Characterization of Gas Injection Flow Patterns Subject to Gravity and Viscous Forces

Cole J.C. Van De Ven* and Kevin G. Mumford

Gas movement in otherwise water-saturated porous media is complex and is important for a variety of applications. The interplay of gravity, capillary, and viscous forces influences the movement and resulting pattern of gas. To develop a better understanding of this competition among these forces, air injection experiments were performed in an intermediate-scale, two-dimensional flow cell at injection rates of 0.1, 10, 100, 250, and 498 mL min⁻¹. The resulting gas patterns were characterized using gas pressure measurements and optical density measurements based on digital images to classify gas flow as continuous, transitional, or discontinuous, and near-pore-scale observations of transient gas flow were made to gain insight concerning the influence of gravity, viscous, and capillary forces. These observations highlighted the importance of gravity and viscous forces, along with capillary forces, for gas flow in water-wet media. Based on these observations, a simplified dimensionless number (the ratio of the Bond and Capillary numbers) was proposed to quantify the interplay of gravity to viscous forces, and its validity for the prediction of the type of gas flow was assessed. This study provides a high spatiotemporal dataset of transient gas movement in homogeneous sand, which can be used to provide insight for multiphase flow modeling efforts and future understanding of gas movement coupled to mass transfer.

Abbreviations: OD, optical density.

The study of gas dynamics in porous media is important for a variety of modern problems and applications including energy development, carbon sequestration, greenhouse gas migration from the subsurface, and groundwater remediation (e.g., Ji et al., 1993; Clayton, 1998; Trevisan et al., 2017; Cahill et al., 2018; Forde et al., 2018; Van De Ven and Mumford, 2018). The flow of gas in the subsurface and the associated geometry of the gas phase will significantly impact mass transfer to the aqueous phase as well as the fate and transport of the gas-phase components (Clayton et al., 1996; Agaoglu et al., 2015). To understand gas flow and associated mass transfer in any of these complex systems, it is important to understand processes that occur at the pore and near-pore scale.

The displacement of one immiscible fluid by another in porous media is governed by the competition between gravity, capillary, and viscous forces (Morrow, 1979; Ewing and Berkowitz, 1998; Lovell et al., 2005). Depending on the magnitude of these forces in a system, the resulting flow can vary widely even within a single medium (Saffman and Taylor, 1958; Paterson, 1984; Wilkinson, 1984; Lenormand et al., 1988). A set of dimensionless numbers have been commonly used to characterize multiphase flow (Lenormand et al., 1988). These dimensionless numbers include the mobility ratio \( M = \mu_2/\mu_1 \), the capillary number \( Ca = \nu \gamma D_r \), and the Bond number \( Bo = \Delta \rho g r^2/\gamma \), where \( \mu \) is the dynamic viscosity, \( \nu \) is the velocity of the fluid, \( \gamma \) is the interfacial tension of the fluid pair, \( \Delta \rho \) is the density contrast between the displacing and displaced fluids, \( g \) is the acceleration due to gravity, \( r \) is a characteristic channel radius, often taken to be the average grain radius; subscript 1 refers to the displaced fluid and subscript 2 refers to the displacing fluid. It is important to note that \( Ca = 1 \) and \( Bo = 1 \) do not necessarily represent conditions under which viscous and capillary forces or gravity and capillary forces, respectively, are equal.

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(e.g., Blunt and Scher, 1995; Brooks et al., 1999). Modifications to these dimensionless numbers can be found in the literature to account for pore-size scaling (e.g., Brooks et al., 1999; Lovoll et al., 2005); however, the classical definition will be utilized here for all analyses.

Work has been done to understand immiscible flow characteristics across a range of these numbers (e.g., Lenormand et al., 1988; Frette et al., 1992, 1994; Brooks et al., 1999). For example, Lenormand et al. (1988) developed an understanding of the interaction between capillary and viscous forces, which they summarized in a flow regime diagram that spans the Ca–M space. The presence of a gravitational gradient causes flow to be either stabilized (when a less dense fluid invades a more dense fluid from above or when a more dense fluid invades a less dense fluid from below) or destabilized. A consideration of the stabilizing or destabilizing influence of gravity is important in a variety of areas including hydrocarbon development, nonaqueous-phase liquid migration, and water table fluctuation (Saffman and Taylor, 1958; Birovljev et al., 1991; Frette et al., 1992; Toussaint et al., 2012).

