Effect of buoyancy on fingering growth activity in immiscible two-phase flow displacements

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Abstract
Immiscible displacement processes have been investigated for decades to understand their applications, such as geosequestration of CO₂ and enhanced oil recovery, in detail. In this study, the effect of buoyancy on fingering growth activity during a drainage process was investigated under the competitive influence of buoyancy, capillary, and viscous forces. A packed bed of glass microbeads was used as a porous medium for immiscible fluid pairing of silicon oil and water as a non-wetting phase (NWP) and wetting phase (WP), respectively. The time lapse 3D structure of finger development was visualized for a Bond number Bo range of 3.84 × 10⁻⁴ to 3.45 × 10⁻³ and a capillary number Ca range of 4.30 × 10⁻⁹ to 4.30 × 10⁻⁷ using an X-ray CT scanner. Three instability regimes—capillary fingering, transition, and gravity fingering enhanced by buoyancy forces—were successfully observed. The crossover from capillary fingering to gravity fingering was observed at Bo values between 1.53 × 10⁻³ and 3.45 × 10⁻³. The gravity fingering structure was observed at Bo = 3.45 × 10⁻³ and Ca = 4.30 × 10⁻⁷. Under gravity fingering conditions, the pressure of the NWP to displace the WP is highest at the tip of the most advanced finger because the buoyancy force is relatively higher than the capillary force. Consequently, massive new invasions were induced near the tip of the most advanced finger. As a result, the fingers vertically extended with a streak-like structure, and the diameter of the fingers was as small as single-pore sizes. The NWP saturation at breakthrough was low and fluctuated in the z direction. The WP was merely trapped as an isolated cluster. Under capillary fingering conditions (Bo < 1.53 × 10⁻³), the fingers not only grew near the tip of the most advanced finger but also grew far below the tip. Some fingers extended to link pores with a small diameter of approximately single-pore size and developed in a horizontal direction, i.e., in the negative z direction as well as in the z direction. The size of trapped WP clusters was distributed from single-pore size to large size, connecting several pores. A skewed distribution of saturation was shown at the breakthrough for low Ca because of competition between capillary fingering and gravity fingering. At high Ca, the pressure gradient established along the z direction as a result of viscous shear force resulted in a gradual decrease in the saturation profile in the z direction.

Keywords : Buoyancy force, Capillary force, Immiscible displacement, Drainage, Active site

1. Introduction

High energy demand for fossil fuels has been foreseen to continue in this century, along with the emission of greenhouse gases produced from combustion reactions. One of the problematic exhaust gases, CO₂, has been a major contributor to climate change (Cox et al., 2000). Switching fossil fuels to renewable energy is a promising alternative to reduce CO₂ emissions. However, developing a renewable energy technology that is equally efficient as fossil fuels is a lengthy process. Currently, a slight increase in the concentration of CO₂ in the atmosphere will cause significant problems for living things. This phenomenon consequently urges us to find an alternative until an acceptable level of CO₂ concentration is established. As a short-term solution, carbon capture and sequestration (CCS) is seen as the best option to date for significant CO₂ emission reduction (Leung et al., 2014; Lackner, 2003).

CCS is commonly divided into three phases: the capture of CO₂ emissions, transportation of the emission source to
a storage site, and sequestration to geological formations such as aquifers and depleted oil and gas fields. In the sequestration process, a deep saline aquifer is considered to be suitable to store CO₂ because of its huge capacity, long duration of storage, economic efficiency, and less environmental toxicity (Ise et al., 2007; Bachu, 2000; Cinar et al., 2009).

Injection of CO₂ into deep saline aquifers involves an immiscible two-phase displacement process of brine water filling the porous rocks by supercritical CO₂. The complexities of displacement flow have attracted the interest of researchers since decades. The process has been studied through experimental and numerical approaches to attain a better understanding of displacement flow; especially, the factors influencing the displacement efficiency of injected CO₂, i.e., CO₂ saturation after injection, have been studied (Lenormand et al., 1988; Saffman and Taylor, 1958; Zhang et al., 2011; Islam et al., 2013; Cindy et al., 2015; Cottin et al., 2010; Tsuji et al., 2016; Wang et al., 2013; Bandara et al., 2011; Suekane and Nguyen, 2013; Setiawan et al., 2014; Suekane et al., 2015). After the injection of CO₂ stops, CO₂ migrates in the reservoirs under buoyancy forces. Some fraction of CO₂ is trapped by capillary force in the porous rock of the reservoirs. The amount of CO₂ trapped by capillary force, i.e., the residual gas saturation, depends on CO₂ saturation after injection (Suekane and Okada, 2013).

