equal to the overall mean CMT registration number for the core (Majid et al. 1990). The difference in thresholding methods was found to have only a minor effect on further volumetric and surface area measurements. Throughout this investigation, we present comparative analyses in the context of those differences.

**Surface and interfacial areas**

Avizo applies a modified form of the marching cubes algorithm to wrap a surface around the binary 3D grid of the segmented image data. The modification to the marching cubes algorithm includes a subvoxel weighting to all interfacial voxels to improve smoothing of surfaces. This modification was employed to approximate the smooth nature of the surface areas of the phases present from step-like grid data. Without the use of the modified marching cubes algorithm, surface areas would appear step-like, and the surface area would be overestimated. Once a surface has been wrapped around each individual blob, volumes are measured as the volume encapsulated by the surface constructed using the marching cubes algorithm.

The overall volumes, specific solid surface areas, specific pore space surface areas, specific fluid surface areas, specific total interfacial areas, and specific meniscus interfacial areas of each subsample were calculated by summing the surface areas and volumes of individual blobs. The specific solid surface area \( \left( a_s \right) \) is defined as:

\[
a_s = \frac{A_s}{V_b}
\]

where \( V_b = V_n + V_w + V_s \) and \( A_s \) are the bulk volume and solid surface area, respectively. The specific pore space surface area \( \left( a_{ps} \right) \) is defined as:

\[
a_{ps} = \frac{A_{ps}}{V_n}
\]

where \( V_n \) is the volume of the phase occupying the voxel, \( A_{ps} \) is the pore space surface area of the phase, and \( V_b \) is the bulk volume of the phase.
Pore-scale analysis of trapped immiscible fluid structures

Table 1 Summary of measurements obtained from various core subsamples. Location refers to the lower-front-left corner of each subsample in \(x\), \(y\), \(z\) voxels, where \(z\) is elevation. The elevation of the subsample refers to the height of the center of the subsample. The acrylic bead pack and glass bead pack scanned dimensions are \(1024 \times 1024 \times 3191\) voxels and \(1024 \times 1024 \times 3109\) voxels, respectively.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Index</th>
<th>Location ((x, y, z))</th>
<th>Elevation (mm)</th>
<th>(\varphi)</th>
<th>(\lambda_{d}(\text{mm}))</th>
<th>(\lambda_{s}(\text{mm}))</th>
<th>(S_{\varphi})</th>
<th>(\lambda_{d}(\text{mm}))</th>
<th>(\lambda_{s}(\text{mm}))</th>
<th>(N)</th>
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<tr>
<td>Acrylic I1</td>
<td>1</td>
<td>(200, 200, 1)</td>
<td>5.5</td>
<td>0.443</td>
<td>5.757</td>
<td>12.984</td>
<td>0.885</td>
<td>1.199</td>
<td>5.104</td>
<td>0.273</td>
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<td>2</td>
<td>(200, 400, 100)</td>
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<td>0.435</td>
<td>5.794</td>
<td>13.31</td>
<td>0.882</td>
<td>1.264</td>
<td>5.086</td>
<td>0.278</td>
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<tr>
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<td>3</td>
<td>(400, 400, 200)</td>
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<td>0.437</td>
<td>5.702</td>
<td>13.057</td>
<td>0.927</td>
<td>0.784</td>
<td>5.269</td>
<td>0.176</td>
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<tr>
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<td>4</td>
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<td>5.686</td>
<td>13.122</td>
<td>0.926</td>
<td>0.783</td>
<td>5.239</td>
<td>0.168</td>
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<tr>
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<td>(200, 200, 800)</td>
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<td>0.429</td>
<td>5.709</td>
<td>13.311</td>
<td>0.931</td>
<td>0.787</td>
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<td>5.732</td>
<td>13.302</td>
<td>0.933</td>
<td>0.789</td>
<td>5.218</td>
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<td>5.669</td>
<td>13.101</td>
<td>0.934</td>
<td>0.789</td>
<td>5.218</td>
<td>0.165</td>
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<td>0.957</td>
<td>0.826</td>
<td>5.449</td>
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<td>5.872</td>
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<td>0.132</td>
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<tr>
<td>Acrylic D1</td>
<td>1</td>
<td>(200, 200, 1)</td>
<td>5.5</td>
<td>0.443</td>
<td>5.757</td>
<td>12.984</td>
<td>0.885</td>
<td>1.199</td>
<td>5.104</td>
<td>0.273</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>2</td>
<td>(200, 400, 100)</td>
<td>8.22</td>
<td>0.435</td>
<td>5.794</td>
<td>13.31</td>
<td>0.882</td>
<td>1.264</td>
<td>5.086</td>
<td>0.278</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>3</td>
<td>(400, 400, 900)</td>
<td>10.97</td>
<td>0.437</td>
<td>5.702</td>
<td>13.057</td>
<td>0.946</td>
<td>0.822</td>
<td>5.209</td>
<td>0.165</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>4</td>
<td>(400, 200, 300)</td>
<td>13.71</td>
<td>0.433</td>
<td>5.686</td>
<td>13.122</td>
<td>0.962</td>
<td>0.827</td>
<td>5.257</td>
<td>0.165</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>5</td>
<td>(200, 200, 800)</td>
<td>27.44</td>
<td>0.429</td>
<td>5.709</td>
<td>13.311</td>
<td>0.931</td>
<td>0.817</td>
<td>5.218</td>
<td>0.165</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>6</td>
<td>(200, 400, 900)</td>
<td>30.18</td>
<td>0.431</td>
<td>5.732</td>
<td>13.302</td>
<td>0.933</td>
<td>0.817</td>
<td>5.218</td>
<td>0.165</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>7</td>
<td>(400, 400, 1000)</td>
<td>32.93</td>
<td>0.433</td>
<td>5.669</td>
<td>13.101</td>
<td>0.934</td>
<td>0.817</td>
<td>5.218</td>
<td>0.165</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>8</td>
<td>(400, 200, 1100)</td>
<td>35.67</td>
<td>0.426</td>
<td>5.653</td>
<td>13.294</td>
<td>0.935</td>
<td>0.817</td>
<td>5.218</td>
<td>0.165</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>9</td>
<td>(200, 200, 1600)</td>
<td>49.4</td>
<td>0.419</td>
<td>5.756</td>
<td>13.724</td>
<td>0.941</td>
<td>0.816</td>
<td>5.366</td>
<td>0.114</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>10</td>
<td>(200, 400, 1700)</td>
<td>52.14</td>
<td>0.414</td>
<td>5.791</td>
<td>13.987</td>
<td>0.933</td>
<td>0.817</td>
<td>5.359</td>
<td>0.114</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>11</td>
<td>(200, 200, 1900)</td>
<td>57.63</td>
<td>0.41</td>
<td>5.779</td>
<td>14.106</td>
<td>0.941</td>
<td>0.818</td>
<td>5.403</td>
<td>0.129</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>12</td>
<td>(200, 400, 2500)</td>
<td>74.1</td>
<td>0.399</td>
<td>5.845</td>
<td>14.659</td>
<td>0.957</td>
<td>0.826</td>
<td>5.449</td>
<td>0.132</td>
</tr>
<tr>
<td>Acrylic D1</td>
<td>13</td>
<td>(400, 200, 2700)</td>
<td>79.59</td>
<td>0.403</td>
<td>5.872</td>
<td>14.599</td>
<td>0.959</td>
<td>0.826</td>
<td>5.449</td>
<td>0.132</td>
</tr>
</tbody>
</table>