Under conditions of instability, the magnitude of the difference in fluid densities causes increased instability in flow patterns as the density contrast increases (Meakin et al., 1992; Frette et al., 1994; Glass and Yarrington, 1996). This influence of gravity has been used to extend the work of Lenormand et al. (1988) along a third dimension to create a Ca–M–Bo diagram, in which the area of the viscous, capillary, and stable regions changes depending on the magnitude of the Bond number (Ewing and Berkowitz, 1998). The focus of the current work is on gravity-destabilized flow in gas–water systems (Bo < 0) in the context of gas injection in otherwise water-saturated porous media, where flow would be expected to be destabilized the more negative the Bond number becomes.

The movement of gas during upward flow is influenced by both the large density contrast between gas and water, and the viscosity contrast between the fluids. Because of the numerous applications of gravity-destabilized gas flow, work to understand the underlying phenomena is a popular area of research for both energy development and air sparging for groundwater remediation. Pioneering work on air sparging by Ji et al. (1993) investigated the effect of grain size and injection rate on gas patterns. Their work found that flow could be channeled (also referred to as continuous, connected, or coherent flow), transitional, or bubble (also referred to as discontinuous, disconnected, or incoherent flow). It then became important for a variety of applications to develop a classification method for gravity-destabilized flow. Experimental work by Brooks et al. (1999) showed that a modified Bond number (Bo multiplied by the aspect ratio between pore throats and pore bodies) could be used to distinguish between continuous and discontinuous flow, which placed an emphasis on grain size as the key parameter to classify gas flow.

Later work showed that consideration of the Bond number alone was insufficient to classify gas flow and that a consideration of the gas injection rate was also important. Selker et al. (2006) found that at high injection rates, regions of both high viscous

influence (near the gas injection) and regions of reduced viscous influence (far from the gas injection) occurred. Geistlinger et al. (2006) developed a dynamic criterion termed the critical flow rate, above which gas flow transitions from discontinuous to continuous in a single channel. This condition was derived to be dependent on flow rate and grain size, based in part on their gas injection experiments in glass beads and other studies. This critical flow rate is defined, when the magnitude of the viscous force is equal to the gravitational forces, as

$$Q_{crit} = \frac{\pi \Delta \rho g r_c^4}{8 \mu g} \quad [1]$$

where $Q_{crit}$ is the critical flow rate, $\Delta \rho$ is the density difference between gas and water, $g$ is the gravitational acceleration, $\mu$ is the dynamic viscosity of the gas, and $r_c$ is the mean radius of a capillary. Stöhr and Khalili (2006) performed similar work in three-dimensional packings of 0.5- to 2-mm glass beads to investigate differences between gas flow patterns at different gas injection rates, as well as to understand the difference between the initial invasion of gas and the flow pattern resulting after gas breakthrough at the surface of the flow cell. They proposed a stability criterion equivalent to Eq. [1]. Additional expressions have been presented to estimate the height of gas clusters during discontinuous flow which consider more than the traditional Bond number (Geistlinger et al., 2006; Mumford et al., 2009a). These conceptualizations are useful for estimating the transition from continuous to discontinuous flow; however, additional work is needed to investigate gas flow in initially water-saturated sands across a wider range of low to moderate gas injection rates as well as to develop a classification based on commonly used dimensionless numbers.

One reason for developing a thorough understanding of the flow geometry during gravity-destabilized gas injection is to allow the development and application of accurate continuum-based and discrete modeling techniques. An example of a continuum model for gas flow is TOUGH2, which has been shown to model gas flow considering gravity, capillary, and viscous forces (Samani and Geistlinger, 2019). Examples of discrete models for gas flow include invasion percolation (Wilkinson, 1984; Wagner et al., 1997) and diffusion-limited aggregation (Paterson, 1984), suitable for conditions under which viscous forces are negligible or dominant, respectively. High spatiotemporal observations of gas movement can be used to evaluate the macroscopic characteristics simulated using these models (e.g., progression of gas movement).

In this study, we attempted to accurately classify gas flow patterns as continuous, transitional, or discontinuous and used dimensionless numbers as a means to predict these flow types. The specific objectives of this study were to: (i) understand the local-scale (~1-mm) movement and connectivity of gas in unconsolidated porous media during low to moderately high gas injection rates; and (ii) determine the suitability of commonly defined dimensionless numbers (Ca and Bo) to classify unstable gas flow. To achieve the objectives, this study used a series of laboratory
experiments conducted in a two-dimensional flow cell to allow visualization of gas flow patterns at high spatial and temporal resolution in combination with gas pressure measurements to investigate gas dynamics at the local scale.