Instability patterns during the displacement depend on the properties of the fluid pair, the characteristics of the porous medium, and the injection rate (Lenormand and Zarcone, 1985; Suekane et al., 2015). At a slow injection rate, capillary force dominates the viscous force and controls the instability patterns (Lenormand, 1989), which can be impeccably described by an invasion percolation model (Wilkinson and Willemsen, 1983). When the non-wetting phase (NWP) is injected into a porous medium filled with the wetting phase (WP) at an infinitesimally low injection speed, the NWP selectively invades through the largest throat among all adjoining throats filled with the WP. This instability mode is often referred to as capillary fingering. In contrast, viscous fingering occurs when a less viscous fluid displaces a more viscous one at high displacement speed (Lovoll et al., 2005).

Lenormand et al. (1988) proposed a famous phase diagram of displacement stability as a function of the capillary number $Ca$ and the viscosity ratio $M$. The difference between fluid densities, however, influences the instability patterns. Since real porous medium systems are not just flat and horizontal, the gravity effect governed by the density difference becomes important (Méheust et al., 2002). Buoyancy stabilizes or destabilizes fluid motion depending on the fluid properties, injection direction, and competition between capillary and viscous forces (Wilkinson, 1986, Suekane et al., 2015). Wilkinson (1984) simulated an invasion percolation model of drainage in the presence of the gravity effect. Frette et al. (1991) compared experimental and computer simulations results of slow upward drainage affected by buoyancy. Another comparison between experimental and numerical results for slow drainage in a two-dimensional porous medium with the effect of buoyancy was performed by Birovljev et al. (1991). They also demonstrated that the front width scales with a dimensionless Bond number ($Bo$) as $\sigma \sim Bo^{-0.57}$, which is in agreement with the invasion percolation theory. Auradou et al. (1999) also performed drainage experiments with varying capillary and buoyancy forces in a centrifuge and observed the transition structures from invasion percolation to a structure comprising compact blobs linked together by streak-like structures. Méheust et al. (2002) investigated the competition among viscous, capillary, and buoyancy forces in a two-dimensional synthetic porous medium. They proposed that the interface scales with the generalized Bond number, defined by the difference between $Ca$ and $Bo$. The effect of buoyancy on the growth of fingering structures was investigated by Lovoll et al. (2004) in two-dimensional porous media. In our previous study (Suekane et al. 2015), the empirical equations for NWP saturation as a function of $Ca$, $M$, and $Bo$ were proposed for upward and downward injection of an NWP to a packed bed of glass beads.

Although many authors have investigated the effect of buoyancy on the development of fingers, to the best of our knowledge, the present study is the first attempt to visualize the three-dimensional (3D) evolution of fingering structures over time at the pore scale. In the present study, drainage processes where an NWP (silicon oil) displaces a WP (water) were visualized by an X-ray CT scanner. The aim of the present work is to address the effect of buoyancy on the growth of 3D fingering structures in an immiscible drainage process under the competitive influence of buoyancy, capillary, and viscous forces. Based on time-lapse 3D images at the pore scale, the transition from capillary to gravity fingering enhanced by buoyancy force was observed.

