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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

CO_2 capture and storage with utilization in enhanced oil recovery (EOR), or CCUS, is perceived as the most cost-effective method of disposing captured CO_2 emissions (Heidug et al., 2015). CO_2-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, CO_2-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 CO_2 and hydrocarbons at the fine scale plays an important role, and therefore, detailed understanding is required for effectively managing CO_2 storage efficiency in CO_2-EOR reservoirs. The same could be said for any CO_2 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. CO_2 is typically lighter that oil, but heavier than gas under typical reservoir conditions. Density instabilities arise from the non-linear change in density as CO_2 and oil mix in the miscible zone. Figure 1 shows two characteristic density curves for binary CO_2-oil mixtures (in this case pure butane and octane). We see that at intermediate concentrations of CO_2, the mixture density reaches a maximum that is higher than either end-point. The density difference between the maximum and pure CO_2 is denoted $\Delta\rho$ while the difference between the maximum and pure oil is $\Delta\rho_2$. This non-monotonic density curve is common for CO_2-oil systems (Aavatsmark, 2018)

The initiation and evolution of convection in a miscible system depends on the initial setting, i.e. whether CO_2 is injected above or below the oil. In the case of CO_2 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 CO_2-brine system. Conversely, if a CO_2 occurs below the oil, the system is inherently unstable (due to the density difference $\Delta\rho_1$), and the CO_2-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.

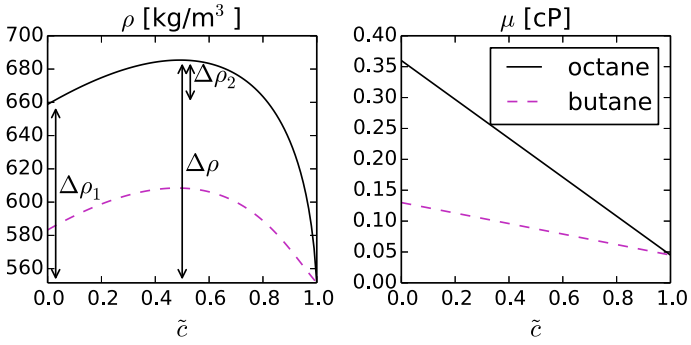

Figure 1 *Density and viscosity of binary CO_2-hydrocarbon mixtures. Properties calculated for CO_2-butane and CO_2-octane mixtures at 200 bar and 353 K using the Pen-Robinson EOS and Trend library.*

There is some experimental evidence of CO_2 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, CO_2-C4 and CO_2-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 *Viscosity and density of pure components in CO_2 mixtures with butane (C4) and octane (C8) at 200 bars and 353 K. Maximum mixture density is also given with each hydrocarbon component.*

Binary component	Density [kg/m^3]	Viscosity [cP]	Max. mixture density
CO_2	551	0.045	–
C4	583	0.13	608
C8	659	0.36	686

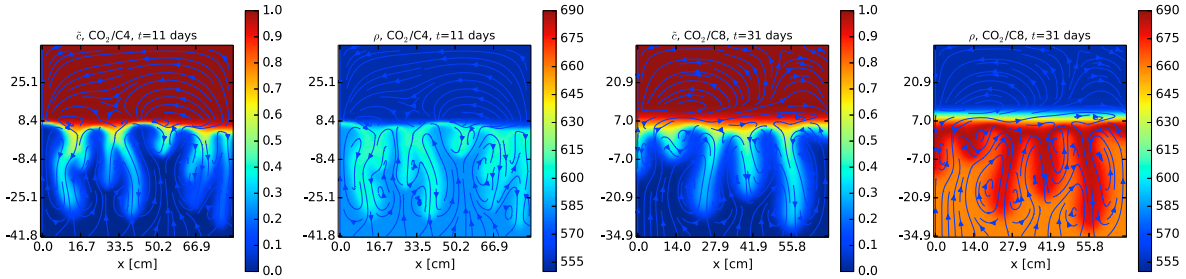

Figure 2 *CO_2 above C4 (left) and C8 (right). For each system, we show the scaled CO_2 concentration [-] and the density [kg/m^3]. Arrows indicate the direction of flow.*

numerical experiments to study the impact of flowing conditions on the evolution of convection.

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 in 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} m^2, in addition to the fluid properties given in Table 1. This method is applied to two cases of CO_2 initially placed above and below the hydrocarbon. In each case, the CO_2 is combined with two different hydrocarbons, C4 and C8, for a total of four simulations.