Materials and Methods
Flow Cell
A quasi-two-dimensional flow cell was used to study gas injections into initially water-saturated sand using transmitted light. The front and back walls of the flow cell were 1.1-cm-thick acrylic plates welded to 1.5-cm-thick side walls. The cell had dimensions of 25 by 25 cm and an internal thickness of 1 cm (Fig. 1) (Van De Ven and Mumford, 2018). The cell lid was sealed with a neoprene gasket. The cell was fitted with a single clear well with dimensions of 25 by 1.3 by 1 cm, separated from the sand pack by a fine steel mesh, which provided an exit pathway for displaced water (shown on the right in Fig. 1). On the left side, a port was fitted with an injection needle located 8.5 cm from the bottom of the cell and halfway between the side walls. The needle tip was angled upward slightly to reduce the possibility of gas migration along the outside of the needle.

Sand Pack and Gas Injection
A total of 13 gas injections were performed using air injected into an initially water-saturated sand ($M = 2 \times 10^{-2}$): one experiment at a rate of 0.1 mL min$^{-1}$ and triplicate experiments each at rates of 10, 100, 250, or 498 mL min$^{-1}$ (Table 1). The sand was washed 20-30 Accusil (AGSCO Corporation), which has a grain size ($d_{50}$) of $0.713 \pm 0.023$ mm (Schroth et al., 1996). Deionized water was used in all experiments and was sparged with air for a minimum of 24 h prior to sand packing, such that it was in equilibrium with the atmosphere, to eliminate mass transfer of injected gas to the water. Sand was carefully emplaced using a continuous wet packing procedure to create a homogeneous pack (Mumford et al., 2009a; Hegele, 2014; Van De Ven and Mumford, 2018). During packing, the cell was vibrated to achieve a dense grain arrangement. This pack was initially free of trapped gas, created by maintaining a water level in the cell above the sand and allowing any air bubbles to be liberated as sand was poured and gently settled in the cell. The gas injection needle was connected to a syringe pump and installed in the flow cell prior to sand emplacement but after filling the cell with water to ensure that the needle was filled with gas at the hydrostatic pressure of the cell prior to beginning gas injection. After packing, the top of the cell was sealed to prevent grain rearrangement using a rigid stainless-steel lid lined with neoprene clamped to the frame of the flow cell. The discharge tube was used to set a constant hydraulic head at the height of the top of the cell.

Table 1. Summary of experiments and the measured flow pattern.

<table>
<thead>
<tr>
<th>Test</th>
<th>Injection rate</th>
<th>Porosity†</th>
<th>Duration of experiment</th>
<th>Flow type</th>
<th>Bond no. (Bo)</th>
<th>Capillary no. (Ca)</th>
<th>Bo/Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>mL min$^{-1}$</td>
<td>s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1-A</td>
<td>0.1</td>
<td>0.366</td>
<td>330</td>
<td>discontinuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$1.07 \times 10^{-6}$</td>
<td>$-1.61 \times 10^{-4}$</td>
</tr>
<tr>
<td>10-A</td>
<td>10</td>
<td>0.375</td>
<td>7.7</td>
<td>transitional</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$1.07 \times 10^{-4}$</td>
<td>$-1.61 \times 10^{-2}$</td>
</tr>
<tr>
<td>10-B</td>
<td>10</td>
<td>0.360</td>
<td>10.2</td>
<td>transitional</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$1.07 \times 10^{-4}$</td>
<td>$-1.61 \times 10^{-2}$</td>
</tr>
<tr>
<td>10-C</td>
<td>10</td>
<td>0.369</td>
<td>9.5</td>
<td>transitional</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$1.07 \times 10^{-4}$</td>
<td>$-1.61 \times 10^{-2}$</td>
</tr>
<tr>
<td>100-A</td>
<td>100</td>
<td>0.370</td>
<td>6.3</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$1.07 \times 10^{-3}$</td>
<td>$-1.61 \times 10^{-1}$</td>
</tr>
<tr>
<td>100-B</td>
<td>100</td>
<td>0.365</td>
<td>5.9</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$1.07 \times 10^{-3}$</td>
<td>$-1.61 \times 10^{-1}$</td>
</tr>
<tr>
<td>100-C</td>
<td>100</td>
<td>0.360</td>
<td>5.0</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$1.07 \times 10^{-3}$</td>
<td>$-1.61 \times 10^{-1}$</td>
</tr>
<tr>
<td>250-A</td>
<td>250</td>
<td>0.366</td>
<td>5.7</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$2.68 \times 10^{-3}$</td>
<td>$-6.45 \times 10^{0}$</td>
</tr>
<tr>
<td>250-B</td>
<td>250</td>
<td>0.379</td>
<td>6.8</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$2.68 \times 10^{-3}$</td>
<td>$-6.45 \times 10^{0}$</td>
</tr>
<tr>
<td>250-C</td>
<td>250</td>
<td>0.364</td>
<td>5.1</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$2.68 \times 10^{-3}$</td>
<td>$-6.45 \times 10^{0}$</td>
</tr>
<tr>
<td>498-A</td>
<td>498</td>
<td>0.374</td>
<td>6.2</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$5.33 \times 10^{-3}$</td>
<td>$-3.24 \times 10^{0}$</td>
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<tr>
<td>498-B</td>
<td>498</td>
<td>0.363</td>
<td>4.7</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$5.33 \times 10^{-3}$</td>
<td>$-3.24 \times 10^{0}$</td>
</tr>
<tr>
<td>498-C</td>
<td>498</td>
<td>0.374</td>
<td>4.7</td>
<td>continuous</td>
<td>$-1.73 \times 10^{-2}$</td>
<td>$5.33 \times 10^{-3}$</td>
<td>$-3.24 \times 10^{0}$</td>
</tr>
</tbody>
</table>