where $A_{ps}$ and $V_{ps}$ are the pore space surface area and volume, respectively. Specific fluid surface areas, both wetting and nonwetting, are defined as:

$$a_{nw, w} = \frac{A_{nw, w}}{V_b}$$  \hspace{1cm} (3)

where $A_{nw, w}$ is the nonwetting or wetting phase surface area. Because CMT is incapable of resolving films, specific interfacial area measurements can be treated in two ways: we either assume there is a film of the wetting phase covering all solid surfaces, and the fluid–fluid interface exists along all nonwetting phase surfaces, or only consider interfacial areas associated with the meniscus, where fluid surfaces in the CMT images meet. The specific nonwetting phase surface area is also the specific total interfacial area. Measuring only the fluid interfacial areas associated with the meniscus, the specific meniscus interfacial area ($a_m$) is defined by Dalla et al. 2002:

$$a_m = \frac{1}{2} \left( \frac{A_w}{V_b} + \frac{A_n}{V_b} - \frac{A_s}{V_b} \right)$$  \hspace{1cm} (4)

where $A_m A_w$, and $A_s$ are the total surface areas of the nonwetting phase, wetting phase, and solid phase, respectively.

**RESULTS AND DISCUSSION**

**Bead packing**

Porosity was measured vertically and radially, while mean distance between solid surfaces was measured along two orthogonal directions, perpendicular to the main flow direction (Fig. 5). The packing of the acrylic and glass beads resulted in average porosities of 0.421 and 0.416, respectively, which falls between the two extremes for idealized packing of regular spheres (i.e., rhombohedral: 0.259; cubic: 0.476). As can be seen from the vertical porosity profile in Fig. 5, larger porosities are observed close to the ends of the bead packs and are the result of bead alignment with the semi-flat surface of the inlet/outlet screens and flow distributors. The drop in porosity at a height of 10 mm on the glass bead pack could be because of local packing variations. Figure 5 also shows the porosity of the bead pack radially, averaged over the full

---

Table 1 (Continued).

