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Field-Scale Implications Of Density-Driven Convection In CO2-EOR Reservoirs

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Summary

In this paper, we present gravity-driven mixing for different CO2-hydrocarbon mixtures using a highly accurate computational model. The simulation results are used to characterize the fine-scale behavior for gravity-stable systems. Preliminary simulations for flowing systems are presented. We discuss the implications for behavior of convective systems at the field scale.
Introduction

CO₂ capture and storage with utilization in enhanced oil recovery (EOR), or CCUS, is perceived as the most cost-effective method of disposing captured CO₂ emissions (Heidug et al., 2015). CO₂-EOR as a business case for CCUS may add additional challenges. First, the storage part of EOR may be increasingly emphasized in order to meet greenhouse gas emissions targets. Second, CO₂-EOR will likely be introduced into the offshore environment, where economic constraints may restrict well density thus impacting flow regimes in the reservoir. In both cases, the interaction between CO₂ and hydrocarbons at the fine scale plays an important role, and therefore, detailed understanding is required for effectively managing CO₂ storage efficiency in CO₂-EOR reservoirs. The same could be said for any CO₂ storage reservoir where existing hydrocarbons are present but not produced.

Density instabilities can occur within the mixing zone that drive convection, which can enhance mixing and ultimately impact flow in gravity-dominated regimes. CO₂ is typically lighter than oil, but heavier than gas under typical reservoir conditions. Density instabilities arise from the non-linear change in density as CO₂ and oil mix in the miscible zone. Figure 1 shows two characteristic density curves for binary CO₂-oil mixtures (in this case pure butane and octane). We see that at intermediate concentrations of CO₂, the mixture density reaches a maximum that is higher than either end-point. The density difference between the maximum and pure CO₂ is denoted Δρ while the difference between the maximum and pure oil is Δρ₂. This non-monotonic density curve is common for CO₂-oil systems (Aavatsmark, 2018).

The initiation and evolution of convection in a miscible system depends on the initial setting, i.e. whether CO₂ is injected above or below the oil. In the case of CO₂ above oil, a density inversion will occur as diffusion mixes the two components into a heavy mixture that is heavier than the oil below. This inversion will eventually become unstable and convect downwards in a similar manner to convection in the well-studied CO₂-brine system. Conversely, if a CO₂ occurs below the oil, the system is inherently unstable (due to the density difference Δρ₁), and the CO₂-rich fluid will rise instantaneously. However, other regions will have a mixture density that is heavier, and those regions will sink. The end result is highly complex convective system driven by two separate density inversions acting in opposite directions.

There is some experimental evidence of CO₂ convection in an oleic phase induced by density effects (Farajzadeh et al., 2007; Khosrokhavar et al., 2014). But to date, the exact quantification of these systems remains elusive. Therefore high-resolution simulations using a numerically accurate method are required. Building upon a previous work (Both et al., 2015), this study investigates both the above and below initial condition for two different binary systems, CO₂-C₄ and CO₂-C₈. The properties of these binary systems are given in Table 1. In the first part of the study, we limit the system size to the “lab-scale” of approximately 1 meter in width. The system is gravity stable. These conditions are needed to benchmark and analyze against laboratory results (the subject of another study) and to compare against analytical stability models (Elenius and Gasda, 2018). However, this idealized system is insufficient for understanding how convection is impacted by flow in the reservoir. Therefore, we also extend the
Table 1 Viscoety and density of pure components in CO2 mixtures with butane (C4) and octane (C8) at 200 bars and 353 K. Maximum mixture density is also given with each hydrocarbon component.

<table>
<thead>
<tr>
<th>Component</th>
<th>Density [kg/m³]</th>
<th>Viscosity [cP]</th>
<th>Max. mixture density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>551</td>
<td>0.045</td>
<td>608</td>
</tr>
<tr>
<td>C4</td>
<td>583</td>
<td>0.13</td>
<td>686</td>
</tr>
<tr>
<td>C8</td>
<td>659</td>
<td>0.36</td>
<td>686</td>
</tr>
</tbody>
</table>

Figure 2 CO2 above C4 (left) and C8 (right). For each system, we show the scaled CO2 concentration [-] and the density [kg/m³]. Arrows indicate the direction of flow.