† The error on all porosity values was ±0.015.
Gas injection was performed through a 15.2-cm-long, 22-gauge (0.413-mm inner diameter) stainless steel needle connected to between one and six gas-tight syringes (Air-Tite, AL50), depending on the desired gas injection rate, using pressure-rated tubing. Each syringe was filled with atmospheric air and a small drop of deionized water to saturate the air with water vapor and eliminate mass transfer of water to the injected gas. The syringe pump (Cole-Parmer, 78-0232C) delivered a constant gas flow, and injection continued until gas first contacted the lid of the cell. After gas injection, the sand was removed, dried, and weighed to determine the porosity of the sand pack (Table 1).

**Gas Pressure Measurement**

The gas pressure of the injected air in the needle was measured using a pressure sensor (Honeywell ABPDJ01PGAA5 for test 0.1 mL min\(^{-1}\), Honeywell ABPDANT005PGAA5 for tests at 10, 100, and 250 mL min\(^{-1}\), and Honeywell ABPDANT015PGAA5 for tests at 498 mL min\(^{-1}\)) open to the atmosphere and recorded using a datalogger (Campbell Scientific, Model CR300) every 0.6 s. Different pressure sensors were used to allow different maximum pressures (6.9, 34, and 103 kPa, respectively) because of increased gas pressures at higher gas injection rates. This increase in pressure was the result of the small-diameter injection needle and increased viscous resistance to injection at higher flow rates. The accuracy of the recorded pressure values is ±1.5% full scale signal (therefore 0.176 cm of water for Test 0.1-A; 0.879 cm of water for Tests 10, 100, and 250; and 2.637 cm of water for Test 498), which are used here to define the uncertainty of measured gas pressures. The measurement of gas pressure was used to differentiate continuous and discontinuous gas flow. Discontinuous flow is expected to produce gas pressure fluctuation as a result of repeated fragmentation and mobilization events due to the effects of capillary pressure along a gas channel (Geistlinger et al., 2006; Mumford et al., 2009a). Although the magnitude of the gas pressure is influenced by the injection needle at high injection rates, any change in the length of the gas flow pathway in the sand due to disconnection would result in a pressure decrease.

**Optical Setup and Image Processing**

To visualize gas migration, the flow cell was backlit with an LED light bank (LEDDGO-1200s) placed 20 cm from the back face of the cell. Digital videos of the gas injection were recorded using a high-resolution camera (Canon EOS 6D fitted with Canon EF 17–35-mm lens) placed approximately 60 cm from the front face of the cell. Videos were recorded in full high definition at a resolution of 1920 by 1080 and a frame rate of 29.97 frames s\(^{-1}\), which was enabled by the use of a complementary metal-oxide semiconductor (CMOS) chip. Camera capture settings were selected through manual optimization to reduce overexposure and obtain a high contrast between local variations of high and low gas density (ISO1000, f16, and shutter speed of 1/60). The camera, flow cell, and light source were placed in an enclosure draped with black fabric to limit ambient lighting. Videos were processed using MATLAB R2017b and converted to still frame images, cropped to include only the sand-packed face of the cell (Fig. 2a), and converted to grayscale images of light intensity (Fig. 2b).