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Index</th>
<th>Location (x, y, z)</th>
<th>Elevation (mm)</th>
<th>$\phi$</th>
<th>$a_{ps}$(mm$^{-1}$)</th>
<th>$a_{nw}$(mm$^{-1}$)</th>
<th>$a_w$(mm$^{-1}$)</th>
<th>$a_m$(mm$^{-1}$)</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass I1 11</td>
<td>(400, 400, 1800)</td>
<td>54.89</td>
<td>0.396</td>
<td>5.652</td>
<td>14.267</td>
<td>0.815</td>
<td>0.993</td>
<td>5.99</td>
<td>0.465</td>
</tr>
<tr>
<td>Glass I1 12</td>
<td>(400, 200, 1900)</td>
<td>57.63</td>
<td>0.396</td>
<td>5.649</td>
<td>14.272</td>
<td>0.829</td>
<td>0.92</td>
<td>5.605</td>
<td>0.438</td>
</tr>
<tr>
<td>Glass I1 13</td>
<td>(200, 200, 2400)</td>
<td>71.36</td>
<td>0.391</td>
<td>5.648</td>
<td>14.455</td>
<td>0.832</td>
<td>0.928</td>
<td>5.766</td>
<td>0.523</td>
</tr>
<tr>
<td>Glass I1 14</td>
<td>(200, 400, 2500)</td>
<td>74.1</td>
<td>0.387</td>
<td>5.649</td>
<td>14.598</td>
<td>0.833</td>
<td>0.918</td>
<td>5.773</td>
<td>0.521</td>
</tr>
<tr>
<td>Glass I1 15</td>
<td>(400, 400, 2600)</td>
<td>76.85</td>
<td>0.382</td>
<td>5.676</td>
<td>14.864</td>
<td>0.829</td>
<td>0.952</td>
<td>5.785</td>
<td>0.53</td>
</tr>
<tr>
<td>Glass I1 16</td>
<td>(400, 200, 2700)</td>
<td>79.59</td>
<td>0.383</td>
<td>5.701</td>
<td>14.888</td>
<td>0.781</td>
<td>1.226</td>
<td>5.787</td>
<td>0.656</td>
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</table>
length of the bead pack. The lowest porosity in the acrylic bead pack was found immediately adjacent to the beads lining the wall, suggesting these beads were tightly (rhombohedrally) aligned to the beads along the wall. In the case of the glass beads, packing is tighter toward the center and related to the greater bead–bead friction of the glass beads, resulting in a translation of cubic packing near the wall toward the center. The mean distances between solid surfaces for the acrylic bead pack was 0.254 and 0.290 mm for the glass bead pack, and vertically uniform in both cases. The difference in the mean distances between bead types is likely the result of a slight bead imperfection in the acrylic beads. There was no bead mobilization observed for either bead pack throughout the investigation.

Capillary and bond numbers

Before the saturated images are analyzed, some review of the forces involved in fluid distribution is needed. The capillary number is a dimensionless number that is used to compare viscous and capillary forces. Classically, the capillary number, $N_{ca}$, is calculated according to $N_{ca} = \frac{\mu v}{\phi \gamma}$, where $\mu$ is the viscosity of the displacing phase, $v$ is the fluid velocity of the displacing phase, $\gamma$ is the interfacial tension between fluids, and $\phi$ is the porosity. The interfacial tension between kerosene and brine is calculated from the individual surface tensions according to the approximation developed by Girifalco & Good (1957), $\gamma = \delta_k + \delta_b - 2C\sqrt{\delta_k\delta_b}$, where $\delta_k$ and $\delta_b$ are the individual surface tensions of the kerosene and brine, respectively, and $C$ is a correction factor set empirically to 0.55. The interfacial tension between kerosene and brine in this investigation and the glass bead investigation was determined to be 54.5 and 55.9 mN m$^{-1}$, respectively. Wardlaw & McKeller (1985) showed that mobilization of trapped immiscible fluid structures (blobs) occurs at $N_{ca} > 10^{-4}$ for a bead pack with median grain diameter similar to that used in this investigation. The displacement of immiscible fluid structures indicates the prevalence of viscous forces over capillary forces. Throughout this investigation, however, capillary forces dominate over viscous forces. The capillary numbers for the first and second imbibitions of the acrylic bead pack are $2.27 \times 10^{-6}$ and $2.90 \times 10^{-6}$, respectively. The capillary numbers for the first and second drainages of the acrylic bead pack are $8.24 \times 10^{-7}$ and $1.01 \times 10^{-6}$, respectively, which are lower than those of imbibitions because of the lower viscosity of brine. The capillary number for the fast imbibition (1) of the acrylic bead pack is $3.14 \times 10^{-5}$. The capillary numbers for the single drainage and imbibition of the glass bead pack is $1.98 \times 10^{-6}$ and $9.21 \times 10^{-7}$, respectively.