2. Notations

\begin{align*}
\alpha & \quad \text{Average pore diameter of a porous medium [μm]} \\
\end{align*}
\[ \begin{align*}
Bo & \quad \text{Bond number [-]} \\
Ca & \quad \text{Capillary number [-]} \\
d & \quad \text{Diameter [mm]} \\
g & \quad \text{Gravitational acceleration [m/s}^2]\text{]} \\
k & \quad \text{Permeability [m}^2\text{]} \\
M & \quad \text{Viscosity ratio between NWP and WP, } \mu_{\text{NWP}}/\mu_{\text{WP}} [-] \\
U_{\text{NWP}} & \quad \text{Darcy velocity of non-wetting phase [m/s]} \\
z' & \quad \text{Coordinate taken in opposite direction to } z \text{ from } z_{\text{tip}}, z' = z_{\text{tip}} - z \text{ [mm]} \\
\Delta \rho & \quad \text{Density difference between NWP and WP [kg/m}^3\text{]} \\
\gamma & \quad \text{Interfacial tension [mN/m]} \\
\mu_{\text{NWP}} & \quad \text{Non-wetting phase viscosity [μPa·s]} \\
\mu_{\text{WP}} & \quad \text{Wetting phase viscosity [μPa·s]} \\
\theta & \quad \text{Contact angle [°]}
\end{align*} \]

3. Experimental Methods

3.1 Experimental apparatus

Water-wet glass microbeads were packed in an acrylic resin tube with a diameter of 10 mm and a height of approximately 35 ± 0.5 mm (Fig. 1). Well-sorted glass microbeads with average diameters of 200 μm (As One, BZ-02, 177–250 μm), 400 μm (As One, BZ-04, 350–500 μm), and 600 μm (As One, BZ-06, 500–710 μm) were used. The glass microbeads were rinsed sequentially using toluene, ethanol, and purified water before the experiments so that the surface was water wet, as well as to ensure the absence of contaminants. The glass microbeads were placed in the middle of the acrylic resin tube, whereas the small glass microbeads (100 μm; As One, BZ-01, 105–125 μm) were packed on the inner wall surface of the tube in an approximately 0.5 ± 0.1-mm thick layer to avoid penetration of injected fluid through the permeable layer formed on the wall surface by sorting. A water-wet glass filter with a thickness of approximately 1 ± 0.5 mm (Fig. 1) was placed at the inlet surface to allow the uniform permeation of the injected fluid.

The porous medium was scanned to measure the porosity \( \phi \) and its average pore diameter \( a \) using a micro X-ray CT apparatus (Comscientechno Co, Scan Xmate-RB 090 SS). Based on the scanning images, the porosity was estimated to be a constant, \( \phi = 0.38 \), for each size of glass microbeads. The average pore diameters were estimated to be 47.4, 94.8, and 142.2 μm for glass microbeads with diameters of 200, 400, and 600 μm, respectively, by linear line equation calculated from Al-Raoush and Willson (2005) result. In addition, from a preliminary water flooding test, the
permeability of the porous medium was \( k = (4.03 \pm 0.039) \times 10^{-11} \text{ m}^2, (1.36 \pm 0.054) \times 10^{-10} \text{ m}^2, \) and \( (5.72 \pm 0.067) \times 10^{-10} \text{ m}^2 \) for glass microbeads with diameters of 200, 400, and 600 \( \mu \text{m} \), respectively.

3.2 Experimental procedure

First, the porous medium was saturated with the WP by employing a vacuum chamber. The porous medium was submerged in the WP, and a vacuum was drawn for several hours to remove as much gas as possible from inside the porous medium. Next, by opening a relief valve in the chamber, a sudden increase of pressure forced the WP to saturate the porous medium. Before the injection of the NWP, we carefully checked the porous medium to ensure that the inlet and outlet nozzles were not clogged with small glass microbeads, which can induce an abnormal pressure gradient during injection. The porous medium was placed in the X-ray CT scanner. Then, the NWP was injected upward at a constant speed using a syringe pump (KD Scientific, IC3100). The injection was stopped when the injected fluid reached the top of the porous medium, referred to as breakthrough, at a height of approximately 35 ± 0.5 mm.

We used silicon oil and water as the NWP and WP, respectively (Table 1). All experiments were carried out at room temperature and pressure condition, 298 K, 0.1 MPa. This room condition was controlled by air conditioner which has an error of ±2 K. Pendant drop and sessile drop method were used to measure interfacial tension and contact angle, respectively, where water was dropped into silicon oil. The dropped fluid was sunk gravitationally since its density is higher. The logarithmic of viscosity ratio, \( \log M \), shows negative value as it means that less viscous displaces more viscous fluid in our experiment. Water was doped with sodium iodide (10 wt%) to enhance the contrast in CT images to distinguish among the NWP, WP, and glass microbeads.

