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Multidimensional Imaging of Density Driven Convection in a Porous Medium

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Abstract

Carbon dioxide (CO_2) sequestration is a climate change mitigation technique which relies on residual and solubility trapping in injection locations with saline aquifers. The dissolution of CO_2 into resident brines results in density-driven convection which further enhances the geological trapping potential. We report on the use of an analogue fluid pair to investigate density-driven convection in 3D in an unconsolidated bead pack. X-ray computed tomography (CT) is used to image density-driven convection in the opaque porous medium non-invasively. Two studies have been conducted that differ by the Rayleigh number (Ra) of the system, which in this study is changed by altering the maximum density difference of the fluid pair. We observe the same general mixing pattern in both studies. Initially, many high density fingers move downward through the bead pack and as time progresses these coalesce and form larger dominate flow paths. However, we also observe that a higher Rayleigh number leads to the denser plume moving faster towards the bottom of the system. Due to the finite size of the system, this in turn leads to early convective shut-down.

Keywords: X-ray computed tomography; density driven convection; solubility trapping

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1. Introduction

The long term geological storage of carbon dioxide (CO_2) for the purpose of climate change mitigation is still an important topic of investigation. The captured CO_2 is injected into deep underground sandstone or carbonate

formations. Examples include, deep saline aquifers or depleted hydrocarbon reservoirs that contain brine and residual oil and gas. The feasibility of large scale (1Mt/year) carbon dioxide injection in these geological settings has been demonstrated by field projects such as Sleipner in the North Sea, Ketzin in Germany, and various sites in North America where several million tonnes of CO_2 have been injected so far[1] as a part of Enhanced Oil Recovery operations. However, many unanswered questions remain surrounding the mechanisms which act towards the long-term sequestration of the injected fluid as well as the long-term behaviour of the host rock formation.

Solubility trapping occurs when CO_2 dissolves in the reservoir brine. The dissolution of CO_2 into the brine results in a mixture that has a larger density than the underlying brine. This causes the CO_2 saturated brine to sink deeper into the reservoir by a process referred to as density-driven convection, which increases storage security by reducing further the likelihood of the CO_2 escaping. CO_2 is injected into a reservoir in the supercritical phase with a density between 200-700 kg/m^3, depending on temperature and pressure [2]. The CO_2 plume will initially move upwards due to buoyancy forces and form a pool overlying the denser resident brine (density between 1000-1200 kg/m^3). At the same time, the dissolution of CO_2 in brine creates a boundary layer that is denser than the underlying (fresh) brine; depending on the pressure/temperature conditions this density increase has been evaluated to be in the order of 1-3% [3]. This density difference may be sufficient to allow for the formation of buoyant instability fingers. If the conditions are met this instability can result in a convection cell that is characterised by the downward movement of the CO_2-saturated brine in the form of fingers, which is being replaced by fresh brine moving upwards.

Density-driven convection can be scaled using the Rayleigh number $Ra = (\Delta\rho gkL)/(\varphi D\mu)$, where $\Delta\rho$ is the density difference; k is the permeability; g is the gravitational acceleration; L is the characteristic length; φ is the porosity; D is the molecular diffusion coefficient; and μ is the viscosity. At the field scale in the Sleipner injection site Ra number of ~10^4 is reported [4] but in natural CO_2 accumulations such as the Bravo Dome, Ra as low as 40 are estimated [5]. This range is most likely due to the permeability of the host rock and the inherent heterogeneity of the geological formation.

There have been numerous experimental and modelling studies where convective dissolution has been investigated in the context of CO_2 sequestration, mainly by means of 2D geometries (e.g. in Hele-Shaw cells) and by using analogue fluid-pairs (e.g. MEG-water [4], water-PPG [6] or gaseous CO_2-water [7]). However, experimental studies are lacking in investigations of this phenomenon in a 3D porous medium (e.g. a sand-pack or a reservoir rock core). In this study, we introduce an experimental analogue of CO_2-saturated brine which allows for the 3D observation of density driven flow in an opaque porous medium using X-ray CT. We use the analogue fluid pair MEG-water where MEG is a mixture of methanol and ethylene glycol, to mimic CO_2 (MEG) and brine (water) respectively.