Intensity images collected during the gas injections were converted to optical density to better distinguish the gas clusters, particularly their edges, and facilitate observations of near-pore-scale gas movement (Fig. 2c). The optical density is defined as the negative logarithmic transform of the transmittance (ratio of transmitted to incident light intensity) (Kechavarzi et al., 2000):

\[
OD = -\log(\tau) = -\log \left( \frac{I_t}{I_o} \right)
\]

where OD is the optical density, \(\tau\) is the transmittance, and \(I\) is the light intensity. The subscripts \(t\) and \(o\) represent the transmitted and incident light, respectively. The OD can be used as an indicator of high and low gas occupation because gas saturation has been shown to vary log-linearly with normalized light intensity (a low OD indicating low gas saturation and high OD indicating high gas saturation) (Tidwell and Glass, 1994; Niemet and Selker, 2001; Mumford et al., 2009a). The incident intensity was measured using images of the fully saturated flow cell captured prior to gas injection. The detection limit of the OD was set to

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Fig. 2. Example of the image processing procedure from Exp. 0.1-A (gas injection at 0.1 mL min\(^{-1}\)) showing (a) raw captured image to (b) light intensity to (c) optical density (OD).
0.02 based on the variance in OD during each experiment in a region known to not contain gas. A median filter was applied to a three- by three-pixel (0.75- by 0.75-mm) area such that OD values are representative of areas no smaller than a single grain diameter. To verify that no grain rearrangement occurred, OD images were systematically assessed for increases in noise and changes in the location of darker pixels before and after gas injection. Because of the importance of a rigid sand packing, further investigation of grain rearrangement in future experiments could be performed using pore-scale techniques (e.g., micro computed tomography); however, that was beyond the scope of this study. The emphasis of this study was on the connectivity of injected gas, patterns formed during gas injection, and the relationships between connectivity and flow patterns to viscous, capillary, and gravity forces, which was based on a combination of OD and gas pressure measurements. The images collected could also be used to calculate gas saturations (Tidwell and Glass, 1994; Nienet and Selker, 2001), but local gas saturations were not the focus of this study.

Results and Discussion

Measured Gas Pressure and Corresponding Flow Pattern

Based on OD to delineate the resulting gas patterns (Fig. 2c and 3), gas injection at 0.1 (Fig. 2c) and 10 mL min$^{-1}$ (Fig. 3a–3c) each produced a single gas channel, which grew vertically until the channel made contact with the lid of the cell. Some lateral movement of the gas channel was seen at these injection rates. The OD map for the 0.1 mL min$^{-1}$ injection shows signs of discontinuity along the height of the gas channel, with regions below the OD detection limit of 0.02 at multiple locations along the gas channel height. Although the OD along the gas channel in the 10 mL min$^{-1}$ injections is also non-monotonic, there are few distinct apparent discontinuities. Unlike in experiments at 0.1 and 10 mL min$^{-1}$, gas injections at 100, 250, and 498 mL min$^{-1}$ showed complex patterns composed of multiple continuous channels (Fig. 3d–3l). At higher injection rates, the injected gas pattern widened as the gas migrated vertically before contact with the lid, and the number of channels increased with increased injection rate. The gas pattern observed was not parabolic in shape as seen by Ji et al. (1993), Selker et al. (2006), and Geistlinger et al. (2006). This is the result of two differences in the experimental setup used in this study. First, gas injection in this study was stopped when the gas reached the top of the cell, not allowing a steady-state gas pattern to form following gas breakthrough (Stöhr and Khalili, 2006). Second, injections in the cited studies used diffusers to inject gas into the sand pack, whereas this study used a needle. The needle allowed a single conduit of gas to form at the point of injection, whereas a diffuser would create multiple initial conduits. Optical density suggests signs of local (i.e., pore-scale) heterogeneity, with varying OD (0–0.2) throughout the gas channels (Fig. 3). Typically, each gas channel was composed of a high-density inner core (OD 0.1–0.2) surrounded by a lower density outer shell (OD 0.02–0.1). In some gas channels, this outer shell may be the result of light refraction along the edge of the channel; however, the outer shell is not present in every channel, suggesting that this lower density region often represents the presence of gas. The optical density of the inner core is consistent with other studies of gravity destabilized gas flow (Mumford et al., 2009a, 2009b).

Representative gas pressure signals of the five injection rates are shown in Fig. 4a, expressed as a gas pressure increase. The measured gas pressure was corrected for the hydrostatic pressure, therefore the gas pressure presented is representative of the entry pressure of the sand and the viscous resistance to gas flow of the growing gas channel(s) through the sand. For slow gas injection rates, the gas pressure is influenced only by the capillary pressure and the water pressure. The gas pressure is plotted with respect to normalized time, where a value of zero is the beginning of gas injection and a value of 1 is the time at which the gas first reached the top of the cell (Table 1).