The control variables were the injection speed and the diameter of glass microbeads. Two dimensionless numbers, the capillary number \( (Ca) \) and Bond number \( (Bo) \), are defined as the ratio of viscous shear force to interfacial tension and the ratio of buoyancy to interfacial tension, respectively. The capillary number and the Bond number are defined as

\[
Ca = \frac{\mu_{NWP} U_{NWP}}{\gamma},
\]

and

\[
Bo = \frac{\Delta \rho g a^2}{\gamma}.
\]
respectively. We intended to conduct experiments at Bond numbers which cover those of real condition of CCS system. The properties of Sc.CO$_2$–water system for typical aquifers condition of 340 K and 10 MPa, which correspond to the depth of about 1,000 m, are listed in Table 1. The Bond number is $8.20 \times 10^{-4}$ for Sc.CO$_2$–water fluid pair for the average pore diameter of 47.4 μm. In this study, Bond number is $3.83 \times 10^{-4}$ for silicon oil–water fluid pair with the same average pore diameter.

Experimental conditions are summarized in Table 2. We injected the NWP at relatively low injection rates in the range of 50–5,000 μL/h, corresponding to $Ca = 4.30 \times 10^{-9}$ and $4.30 \times 10^{-8}$. This slow injection enabled us to obtain images several times to visualize the evolution of 3D fingering over time. In the absence of buoyancy, the crossover from capillary fingering to viscous fingering occurs at a capillary number of $1.0 \times 10^{-6}$ to $1.0 \times 10^{-4}$, depending on the viscosity ratio (Lenormand et al., 1988). In the present study the capillary number was far below this threshold, so capillary fingering may dominate over viscous fingering.

### 3.3 Image processing

Tomographic images of $992 \times 992 \times 992$ pixels at a resolution of 16.262 μm/pixel were acquired using the micro X-ray CT scanner. We defined the region of interest (ROI), which is covered by the image volume, as a cylindrical domain with a height of 15 mm from the port inlet ($z = 0$ mm) to $z = 15$ mm with a diameter of 9 mm. The layer of fine particles placed on the inner wall of the packed bed was excluded from the ROI. We used pore volume (PV) as a measure of the volume of injected fluid, which was defined by the volume of pores in the ROI. Since the CT scan takes 78 s to capture one image, injection was stopped every 0.01 PV to suppress the movement of fluid during imaging. The obtained images were then reconstructed using reconstruction software (Comscantechno, Cone CT). To eliminate drift in the gray-value intensity of images for each experiment and scan, the brightness of each scanned CT image was adjusted such that the gray-value intensity of the acrylic tube and surrounding air remained constant. All scans were performed using the same intensity of the X-ray source of 90 kV and 90 μA. Next, a threshold value for every slice of images was adjusted by employing image processing software, ImageJ. The noise of every slice then was removed using the “remove outliners” command in ImageJ.

| $Ca$     | $Bo$   |
|----------|--------|
| $4.30 \times 10^{-9}$ | $3.83 \times 10^{-4}$, $1.53 \times 10^{-3}$, $3.45 \times 10^{-3}$ |
| $4.30 \times 10^{-8}$ | $3.83 \times 10^{-4}$, $1.53 \times 10^{-3}$, $3.45 \times 10^{-3}$ |
| $4.30 \times 10^{-7}$ | $3.83 \times 10^{-4}$, $1.53 \times 10^{-3}$, $3.45 \times 10^{-3}$ |