2. Methods

X-ray CT allows for the static imaging of an opaque 3D porous medium. When the process under study is slow enough, dynamic behaviour of the system can also be evaluated. In this study we use a 5 L spherical bowl made of PET that is placed on the scanner bed which is held in the (conventional) horizontal position. The bowl is wet-packed with beads (water is the working fluid; beads have diameter of 0.5 mm) and a layer of packed beads (previously saturated with MEG) is poured on top, in order to start the experiment. To improve the X-ray contrast between the fluids, both liquids are doped with salts. The working fluid (water) is doped with sodium chloride, NaCl, and the MEG is doped with potassium iodide, KI. It was necessary to dope both fluids to maintain the representative density difference which mimics the CO_2-brine system. The entire bowl is scanned every 20-30 minutes for 12 hours where one scan takes 1 minute to complete. Each slice has a thickness of 2 mm with an x − y resolution of 512 pixels or 234.4 µm.
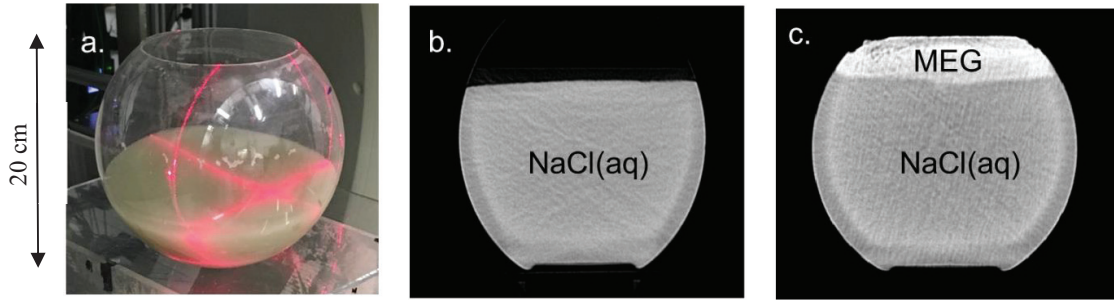
Fig1. (a) the bowl partially-filled with beads; (b) and (c) are raw CT images of the central slice of the bowl prior and after addition of the MEG layer

In this study two mixtures of MEG (MEG-1 and MEG-2) were used. These possess slightly different maximum densities upon mixing with water, otherwise all other experiment parameters were kept constant as outlined in Table 1. Thus, the Rayleigh number is changed solely from the change in maximal density difference and the characteristic length used is the height of the system which is 20 cm, the viscosity of 8.9×10^{-3} kg m^{-1}s^{-1} and a diffusion coefficient of 1.5×10^{-5} cm^2 s^{-1}. The permeability is calculated from the Kozeny-Carman equation with a random close pack porosity assumed to be 36%.

Table 1. Properties of the system.

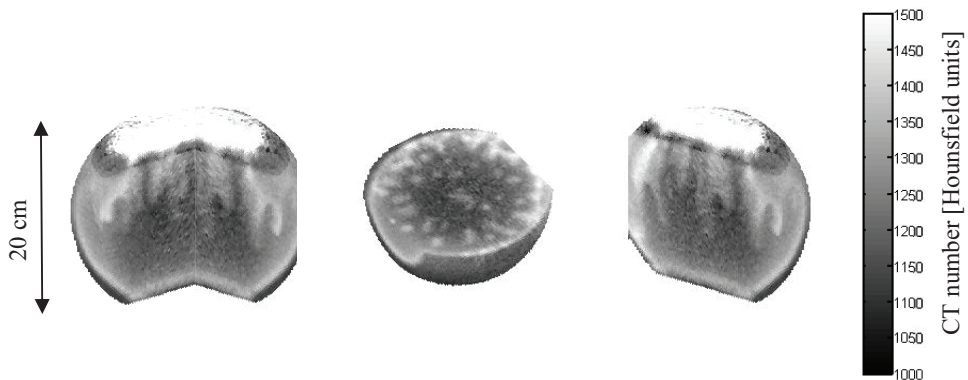| Fluid Pair	Density difference (%)	Permeability (cm^2)	Ra number
MEG-1	0.5	1.6×10^{-6}	5,000
MEG-2	1	1.6×10^{-6}	10,000