The bond number is a dimensionless number that is used to compare gravity and capillary forces. Classically,
the bond number, \( N_b \), is calculated according to \( N_b = \frac{\Delta \rho g \bar{r}^2}{\gamma} \), where \( \Delta \rho \) is the difference in fluid densities, \( g \) is the acceleration of gravity, and \( \bar{r} \) is half of the mean pore size (assuming spherical pores). Flow is considered capillary dominated below bond numbers of \( 10^{-2} \) (Morrow et al. 1988). The mean bond number for the fluids/acrylic bead pack and fluids/glass bead pack are \( 1.03 \times 10^{-3} \) and \( 0.77 \times 10^{-3} \), respectively. The maximum possible \( \bar{r} \) is near the median grain radius, and the maximum bond number expected to be encountered in the pore space is near \( 4.27 \times 10^{-3} \). As a result of the low order of magnitude of the bond number, it is considered that surface tension forces (capillarity) dominate over gravitational effects in this experimental investigation. However, our bond numbers are close to the transition from capillary dominant to gravity dominant; thus, some gravity segregation may still take place.

**Saturation profiles**

This section presents a detailed description of saturation profiles resulting from the different cycles of drainage and imbibition in the acrylic bead pack, pore-scale flow mechanisms that explain such saturation profiles, and comparison with related findings for a glass bead pack reported by Karpyn et al. (2010). A schematic diagram of the saturation history of the acrylic bead pack is presented in Fig. 6. The overall wetting phase saturation of the first, second, and third imbibitions (I1, I2, and I3) of the acrylic bead pack are 0.9168, 0.8478, and 0.8277, respectively; the overall wetting phase saturation of the first drainage (D1) is 0.2386. The wetting phase saturation corresponding to the drainage and imbibition cycles of the glass bead pack was 0.6837 and 0.8055, respectively. The wetting phase saturation for both bead packs after imbibition was similar, while drainage in the acrylic bead pack was more successful at displacing the wetting phase than its glass counterpart.

A counterintuitive observation is made from these results: the wetting phase saturation decreases with subsequent imbibition cycles. In other words, the overall nonwetting phase trapping because of imbibition increased with increasing initial wetting phase saturation. In the following paragraphs, we elaborate on the displacement mechanisms that lead to these experimental observations and the importance of saturation history. Vertical saturation profiles along the axis of the bead pack (Fig. 7) further illustrate...
the changes in saturation distribution for drainage and imbibition cycles.

Beginning with the analysis of the acrylic bead results, and in chronological order, the first imbibition (I1) is the result of continuous and prolonged kerosene (wetting phase) flooding from the top of the sample. The minor effects of gravity segregation and direction of flooding on the vertical saturation profile can be observed as a slight decrease in kerosene saturation with increasing distance from the top inlet. Notice that the wetting phase saturation is lower in the bottom 5 mm of the sample (imbibition outlet), following the I1 curve. In this region, end effects disturb the fluid distribution; this is because of a discontinuity in capillary pressures encountered where the porous medium meets the screen and flow distributor (Huang & Honarpour 1998). The initial conditions for this first imbibition were perfectly uniform, 0% wetting phase saturation along the sample. Thus, the variation in the resulting vertical saturation profile at the end of imbibition is relatively insignificant 5 mm above where the bead pack meets the nylon screen. Fluid–fluid interfaces are typically characterized as being either main terminal menisci (MTMs) or arc menisci (AMs). Spherical interfaces with two nearly equivalent radii of curvature that act as the invading menisci at the pore–throat junction are MTMs. AMs have an infinite radius of curvature parallel to flow and do not act as invading menisci, except for the snap-off displacement mechanism. The amount of trapped nonwetting phase at the end of the first imbibition is about 0.089%, which may have occurred owing to two underlying displacement processes: (i) bypassing of the non-wetting phase through displacements initiated by MTMs formed during I1, and (ii) swelling of the wetting layers (AMs) leading to snap-off displacements. We believe that the contribution of the latter is less significant because I1 was initiated from 0% wetting phase saturation, and therefore, there were no wetting layers to start with, although it is possible for these layers to form ahead of the displacement front.