The gas pressure increased with increased gas injection rate due to higher viscous resistance through the injection needle as well as through the sand. The pressure signals for 0.1 and 10 mL min$^{-1}$ (Fig. 4b) differed from the 100, 250, and 498 mL min$^{-1}$ experiments (Fig. 4a). The gas pressures for 0.1 and 10 mL min$^{-1}$ were non-monotonic, whereas for the 100, 250, and 498 mL min$^{-1}$ experiments, the gas pressure increased with time. This increase was the result of an increase in the length of the gas channel between the injection point and the cell lid, with viscous resistance occurring throughout that length. The lack of pressure fluctuation at the higher gas injection rates suggests that no fragmentation or mobilization events occurred, indicative of continuous gas flow through at least one gas channel that remained connected to the injection needle throughout the height of the injection pattern. The gas pressure measurements at 100, 250, and 498 mL min$^{-1}$ showed a change in slope in the early time of injection (seen from 0 to 0.18 in Fig. 4a), which corresponds to the initial entry of gas observed in the images. It should be noted that the pressure signal for 100 mL min$^{-1}$ exhibited a decreasing positive slope and, if gas had been injected in a larger domain, the gas pressure may have plateaued.

The pressure signal for the 0.1 mL min$^{-1}$ experiment was consistent with pressure measurements made at low injection rates (0.001 and 0.01 mL min$^{-1}$) by Mumford et al. (2009a). The non-monotonicity of gas pressure in the 0.1 mL min$^{-1}$ experiment is attributed to: (i) initial pressurization for entry into the sand (near linear increase in pressure from 0–0.68 normalized time), (ii) drainage during vertical gas channel growth (decrease in pressure from 0.7–0.75 normalized time), and (iii) pressure fluctuation due to gas channel fragmentation (from 0.75–1 normalized time). Treating the peak gas pressure measured in the 0.1 mL min$^{-1}$ experiment as the entry pressure for the sand around the needle, that entry pressure of 9.51 cm is in good agreement with the reported entry pressure values for this sand of 8.66 cm (Schroth et al., 1996) and 10.1 cm (Hegele, 2014). The observed pressure fluctuation indicates fragmentation and mobilization of the injected
gas, characteristic of discontinuous gas flow and consistent with observations of OD, suggesting disconnection along the height of the channel.

The pressure signal for the 10 mL min⁻¹ experiment was unique from those produced by the other injection rates, with characteristics of both continuous gas flow (increasing pressure with no distinct drainage period) and discontinuous gas flow (pressure fluctuation). The uncertainty (dotted lines in Fig. 4b) was wider for the 10 mL min⁻¹ injections than the 0.1 mL min⁻¹ injection due to the use of a pressure sensor with a higher range, but
the pressure fluctuations observed in all replicates suggest periods of discontinuous flow. This is consistent with the OD maps that show non-monotonicity and some indications of discontinuity in the gas channel (Fig. 3a–3c). The gas pressure and OD suggest that 10 mL min\(^{-1}\) injection in the sand resulted in a transitional flow pattern, with characteristics of both continuous and discontinuous flow. The flow rate of 10 mL min\(^{-1}\) is an example of why it is important that investigations looking at gravity-dominated gas injection collect both visual and pressure data to accurately characterize the flow type under varying conditions, as a transitional regime can display signs of both continuous and discontinuous flow.

Using Eq. [1], Geistlinger et al. (2006) calculated the critical flow rate for gas injection into water-saturated 0.5- and 1.0-mm glass beads to range from 0.1 to 0.6 and 4.7 to 22 mL min\(^{-1}\), respectively. This calculation depends greatly on the chosen \(r_c\) value because of the \(r_c^4\) dependence of Eq. [1]. Because the measured porosities of the sand used in this study are in the same range as the 1-mm glass beads of Geistlinger et al. (2006), \(r_c\) can be calculated similarly. Therefore, the \(r_c\) for the sand used was calculated to be 0.173 mm, giving a critical flow rate of 11.2 mL min\(^{-1}\). In this study, gas injections were found to be transitional at 10 mL min\(^{-1}\), similar to that predicted by Eq. [1].

**Observed Roles of Gravity, Capillary, and Viscous Forces**

Observations of the initial invasion of gas into the sand, at high spatial and temporal resolution, can be used to understand the role of gravity, capillary, and viscous forces and how the competition of these forces can influence the invasion pattern (Fig. 5).