Simulation results: CO_2 above hydrocarbon

Figure 2 shows the finger evolution for CO_2 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 CO_2 and hydrocarbon retreats in time due to mass transfer of CO_2 to the oil region. The fingers are initiated at approximately 3 days for CO_2-C4 and 22 days for CO_2-C8. The finger speed is 4 cm/d for C4 and 2 cm/d for C8, despite very similar $\Delta\rho_2$. This is explained by differences in viscosity. The transfer rate of CO_2 into C4 is 0.3 kg/m^2/d, and for C8 is 0.1 kg/m^2/d. Both rates 100 times larger than that of CO_2 mass transfer into brine which ranges from 5 to 15×10^{-4} kg/m^2/d (Elenius et al., 2014).

Simulation results: CO_2 below hydrocarbon

Figures 3 and 4 show the dynamics of convection when CO_2 is initially below the oil. Again, the finger widths are on the centimeter scale. The initial system is immediately unstable since CO_2 is lighter than the oil, resulting in CO_2 fingers migrating upwards. Diffusion leads to intermediate concentrations with a larger density than either the oil on the outside or the CO_2 on the inside of the fingers. As a consequence,

the mixed fluid flows down along the exterior of the finger and into the CO_2 region below. As a result, the CO_2 fingers are being consumed as they propagate, and eventually will lose their buoyancy drive once the CO_2 region below is fully mixed. The speed of downward migrating fingers is 20 cm/d in both systems. The speed of upward migrating CO_2 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 CO_2-brine system. However, we note that the mixing is limited to the region below the CO_2 front. Once the fingers stop advancing upwards, further mixing of CO_2 and oil is diffusion controlled.

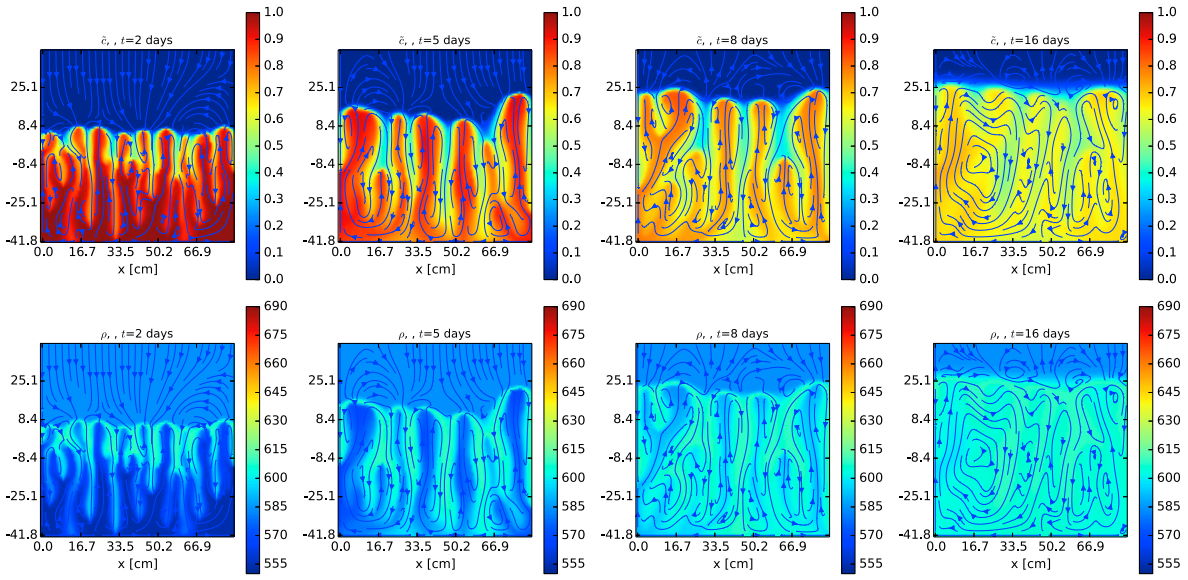

Figure 3 *Scaled CO_2 concentration (top) and density (bottom) when CO_2 is placed below C4.*