The saturation profile at the end of I1 then became the initial state for the first drainage (D1), and the resulting variation in the vertical saturation profile becomes even more pronounced as the non-wetting phase (brine) is flooded from the bottom during drainage. The saturation profile at the end of drainage also shifted to the left because attributed to the expected overall decrease in wetting phase saturation. The flow mechanisms observed here suggest that gravity segregation still plays a rather significant role in producing the above-mentioned fluid occupancy, i.e., higher nonwetting (heavier) phase saturation at the bottom of the pack.

At the end of first drainage (D1), wetting phase saturation is still relatively high (above 30%) in the upper half of the core, which suggests that this fluid phase remained widespread and perhaps highly interconnected in this region. In the top 5-mm section of the sample in the drainage profile D1 (drainage outlet), there is an increase in wetting phase saturation owing to capillary end effects. This saturation condition is the initial state for the second imbibition (I2), in which the wetting phase is once again flooded from the top of the core. The difference between the first and the second imbibition is precisely the initial saturation state. Second imbibition (I2) took place in the presence of a resident wetting phase that led to significant differences in the final saturation profile.

The initial wetting phase saturation at the beginning of I2 in the top 50 mm of the pack is much higher than the bottom 40 mm. This translated into a greater amount of trapped nonwetting phase at the top 50 mm of the pack. Initially, this may look opposite to what one would expect, but the behavior can be explained considering the following mechanisms. In the top 50 mm of the pack, there are many more kerosene-filled elements that can act as initiation points for kerosene-to-brine displacements during imbibition. In order words, abundance of MTMs improves the efficiency of the bypassing of brine, which in turn leads to greater trapped brine saturations. Whereas in the bottom 40 mm, there are many fewer kerosene-filled elements (lower wetting phase saturation) than in the top 50 mm, and hence, many fewer MTMs are present. This means that bypassing of brine, and therefore trapping, is less efficient. Furthermore, one would expect to see trapping of brine taking place through snap-off displacement mechanisms by swelling of the wetting kerosene layers. We believe the pressure drop for the flow through these layers is relatively high in the acrylic system, meaning that swelling of the layers away from the inlet is more difficult. And this also helps to reduce the amount of trapping that takes place in the bottom 40 mm of the pack. In other words, the pack experiences a more frontal-advance displacement at the bottom 40 mm, which leads to lower trapped brine saturation. The above analysis is supported by the observation that the saturation profiles for the bottom 40 mm of the pack at the end of I1 (with zero initial wetting phase saturation, \(S_{wpi} = 0\)) and at the end of I2 (with \(S_{wpi} \approx 0.09\)) are almost identical, i.e., the presence of wetting kerosene layers did not affect the amount of trapped nonwetting phase saturation.

Also, in the top 50 mm of the pack, the amount of trapped brine at the end of I2 is much higher than that of I1 for the same region. This is again consistent with our expectation. The initial wetting phase saturation for I1 was zero, and therefore, there were no MTMs initially in place that could act as initiation points for kerosene-to-brine displacements. Whereas there were a significant number of MTMs available at the beginning of I2 in the top 50 mm.

A second drainage cycle follows I2, and the resulting saturation distribution becomes the initial condition for the
third imbibition (I3). The sample was not scanned after the second drainage, but we believe the saturation profile is well represented by curve D1 in Fig. 7, consistent with the strong similarities between the second and third imbibitions. From the second (slow imbibition, I2) to the third (fast imbibition, I3), imbibition flooding flow rate was increased by more than one order of magnitude. Third imbibition, at high flow rate, was expected to decrease trapping of nonwetting brine phase relative to the second imbibition, but the trapped brine saturation was very similar for both floods. These results suggest that the increase in flow rate from I2 to I3 was not enough to leave the capillary-dominated flow regime. Therefore, the resulting saturation profiles in I2 and I3 represent the same displacement mechanisms, with a small mismatch owing to experimental error.

The drainage and imbibition wetting phase saturation profiles for the glass bead pack contain both similarities and differences with the saturation profiles of the acrylic bead pack. The most striking difference is that the saturation profiles of the drainage and imbibition in the bottom two-thirds of the glass bead pack are almost identical. Note that, as the glass bead pack was also presaturated with brine, the first flooding is a drainage.

The drainage saturation profile is the result of continuous injection of kerosene from the bottom of the core. At the very bottom of the profile is a peak in wetting phase saturation. This is also a result of end effects; here, the capillary pressure discontinuity leads to accumulation of the heavier (brine) wetting phase. In the bottom two-thirds of the glass bead pack are almost identical. Note that, as the glass bead pack was also presaturated with brine, the first flooding is a drainage.

The drainage and imbibition wetting phase saturation profiles for the glass bead pack contain both similarities and differences with the saturation profiles of the acrylic bead pack. The most striking difference is that the saturation profiles of the drainage and imbibition in the bottom two-thirds of the glass bead pack are almost identical. Note that, as the glass bead pack was also presaturated with brine, the first flooding is a drainage.