Numerical method

The convect simulator (Gasda and Elenius, 2018) was developed that solves the non-dimensional flow and transport equations for a two-component single-phase mixture using a fully implicit solution method. We note that the common Boussinesq assumption is not used. All results are rescaled to dimensional units given the chosen fluid and rock properties. Boundary conditions can be set as Dirichlet or Neumann depending on the desired problem. The non-dimensional system can be rescaled to any desired set of parameters. Here, we rescale to a system with porosity 0.1, permeability 100 mD, diffusivity $10^{-9}$ m², in addition to the fluid properties given in Table 1. This method is applied to two cases of CO2 initially placed above and below the hydrocarbon. In each case, the CO2 is combined with two different hydrocarbons, C4 and C8, for a total of four simulations.

Simulation results: CO2 above hydrocarbon

Figure 2 shows the finger evolution for CO2 above an oil. Note that the domain is less than a meter in each direction, and that the finger width is centimeter scale. The fingers form and migrate downwards because diffusion at the interface leads to a zone with density larger than the oil density. The initial interface between the CO2 and hydrocarbon retreats in time due to mass transfer of CO2 to the oil region. The fingers are initiated at approximately 3 days for CO2-C4 and 22 days for CO2-C8. The finger speed is 4 cm/d for C4 and 2 cm/d for C8, despite very similar $\Delta \rho$. This is explained by differences in viscosity. The transfer rate of CO2 into C4 is 0.3 kg/m²/d, and for C8 is 0.1 kg/m²/d. Both rates 100 times larger than that of CO2 mass transfer into brine which ranges from 5 to $15 \times 10^{-4}$ kg/m²/d (Elenius et al., 2014).

Simulation results: CO2 below hydrocarbon

Figures 3 and 4 show the dynamics of convection when CO2 is initially below the oil. Again, the finger widths are on the centimeter scale. The initial system is immediately unstable since CO2 is lighter than the oil, resulting in CO2 fingers migrating upwards. Diffusion leads to intermediate concentrations with a larger density than either the oil on the outside or the CO2 on the inside of the fingers. As a consequence,
the mixed fluid flows down along the exterior of the finger and into the CO2 region below. As a result, the CO2 fingers are being consumed as they propagate, and eventually will lose their buoyancy drive once the CO2 region below is fully mixed. The speed of downward migrating fingers is 20 cm/d in both systems. The speed of upward migrating CO2 fingers is 5 cm/y in C4 and 10 cm/y into C8 (until they stop). The mixing is very efficient in both cases, approximately 1000 times faster than in a CO2-brine system. However, we note that the mixing is limited to the region below the CO2 front. Once the fingers stop advancing upwards, further mixing of CO2 and oil is diffusion controlled.

**Figure 3** Scaled CO2 concentration (top) and density (bottom) when CO2 is placed below C4.

**Figure 4** Scaled CO2 concentration (top) and density (bottom) when CO2 is placed below C8.

**Field-scale Impacts**

There are field-scale implication for CO2-oil mixing in a gravity-stable system (Gasda and Elenius, 2018). When CO2 injection above a oil layer will result in the oil becoming completely mixed with CO2 within a few years. After that time, any remaining CO2 injected would form a gas cap on top of the oil. On the other hand, if CO2 is injected from below an oil leg, the mixing is highly efficient, with
CO₂ being consumed within a few months due to oil convecting downward, but CO₂ mixing upward is limited. Thus, an oil leg a few meters in thickness is sufficient to prevent further upward migration of CO₂. This implies that any lighter gas phase such as methane that sits above the oil leg would not be contaminated by CO₂ in this simple case, which has important implications for the Snøhvit field case. This analysis shows that the oil leg may be sufficient to slow down CO₂ transport into the gas cap and reduce the possibility of breakthrough at the production wells.

To extend the gravity-stable case to include flowing conditions, Figure 5 shows results from a 1-m wide cube system, where CO₂ is injected into an oil from the side. The fluids are fully miscible, yet a segregation of the different density fluids occurs within a few hours. The high-density mixture that occurs at the concentration front sinks to the bottom of the domain, while the lighter CO₂-rich region rises the the top. The CO₂-rich region is quickly consumed by the convection of the dense mixture downwards. Although this case is quite interesting, a larger domain is needed to fully examine the evolution of the convection. Also, more work is needed to explore interaction between gravity and viscous fingers for this system. Ongoing work is focused on implementation of convective mixing in the multiphase compositional simulator eWoms (Lauser, 2013) which is part of the OPM framework (OPM-2016, 2016).

**Figure 5** Scaled CO₂ concentration (top) and density (bottom) when CO₂ is injected from the side.

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**References**