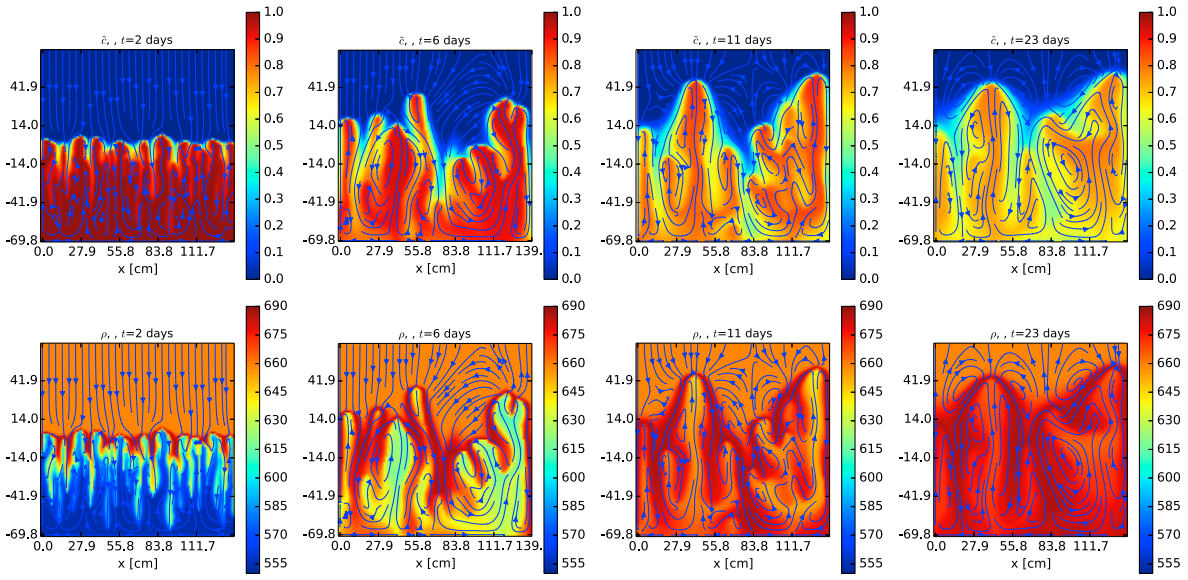

Figure 4 *Scaled CO_2 concentration (top) and density (bottom) when CO_2 is placed below C8.*

Field-scale Impacts

There are field-scale implication for CO_2-oil mixing in a gravity-stable system (Gasda and Elenius, 2018). When CO_2 injection *above* a oil layer will result in the oil becoming completely mixed with CO_2 within a few years. After that time, any remaining CO_2 injected would form a gas cap on top of the oil. On the other hand, if CO_2 is injected from *below* an oil leg, the mixing is highly efficient, with

CO_2 being consumed within a few months due to oil convecting downward, but CO_2 mixing upward is limited. Thus, an oil leg a few meters in thickness is sufficient to prevent further upward migration of CO_2. This implies that any lighter gas phase such as methane that sits above the oil leg would not be contaminated by CO_2 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 CO_2 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 CO_2 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 CO_2-rich region rises the the top. The CO_2-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).

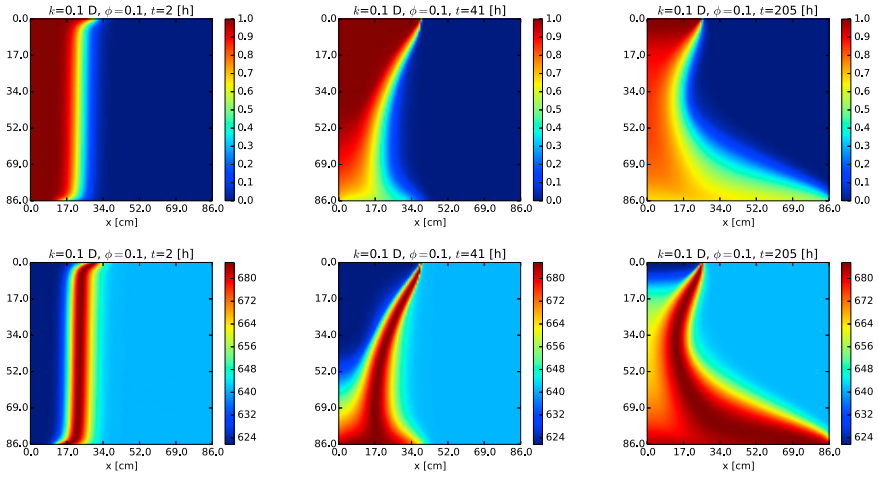

Figure 5 *Scaled CO_2 concentration (top) and density (bottom) when CO_2 is injected from the side.*

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