3. Results

Fig 2. Three reconstructions of the experiment with MEG-1 at 50 minutes

As an example of general validity, figure 2 shows a 3D reconstruction of the bowl in three different formats for the experiment carried out with fluid pair MEG-1. In each reconstruction a different part of the bowl has been cropped away to enable a more complete understanding of the finger dynamics. The first of the three reconstructions (a) suggests that the finger development is circumferentially consistent; the fingers are of a similar size and shape. In the horizontal cross section (b) the fingers appear to form across the entirety of the bowl but most prominently at the edges. In the vertical cross section (c) the shape and width of the fingers can also be observed across the entire cross section.

In figure 3, still-frames of the central slice of the bowl are shown over time for the experiments carried out with MEG-1 and MEG-2. A similar qualitative mixing pattern is observed between the two experiments; small regularly spaced fingers are first formed which propagate through the bowl coalescing into larger fingers. Also it is observed that the fingers develop independently from the wall boundaries and from themselves.

Other than the maximal density difference of each solution all other parameters were kept constant. Therefore, the time for finger development and propagation is due to this variation. So, we can relate the convective shutdown time to the density difference qualitatively by observing the evolution of the fingers at the same time for MEG-1 and MEG-2 experiments. At 80 minutes it can be seen that the fingers in the MEG-2 experiment have moved further down into the bowl than in the MEG-1 experiment and the fingers themselves are larger and fewer. By 200 minutes in the MEG-2 experiment, the fingers have reached to bottom and convective shutdown begun. At the same time in the MEG-1 experiment the fingers are freely moving and convection continues until 480 minutes where a single finger is still visible. Further to this the MEG layer itself is depleted more quickly in the case of MEG-2 compared to MEG-1. At 200 minutes the MEG has almost completely mixed for MEG-2 whereas the layer in MEG-1 is still visible. Therefore it can be said that the mixing is faster in MEG-2 compared to MEG-1.
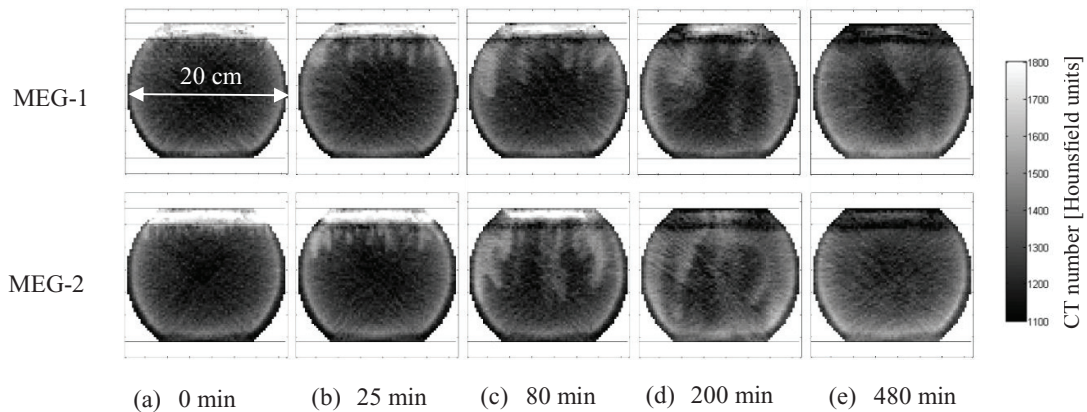

Fig 3. 2D maps of finger development in the central slice over time for experiments with MEG-1 and MEG-2

4. Conclusions

A method for imaging density-driven convection in an opaque porous medium has been developed using the analogue fluid pair MEG-water and two MEG solutions with differing maximal density difference were used. The finger development was visualized by using X-ray CT and the process of convective mixing has been qualitatively analysed. Initially, many small fingers form across the entire cross section of the bowl; at later times coalesce to create fingers of larger diameter. Furthermore, with a larger density contrast, the initial number of fingers is larger and they extend into the bowl more quickly reducing the total mixing time. Future work will focus on quantification and the introduction of heterogeneous packing.

Acknowledgements

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