### 4. Results and Discussion
#### 4.1 Growth of the finger structure.

Growth of the fingers of the injected NWP is shown for various conditions in Fig. 2, where the active site is denoted in blue. The active site, defined as the newly developed site of the finger, was estimated by subtracting two succeeding image volumes. That is, in the leftmost finger of Fig. 2a, the NWP shown in gray developed at the first injection of 0.01 PV, and the NWP shown in blue developed during the succeeding injection between 0.01 PV and 0.02 PV. At the highest Bond number, $Bo = 3.45 \times 10^{-3}$ (Fig. 2a), the active site was concentrated around the tip of the most advanced finger. The pressure causing the NWP to displace the WP should be high at the tip of the most advanced finger because the buoyancy force is high compared with the capillary force. Consequently, massive new invasions were induced near the tip of the most advanced finger, where the probability that the pressure of the NWP is higher.
than the capillary entrance pressure to displace the WP is high. For the injections of 0.06–0.09 PV, there was almost no active site because the active site was outside of the ROI \((z > 15 \text{ mm})\). We refer to the fingering enhanced by the buoyancy force as *gravity fingering*, characterized by a narrow streak-like pattern. The active sites far below the tip of the finger were small with sizes of a few pores, as shown for the injections of 0.02–0.05 PV.

![Diagram of fingering](image)

**Fig. 2** Growth of finger structure of injected NWP at \(Ca = 4.30 \times 10^{-7}\), (a) \(Bo = 3.45 \times 10^{-3}\), (b) \(Bo = 1.53 \times 10^{-3}\), and (c) \(Bo = 3.84 \times 10^{-4}\) in the ROI (height = 15 mm, \(d = 9 \text{ mm}\)). The injected fluid of the first image is in gray, and the growth structure obtained by subtracting the first image from the succeeding image is in blue. The coordinate system \(z\) vertically aligns upward in the mean flow direction from the inlet of the packed bed, and the coordinate \(z'\) is taken to be in the opposite direction to \(z\) from the tip of the most advanced finger. Red arrows denote the typical structure of capillary fingering.

At lower \(Bo\), fingers grew not only near the tip of the most advanced finger but also far below the tip, as shown in
Figs. 2b and 2c (quantitative estimation is shown later in Fig. 6). At $Bo = 1.53 \times 10^{-3}$ (Fig. 2b), some fingers, which extended to link pores, had diameters of approximately single-pore size. The fingers developed in the horizontal direction and the negative $z$ direction, denoted by red arrows, as well as in the $z$ direction, representing capillary fingering. At low injection speed and negligible influence of buoyancy, i.e., at low $Ca$ and low $Bo$, the capillary force solely governs the drainage process. The pressures in both the NWP and in the WP are uniform and constant. The NWP invades the pore with the lowest capillary entrance pressure, i.e., the largest throat diameter among the pores filled with the WP adjacent to the NWP. The invasion percolation theory models this process (Wilkinson and Willemsen, 1983). At $Bo = 3.84 \times 10^{-4}$ (Fig. 2c), the image subtraction between two images was performed every 0.03 PV because the breakthrough occurred more slowly. The injected NWP fluid extends in the $z$ direction because of the large number of non-invaded pores, as well as in the horizontal direction until the depletion of sufficient space to invade. Consequently, a large fraction of active sites was located near the tip of the most advanced finger, but some active sites were located far below the tip. While the NWP saturation in the horizontal cross section is low, the number of active sites tends to diminish as the fingers fill the cross section.

As mentioned above, capillary fingering can be modeled with the invasion percolation theory (Wilkinson and Willemsen, 1983). Capillary fingering is known to show a fractal nature, where no characteristic length scale exists. As a result, the size of the trapped phase is distributed along the scaling law. Figure 3 shows the distribution of the isolated clusters of the WP. For low $Bo$ (Fig. 3a), a huge number (2,340) of trapped clusters exist in the ROI because the invasion was dominated by capillary fingering. The size of trapped clusters is distributed from single-pore size to large size, connecting several pores. For higher $Bo$ (Figs. 3b and c), the WP was merely trapped as clusters because the NWP invaded the WP with a streak-like structure without disconnecting the WP. Most of the trapped WP has the size of a single pore, and 266 and 80 WP clusters were trapped in Figs. 3b and 3c, respectively.

4.2 Effect of $Bo$ and $Ca$ on the saturation of NWP.

The distribution of the NWP saturation, which is defined as the ratio of NWP volume to PV, along the height of the
porous medium from the port inlet (z = 0 mm) to a height of 15 mm is shown in Fig. 4 for all experiments. The NWP saturation is averaged over the horizontal cross-section in the ROI.