The specific solid surface area was calculated for each sub-sample using Eq. 1. According to the smooth-sphere assumption ($a_s = 6(1 - \phi)/d$), a measure of specific solid surface area determined from mean porosity ($\phi$) and mean grain diameter ($d$), the bead packs would have an expected specific solid surface area of 6.78 mm$^{-1}$. The measured specific solid surface areas of the glass and acrylic bead packs are 5.65 and 5.76 mm$^{-1}$, respectively. The smaller measured specific surface areas are possibly because of distribution of bead sizes and packing. There is also a systematic underestimation of bead surface areas at bead contact points because of CMT resolution limitations.

Table 1 includes a detailed summary of surface and interfacial areas, obtained from subsamples of the acrylic and glass bead pack scans, for all flooding cycles. Figure 8 presents specific surface areas for wetting and nonwetting phases as a function of saturation, including results from all flooding cycles and both bead packs. Diagonal lines in Fig. 8 represent the specific solid surface area in contact with the wetting (W) and nonwetting (NW) phase, estimated from the total specific solid surface area and saturation according to Eqs 5 and 6 as follows:

$$a_{nw} = a_s(1 - S_w)$$  (5)

$$a_w = a_s S_w$$  (6)

For the nonwetting phase (black lines and symbols in Fig. 8), this surface area to saturation approximation proves to be in close agreement with actual specific nonwetting phase surface area regardless of core position, flooding cycle, saturation history, or wettability. These results are also in good agreement with previous studies that measured specific total interfacial areas using CMT for bead packs, sands, and soils (Culligan et al. 2004, 2006; Brusseau et al. 2009). Two other empirical specific non-wetting phase surface area–saturation relationships have been presented by Constanza-Robinson et al. (2008):

$$a_{nw} = a_s([-0.09112]S_w + 0.09031]$$  (7)

and Brusseau et al. (2009):

$$a_{nw} = \frac{2.6(1 - S_w)}{MGD}$$  (8)

These two relationships produce almost identical results, indecipherable on a plot, thus only one line representing
both functions is plotted in Fig. 8 (black dotted line). The linear function proposed here based on specific solid surface area proved to fit the data more accurately than the functions of Constanza-Robinson et al. (2008) and Brusseau et al. (2009), although the differences are small. The linear behavior of the nonwetting specific surface area as a function of saturation for both bead packs shows that wetting characteristics do not have a significant influence on the specific nonwetting phase surface area.

The specific surface area of the wetting phase and the corresponding specific solid surface area are represented by gray symbols and lines, respectively, in Fig. 8. In this case, the approximation proposed by Eq. 6 is not a good representation of specific wetting phase surface area. The contact angle measured through the wetting phase is 17° on glass and 19° on the acrylic beads. However, the difference in specific wetting phase surface areas observed for these two cases suggests the possibility of wettability alteration of the polyethylene surface during the presaturation with brine. Recently, Fathi et al. (2010) showed that ionic type and concentration of a brine used in water flooding of oil-wet chalk altered the wettability of the rock and that greater concentrations of Na+ rendered the rock more water-wet. Similarly, the acrylic beads may have become more water-wet after presaturation with brine, thus increasing the contact angles and weakening the spreading of the wetting phase on the acrylic beads. Under this assumption, we expect to find larger meniscus interfacial areas in the glass bead pack contributing to the specific wetting phase surface area. The contribution of meniscus interfacial areas to the specific nonwetting phase surface area compensates for the fact that the nonwetting phase occupies the larger, more continuous pores and has less contact with solid surfaces, thus resulting in a linear trend well represented by the saturation approximation given by Eq. (5).

A closer look at specific meniscus interfacial area is presented in Fig. 9. This is a measure of the fluid–fluid interfaces alone, ignoring the presence of wetting layers on the solid surface. This measurement is important for calculations such as the amount of mass transfer between phases. The meniscus interfacial area peaks when there is maximum interference between the fluid phases; that is, when (i) immiscible fluid bodies are not highly interconnected in the pore space creating numerous MTMs and (ii) fluid saturations are similar. These maxima were found at wetting phase saturations between 0.35 and 0.55 for both acrylic

### Fig. 8. Specific nonwetting (black) and wetting (gray) phase surface areas versus wetting phase saturation for the acrylic bead pack (filled) and the glass bead pack (open) and all scanned flooding cycles (I1 – squares, D1 – circles, I2 – diamonds, I3 – triangles.) Also shown are approximations for the specific surface areas predicted according to Eqs 5 and 6 (solid and dashed lines, respectively).