The left-most images in Fig. 5 (a-i, b-i, c-i, and d-i) show the initial injection of 0.04 cm\(^3\) of air at 10, 100, 250, and 498 mL min\(^{-1}\). Across all injection rates, this early-time small volume of gas moved radially out from the needle tip. The pattern for some injections was asymmetrical due to pore-scale heterogeneity in the sand pack and viscous destabilization. Although the pattern at this early time is similar for all flow rates, the invaded area increases with increased flow rate, with initial diameters of the invaded gas area equal to 0.64, 0.92, 1.03, and 1.62 cm for the respective injection rates. Correspondingly, the OD in this area decreased with increased flow rate, as a greater number of pores were occupied by the same total gas volume. Differences in the initial injection patterns at the increased injection rates can also be seen in the center images of Fig. 5 (a-ii, b-ii, c-ii, and d-ii) after the injection of 0.21 cm\(^3\) of air. For the 10 and 100 mL min\(^{-1}\) injection rates, gas progression is seen to be mostly vertical, creating a single gas channel, whereas for the 250 and 498 mL min\(^{-1}\) injection rates, gas migration continues radially from the injection source, albeit in a fingered manner. This suggests that viscous forces have little role in early invasion at 10 and 100 mL min\(^{-1}\) and that gravity dominates, but viscous forces are significant for 250 and 498 mL min\(^{-1}\). At a rate of 498 mL min\(^{-1}\) (Fig. 5d-ii) there is a strong influence of viscous forces, with gas progressing radially outward in both the upward and lateral directions in the form of sharp fingers, which was seen for all replicate experiments at 498 mL min\(^{-1}\). Although this pattern shows that viscous forces dominate the initial injection at this flow rate, the less-extensive downward invasion indicates that buoyancy forces are still influencing the gas flow. The right-most images in Fig. 5 (a-iii, b-iii, c-iii, and d-iii) after the injection of 0.54 cm\(^3\) of air shows the invading gas progressing vertically away from the initial injection source pattern (seen clearly in Fig. 5d-iii, where the lateral fingers become vertical fingers).

Based on the OD maps (Fig. 5), viscous forces influence the transient migration of gas across a minimal distance from the injection source (<4.3 cm away for the highest flow rate), even at the higher gas injection rates used in this study. An approximately elliptical initial invasion pattern has been observed and described in the literature to be the result of flow in homogeneous media being driven primarily by the imposed pressure gradient from injection, therefore creating a dense, radially symmetric gas pattern (termed the *near source region*) (Selker et al., 2006). However, this was not observed in this study beyond the area immediately surrounding the injection point. The change in gas flow to a sharp, fingered pattern provides insight into the expectation of migration patterns at the low mobility ratio and negative Bond number of gas–water systems. Much of the work on the injection of non-wetting fluids at high injection rates is based on fluid pairs with minimal density difference, but those previous results may lead to a misrepresentation of the conceptual...
model for higher flow rate gas injection. For example, Frette et al. (1994) described higher flow rate injections to create “dense, ball-like displacement structures;” however, the density of their invading and defending fluids were the same and had a mobility ratio of $7 \times 10^{-2}$. The findings of this study highlight that the contrast in density between gas and water creates a strong, gravity-dominated system that can negate the effects of viscosity across short distances and that the viscous region is made up of viscous fingering. The findings of this study also support the three-dimensional flow regime diagram proposed by Ewing and Berkowitz (1998), in which at relatively low $Ca$ and $M$, flow becomes increasingly more unstable as $Bo$ becomes more negative.
Dimensionless Number Analysis and Gas Flow Pattern

The near-pore-scale observations of gas movement during gas injection showed that gravity and viscous forces strongly influenced the resulting gas pattern during the initial injection into the sand. Because of this strong influence of gravity and viscous forces, it may be convenient and edifying to describe these systems using a dimensionless number that compares these forces. We propose combining the Bond and Capillary numbers to compare the gravity and viscous forces as

\[
\frac{Bo}{Ca} = \frac{\Delta \rho g r^2}{\gamma} \left( \frac{\rho_d \mu_d}{\gamma} \right)^{-1} = \frac{\Delta \rho g r^2}{\rho_d \mu_d}
\]  

[3]