At low Bo (Figs. 4g–4i), where capillary fingering dominated the invasion process, the fingers developed in the z direction and the saturation increased uniformly for all z locations up to 0.25–0.35. For low Ca, breakthrough occurred before increase of the saturation around z = 15 mm. For high Ca, higher pressure in the NWP results in a uniform saturation profile at the breakthrough (Fig. 4i). At a Bo of $1.53 \times 10^{-3}$ (Figs. 4d–4f), skewed distribution of the saturation is shown at the breakthrough for low Ca (Figs. 4d and 4e) because of competition between capillary fingering and gravitational fingering. At high Ca (Fig. 4f), the pressure gradient established along the z direction by the viscous shear force results in a gradual decrease of the saturation profile in the z direction. At Bo $= 3.45 \times 10^{-3}$ (Figs. 4g–4i), the saturation profiles at the breakthrough fluctuated intensively for all Cas, similar to Figs. 4d and 4e. Ide et al. (2007) reported that for high-buoyancy force displacements, the NWP injected fluid flew upward as soon as it was injected into the WP fluid. The results in this paper are consistent with the results of Ide et al. (2007).

To confirm mass conservation during the injection of the NWP, the volume of the active site, detected by subtracting two succeeding images, as shown in Fig. 2, is plotted in Fig. 5. The estimated change in volume fluctuated...
around 0.01 PV with a standard deviation of 1.2 to 2.1 μL and with an error of 14%–25%. In an invaded pore, the WP remains in the pore space as a thin film wetting the solid surface or sharp corner by capillary force, but in the CT images, the WP is not detected because of the limits of image resolution. As the fingers developed, their tips went outside the ROI in the radial direction as well as in the z direction.

Fig. 5 Comparison of the measured injection volume of the NWP (i.e., through image analysis) every 0.01 PV at $Bo = 3.84 \times 10^{-4}$.

The effect of $Bo$ on the distribution of active sites is shown in Fig. 6. The coordinate $z'$ is defined in the opposite direction with respect to $z$ from the tip of the most advanced finger. First, the volume of every slice was calculated in $z'$ coordinates. Then, the increase in volume was calculated by subtracting the volume of a slice from that of the succeeding slice. Following that, the increase in volume was averaged for all injection periods until breakthrough and was normalized by the total volume of the NWP injected. The height position $z'$ was normalized by the average pore diameter $a$. At high $Bo = 3.45 \times 10^{-3}$, the active sites were located near the tip of the most advanced finger ($0 < z'/a < 50$) for all Ca values. At low $Bo = 3.84 \times 10^{-4}$, the active sites were distributed more uniformly over a wide range of $z'/a$ from 0 to approximately 200, reflecting the characteristics of capillary fingering. The change in injection speed slightly affected the distribution of the active sites because the present range of Cao was far below the threshold of the crossover from capillary fingering to viscous fingering ($Ca = 10^{-4}$–$10^{-6}$) (Lenormand et al., 1988).

Fig. 6 Increase in NWP volume against the position of finger growth measured from the most advanced finger tip $z'$ (mm) for Bond numbers (a) $Bo = 3.84 \times 10^{-4}$, (b) $1.53 \times 10^{-3}$, and (c) $3.45 \times 10^{-3}$.

Figure 7 shows the effect of $Ca$ on the averaged NWP saturation in the ROI for various $Bo$ values. The averaged saturation in the ROI fell in the range from 14.25% to 27.03%. For all injection rates, the saturation increased with a decrease in $Bo$ because the enhancement of buoyancy force became weaker. At high $Bo$, the effect of destabilization of buoyancy force became stronger. In capillary fingering regimes ($Bo = 3.84 \times 10^{-4}$), the saturation slightly increases with increasing $Ca$ (Lenormand and Zarcone, 1985, Wang et al., 2013) until it reaches the transition regime to viscous fingering because of the pressure gradient established in the NWP. At a high $Bo$ of $3.45 \times 10^{-3}$, the saturation of the NWP is almost constant with respect to $Ca$ because the finger extends faster with increasing $Ca$.