### Fig. 9. Specific meniscus interfacial area versus wetting phase saturation for the acrylic bead pack (filled) and the glass bead pack (open) and all scanned flooding cycles (I1 – squares, D1 – circles, I2 – diamonds, I3 – triangles.)
and glass bead packs. The trends observed in the specific meniscus interfacial area in Fig. 9 are in agreement with the investigations of Culligan et al. (2006) who report a specific meniscus interfacial area maximum at wetting phase saturations between 0.25 and 0.40 for strongly wetting bead packs. Previous investigations utilizing pore-network models to acquire measurements of meniscus-related interfacial areas have reported maxima at wetting phase saturations ranging anywhere from 0.25 to 0.70 depending on wettability, saturation history, network geometry, and trapping assumptions (Reeves & Celia 1996; Held & Celia 2001; Jockar-Niasar et al. 2008; Raeesi & Piri 2009). The trend toward a maximum specific meniscus interfacial area as a function of wetting phase saturation appears to be a common characteristic for the range of conditions investigated here. However, the magnitude of the maximum specific meniscus interfacial area does appear to be sensitive to the strength of wettability, which is the most salient difference between the glass and the acrylic bead pack, and is the cause for the increase in specific meniscus interfacial area.

During drainage, the nonwetting phase displaces the wetting phase mainly through piston-like displacements (displacements initiated by MTMs). When drainage is started from high initial wetting phase saturation, piston-like displacements will initially lead to an increase in the number of MTMs as the nonwetting phase invades more wetting-phase-filled elements and creates new MTMs with the wetting phase in the neighboring elements of the invaded pores. The nonwetting phase in the center of the invaded elements will also create new interfacial areas with the wetting phase sitting in the crevices of those elements. Progress in drainage will ultimately lead to a reduction in the number of MTMs as the branches of the invading nonwetting phase meet. This process also leads to a reduction in the amount of interfacial area in the crevices as the capillary pressure increases during the drainage, i.e., the interfaces are pushed further into the corners. This increase and then decrease in the interfacial area automatically generates a maximum in between. Because we measure interfacial areas only at the end of drainage, we do not cover the entire range of interfacial area variation during drainage. But when interfacial area data from drainage for the entire pack are considered, one can see the trend discussed above, because not all the sections of the pack, as shown in Fig. 7, experience the entire saturation span of a full drainage. This behavior can be seen for both acrylic and glass bead packs in Fig. 9. The trends for both packs are analogous as the displacement mechanisms are similar. Also, the drainage process is nonhysteresis in capillary-dominated systems.

During imbibition, however, wetting phase displaces the nonwetting phase through piston-like, snap-off, and pore-body-filling displacements, which ultimately lead to complete trapping of the nonwetting phase. At the end of this process, the fluid-fluid interfacial area is mainly between the trapped nonwetting phase and the surrounding wetting phase. Figure 9 shows the values for different imbibition processes in both packs as well.

Nonwetting blob analysis

The CMT images analyzed in this work contain a large number of individual fluid structures. A summary of the measurements obtained from each subsample can be found in Table 1. This table contains information on the location of subsamples, as well as the porosity, saturation, number of nonwetting phase blobs, specific surface, and interfacial areas of each subsample. Although Table 1 indicates the number of nonwetting structures (N) found in various subsamples, it should be noted that some of these structures may not be disconnected outside of the subsample. Blob size frequency distributions were constructed for a few representative subsamples for each cycle of imbibition and from both the acrylic and glass bead packs (Fig. 10). The indexing used for each subsample corresponds to the indexing in Table 1. The subsamples shown are from portions of the bead pack at or near residual nonwetting phase saturation; thus, the blob populations shown represent a trapped blob population. The blob size distributions for the three imbibitions of the acrylic bead pack are quite similar, except for a small increase in the number of larger blobs as the cycles of imbibition progressed (Fig. 10). This is the result of greater trapping of the nonwetting phase (i.e., lower wetting phase saturation) in the top 50 mm of the bead pack. Comparison of blob size distribution at the end of imbibition for both bead packs (Fig. 10) shows that the acrylic bead pack blob population is significantly larger than that of the glass bead pack. This observation is consistent with the three-dimensional visualizations presented in Fig. 4. The differences in blob size distributions are found mostly in the range of 0.01–0.1 mm$^3$. The greater number of small blobs in the acrylic bead pack can be attributed to the previously mentioned difference in the strength of wettability of the two experiments, where the acrylic surface has a weaker wettability. The contribution of each blob size to the total saturation of the nonwetting phase is presented in Fig. 11. As expected, the blob populations of the three imbibitions of the acrylic bead pack (Fig. 11A–C) are similar, except that there are generally larger blobs found in the second and third imbibitions, a result of higher nonwetting phase saturations, particularly in the upper 50 mm of the bead pack. Although there are far more small blobs in the acrylic bead pack, these blobs have minimal contribution to the overall volume of nonwetting phase present. Thus, the glass bead pack cumulative saturations (Fig. 11D) appear quite similar to those of the acrylic bead pack.
Fig. 10. Distribution of blob volume sizes for (A) the first imbibition (I1), (B) the second imbibition (I2), (C) the third imbibition (I3) of the acrylic bead pack, and (D) the first imbibition (I1) of the glass bead pack.