The \(|Bo/Ca|\), which compares the gravity to viscous forces (Eq. [3]), was computed for the gas injection rates and sand used in this study (Table 1), and the values were all >1. To assess the utility of \(|Bo/Ca|\) to distinguish discontinuous, transitional, and continuous flow patterns, \(|Bo/Ca|\) values were plotted against the observed flow pattern, determined by the OD and gas pressure measurements (Fig. 6). Figure 6 also presents the results of previous studies that either reported Bo and Ca values or presented sufficient information that allowed their calculation. Gas injection studies were selected that explicitly stated the flow pattern observed either visually or using pressure data for verification (Ji et al., 1993; Brooks et al., 1999; Geistlinger et al., 2006; Mumford et al., 2009a; Hu et al., 2010, 2011; Mao et al., 2017). If not reported, \(\Delta \rho\) was assumed to be 997 kg m\(^{-3}\) and \(\mu\), to be 0.019 mN m\(^{-2}\) s\(^{-1}\), and the characteristic radius was taken to be the radius of the average grain size reported in each study. The velocity of the invading gas was calculated from the reported injection rates, assuming that the initial gas invasion was through a single pore, and therefore computed as the volumetric flow rate divided by the cross-sectional area of an average grain (representative of a pore body).

Figure 6 shows that the majority of discontinuous gas flow has been reported for \(|Bo/Ca| > 10^2\) and most continuous gas flow for \(|Bo/Ca| < 10^2\), with transitional flow occurring for \(10^1 < |Bo/Ca| < 8 \times 10^3\). This suggests that the ratio of gravity to viscous forces can be used to classify unstable gas flow in water-saturated sand but that equal Bond and Capillary numbers (\(|Bo/Ca| = 1\)) is not an explicit definition of the transition from discontinuous to continuous gas flow. It is noted that the characteristic radius has been defined in a variety of ways in the literature and that a characteristic radius less than the average grain radius shifts the magnitude of the \(|Bo/Ca|\) at which transition occurs closer to unity. An explanation for the overlap in data presented in Fig. 6 is that when flow approaches the transition zone, it is very difficult to differentiate continuous, transitional, and discontinuous gas flow without measuring gas pressure, which was not done in many previous studies.

Summary and Conclusions

Gravity-distabilized gas injection in saturated porous media was investigated to better understand transient flow patterns at varying gas injection rates. Air was injected into 20-30 Accusil sand at 0.1, 10, 100, 250, and 498 mL min\(^{-1}\). Light transmission images and gas pressure measurements were analyzed to provide insight into expected gas flow patterns that can be applied to a number of applications where unstable gas migration occurs. Data during gas injections was collected at spatial (1 mm) and temporal (29.97 frames s\(^{-1}\)) resolutions higher than previously presented in the literature to create a better understanding of transient injection conditions.

For the five injection rates studied, discontinuous gas flow clearly occurred during only the 0.1 mL min\(^{-1}\) experiment, based on fluctuations in the measured gas pressure increase. At an injection rate of 10 mL min\(^{-1}\), pressure measurements and observed gas patterns showed characteristics of both discontinuous and continuous flow, suggesting transitional flow behavior. As previously seen in the literature, at gas flow rates \(\geq 100\) mL min\(^{-1}\), gas flow was continuous and consisted of multiple gas channels. For gas injections at all injection rates in this sand, the gravity drive of the highly buoyant gas quickly dominated over viscous forces, creating a viscous-dominated zone that did not extend greater than 4.3 cm.
from the injection point. It is important to note that increased gas flow rates and decreased grain sizes are likely to increase the extent of this zone, but these results highlight that when conceptualizing the architecture of high flow rate gas injections, caution must be taken to consider the high-density difference between gas and water such that the extent of the viscous-dominated zone is not overestimated.

The combination of data collected in this study and available data in the literature shows that the ratio of Bond number to Capillary number can be used to classify the flow type during upward gas flow. Furthermore, that equal Bond and Capillary numbers (|Bo/Ca| = 1) is not required for the onset of continuous gas flow but that continuous gas flow can occur for values up to two orders of magnitude (|Bo/Ca| = 10^2). One must, however, exercise caution when using dimensionless numbers because they provide only an indication of the relative magnitude of the forces being considered.

The results of this study provide a detailed dataset to improve the understanding of the transient behavior of gas under gravity-destabilized conditions and to support future modeling efforts of gravity-destabilized gas flow. The behavior that underlies the conceptual models for approaches based on invasion percolation and diffusion-limited aggregation was not strictly observed in this study, and reconsideration or modification of those modeling approaches may be required to accurately represent the range of observed behavior. It is also expected that a better understanding of near-pore-scale gas movement and the resulting gas patterns under a variety of conditions will help to guide efforts to simulate gas–water mass transfer in porous media, particularly by linking flow conditions to source architecture, effective interfacial area, and relative permeability. Further research will relate local observations at the near-pore scale to global observations across length scales of interest for modeling and field research.

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References