4.3 Diagram

The regimes from capillary to gravity fingering are plotted in a $Ca$-$Bo$ diagram (Fig. 8). This diagram is the main...
result of our study since it uses Ca-Bo instead of Ca-M that has been widely used. In Méheust et al. (2002) work, the Capillary and Bond numbers were comparable. Therefore, they could calculate the difference between Capillary and Bond numbers as another dimensionless number, generalized Bond number, to investigate quantitatively fingering development. However, the Capillary number was too small in our study which caused difficulty to determine the region of fingerings quantitatively. When a large number of WP clusters, including large clusters extending over several pores, were trapped in the ROI, as shown in Fig. 3a, we judged the fingering pattern to be capillary fingering. The NWP was uniformly distributed in the radial direction in the middle plane (z = 7.5), as shown in the inset in Fig. 8. If the size of the trapped WP is lower than single-pore scale, as shown in Figs. 3b and 3c, we judged the crossover from capillary fingering to gravity fingering to have occurred. As shown in Fig. 8, in the transition zone, the NWP penetrated around the center of the packed bed. When there was almost no trapping of the WP (80 clusters, as shown in Fig. 3c) and the NWP penetrated in the vertical direction with a streak-like structure with diameters as low as single-pore size (Fig. 8), we judged the fingering pattern to be gravity fingering. Capillary fingering occurred at Bo = 3.84 × 10^{-4} and 1.53 × 10^{-3} for all injection rates. The crossover occurred at Bo values between 1.53 × 10^{-3} and 3.45 × 10^{-3}. At Bo = 3.45 × 10^{-3} and Ca = 4.30 × 10^{-7}, gravity fingering was clearly observed.

Fig. 7 Averaged saturation of injected NWP in the ROI at breakthrough for several Bo values with respect to Ca.

Fig. 8 The fingering diagram for Ca and Bo comprises capillary fingering, gravity fingering, and the transition with cross-sectional images where the NWP is denoted in blue at a height of z = 7.5 mm.

5. Conclusion

The motivation of this study was to characterize the effect of buoyancy on fingering growth activity during a drainage process under the competitive influence of buoyancy, capillary, and viscous forces. A packed bed of glass
microbeads was used as a synthetic porous medium for a fluid pair of silicon oil and water as an NWP and WP, respectively. For a range of $Bo$ from $3.84 \times 10^{-3}$ to $3.45 \times 10^{-3}$ and $Ca$ from $4.30 \times 10^{-9}$ to $4.30 \times 10^{-7}$, the time-lapse 3D structure of finger development was visualized with the aid of an X-ray CT scanner.

The results successfully showed three instability regimes: capillary fingering, transition, and gravity fingering enhanced by buoyancy force. The transition was observed at $Bo$ values between $1.53 \times 10^{-3}$ and $3.45 \times 10^{-3}$. At $Bo = 3.45 \times 10^{-3}$ and $Ca = 4.30 \times 10^{-7}$, the gravity fingering structure was observed.

Under gravity fingering conditions, the pressure of the NWP for displacing the WP should have been the highest at the tip of the most advanced finger because the buoyancy force was higher than the capillary force. Consequently, massive new invasions were induced near the tip of the most advanced finger. As a result, fingers extended vertically with a streak-like structure with the diameters of fingers down to single-pore size. The NWP saturation at breakthrough was low and fluctuated in the $z$ direction. Buoyancy force destabilized the displacement process in this study. The WP was merely trapped as an isolated cluster.

Under capillary fingering conditions ($Bo < 1.53 \times 10^{-3}$), fingers grew not only near the tip of the most advanced finger but also far below the tip. Some fingers extended to link pores with small diameters of approximately single-pore size and developed in the horizontal direction, in the negative $z$ direction, and in the $z$ direction. The trapped WP clusters were distributed from single-pore size to large size, connecting several pores. A skewed distribution of the saturation was shown at the breakthrough for low $Ca$ because of competition between capillary fingering and gravity fingering. At high $Ca$, the pressure gradient established along the $z$ direction by the viscous shear force resulted in a gradual decrease of the saturation profile in the $z$ direction.

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