Fig. 11. Cumulative contribution of blobs to total fluid saturation for the (A) the first imbibition (I1), (B) the second imbibition (I2), and (C) the third imbibition (I3) of the acrylic bead pack, and (D) the first imbibition (I1) of the glass bead pack.
Individual blob volumes are plotted against individual blob surface areas (Fig. 12), for all imbibitions of both bead packs. As a reference to the pore space which they inhabit, these figures also contain the specific surface area of a sphere (solid lines) and the specific pore space surface area (dashed lines). For both bead packs, the minimum surface area to volume ratios are well-defined by pore space measurements and basic geometric assumptions. For blobs smaller than the minimum bead volume, the minimum surface area is close to that of a sphere. For the blobs larger than the minimum bead volume, the minimum surface area is close to the specific pore space surface area. This is because of the fact that the largest possible sphere that can inhabit the pore space is close to the size of the smallest beads. For the three imbibitions in the acrylic bead pack, blob populations are similar below the minimum bead volume. Blobs larger than the minimum bead volume are, in general, smaller at the end of first imbibition when compared to second and third imbibitions and therefore exhibit a larger surface area. The blobs found in the glass bead pack have slightly smaller surface areas than those in the acrylic bead pack is consistent with the slightly lower specific nonwetting phase surface areas observed in the glass bead pack (Fig. 8).

**CONCLUSIONS**

This investigation shows evidence of gravitational segregation and initial saturation conditions affecting final saturation.
tion profiles. Capillary end effects appear to be limited to within 5 mm of the outlet. Changes in flow rate of more than one order of magnitude during imbibition cycles in the acrylic bead pack resulted in nearly identical fluid distributions, confirming the stability of pore-scale displacement mechanisms in spite of the difference in flow rate (with both flow rates within capillary-dominated regime). We present evidence of hysteresis in saturation profiles at the end of imbibition cycles that started from different initial wetting phase saturations. This hysteresis is noticeable when the initial wetting phase saturation is in the range of the maximum specific meniscus interfacial area, which indicates a transition of the nonwetting phase from a connected to a disconnected state.

The specific nonwetting phase surface area is well approximated by the solid specific surface area, independent of core position, cycle of flooding, saturation history, and wettability. The specific wetting phase surface area is a monotonic function of wetting phase saturation, but is not linear as a result of the concave nature of fluid–fluid interfaces. The specific wetting phase surface area of the acrylic bead pack is overall less than that of the glass bead pack, while the nonwetting phase specific surface area of the acrylic bead pack is greater than that of the glass bead pack, indicating the acrylic bead pack may be more weakly wetting than the glass bead pack. Although both bead packs displayed the same trends for specific meniscus interfacial areas as a function of saturation, peaking between wetting phase saturations of 0.35–0.55, the glass bead pack had significantly greater specific meniscus interfacial areas, possibly explained by a stronger wettability, resulting in greater concavity of the fluid–fluid interface and spreading of the wetting phase.

The blob size distributions and surface areas of blobs were representative of phase connectivity; with increasing nonwetting phase saturation, fewer and larger blobs were found. The increase in the number of larger blobs observed as cycles of imbibitions progressed in the acrylic bead pack demonstrated the importance of saturation history to blob size distribution. When the wetting phase has an established presence in the pore space, subsequent imbibitions can more efficiently traverse the porous medium via previously established paths, resulting in fewer and larger blobs. The surface areas of individual blobs were found to correlate with the specific surface area of a sphere for blob volumes smaller than the minimum grain volume and with the specific pore space surface area for larger blob volumes. The glass bead pack blobs have generally smaller surface areas, which again can be attributed to differences in strength of wettability and thus fluid–fluid curvature.

Although this investigation was conducted using bead packs, the results can be applied to equivalent porous systems such as medium grained weakly oil-wet and water-wet sandstones. These results demonstrate how pore space geometry, wettability, and saturation history influence the distribution of immiscible fluids within the pore space; these general observations can be a powerful resource for the improvement of property prediction for multiphase fluid flow applications in porous media, such as relative permeability and capillary pressure.

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