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Application of gravity currents to the migration of CO_2 in heterogeneous saline formations

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Abstract

Gravity currents form when carbon dioxide is injected into a saline formation beneath a sealing caprock, since under most conditions the injected CO_2 is significantly less dense than the formation water. The phenomena of gravity currents are examined for the simplest kind of heterogeneity, that of two horizontal layers of contrasting permeability. The results of numerical simulations of single phase flow are compared with both laboratory experiments and analytical predictions. The results on gravity currents are applied to the spreading of the gas phase CO_2 and also to the slumping of the dissolved CO_2.

Keywords: Gravity currents; Carbon dioxide; porous media; simulation; TOUGH2

1. Introduction

A crucial aspect of the underground storage of CO_2 is the spreading and movement of the injected CO_2 in both the gas phase and the aqueous phase. Deep saline formations with a laterally extension top seal are globally abundant and are widely being considered as suitable sites for CO_2 storage. When CO_2 is injected into such a formation, the subsequent lateral spreading is strongly affected by gravity, since under most conditions the injected CO_2 is significantly less dense than the formation water. This is similar to gravity currents in a porous medium for single-phase systems, where for example a saline fluid of greater density is injected into a porous medium saturated with pure water (Lyle et al. [1]). In this paper theoretical results for gravity currents are tested against simulations and applied to CO_2 injection projects.

Lyle et al. [1] and Bickle et al. [2] have analyzed gravity currents in homogeneous systems, and produced results for the scaling of the radial migration as a function of time. Two distinct regimes are evident. In the first regime, while continuous injection is taking place, the radial extent increases as $t^{1/2}$ where t is time. In the second post-injection regime, when the spreading is driven only by gravity, it increases as $t^{1/4}$. In both of these cases, the gravity current theory developed in the literature, which we discuss below, is based on the assumptions that the high density

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region and the low density *in situ* water remain separated by a sharp interface, that the two fluids have the same viscosity and that the motion of the *in situ* water can be ignored.

Gravity currents have received attention in the area of CO_2 storage due to the importance of determining the maximal potential spread of the injected CO_2. The associated literature goes back to the simple gravity current theory of Huppert [3] and Lyle et al. [1], and more recently has accounted for many different effects such as incorporating a sloping cap rock (Hesse et al. [4]; Vella [5]), allowing for residual a volume of residual CO_2 (Hesse et al. [4]) (but only for two-dimensional (2D) not radial), and heterogeneous media where draining into one layer below the main reservoir is accounted for (Pritchard et al. [6]). Hesse et al. [7] analysed the transition time from early to late similarity behavior. To date the theory has not included any dispersive effects that would smooth the interface between the two fluid regions, nor does it allow for anisotropic permeability (vertical permeability on a reservoir scale is typically much less than horizontal permeability).

The aim of this paper is twofold – (1) to compare the theory of gravity currents with experiments and simulations in homogeneous and heterogeneous porous media, and (2) to test the applicability of gravity currents to the simulation of CO_2 storage. In regard to (1) we discuss the comparison of simulations with laboratory-scale experimental data, and the comparison of simulations with theory. In the laboratory, dyed salt water is used to visualize the profile of the spreading gravity current, and a random close packing of small glass balls in a perspex box forms the porous medium. The combination of theory, experiments and simulation, has not been discussed together previously. The multi-phase porous media code TOUGH2 is used to solve the single phase porous media transport equations with variable salinity as well as to simulate field-scale CO_2 injection. For the latter, there are two kinds of gravity current to consider. The first is the movement of the gas phase due to buoyancy, during and after injection. Since it is a two-phase process, the single-phase theory is lacking some of the physics (e.g. viscosity differences, relative permeability and capillary pressure effects), and may need to be modified. The second phenomenon is the movement of dissolved carbon dioxide, which can slightly increase the density of the formation water, so that on long time scales (hundreds to thousands of years) a weak gravity current occurs, both due to fingering down from a thin overlying gas layer, and also from slumping of dissolved carbon dioxide from the centre of the injection plume.

2. Comparison of theory, experiments and simulation

We distinguish between gravity currents formed by a constant rate of injection of fluid (either salt solution or CO_2), and those formed by the release of a fixed volume of fluid. In practice, when injection ceases then there is a transition from constant rate to fixed volume, as discussed by Hesse [7]. Furthermore, we use either a radial axisymmetric geometry or a 2D Cartesian vertical slab, both of which are applicable to field scale studies. We consider either a uniform porous medium, or a stratified medium consisting of two layers of uniform but different permeabilities, the simplest form of heterogeneity. The simulations were carried out with TOUGH2. In all cases top and bottom boundaries are simulated as being impermeable, while the right vertical boundaries (far from the origin of the gravity current) are held at constant pressure, and the left vertical boundaries are no-flow, representing the line of symmetry. Fluid is introduced into the porous medium by adding the corresponding source term to a particular computational cell, near the intended injection position.

2.1. Constant rate, axisymmetric, homogeneous

. The experimental data and associated theory results come from Lyle et al. [1], who found a close agreement between an analytic similarity theory and experimental data: this is seen in Figure 1, along with simulation predictions. The porous medium in the experiment is a 90° sector tank filled with 3mm glass spheres and saturated with pure water. The gravity current is created by injecting brine in one corner. The permeability of the porous medium is measured separately as 6.8×10^{-9} m^2 and the porosity is 37%. The simulation also agrees moderately well, though it over-predicts both theory and experimental data in lower radial positions, at all four times. The over-prediction in the simulation may be due to the pressure boundary conditions used in the simulation, which do not entirely reflect the experiment, where the tank is open on the top but otherwise confined. The simulation also assumes a perfect radial symmetry, which may not be present in the experiment.

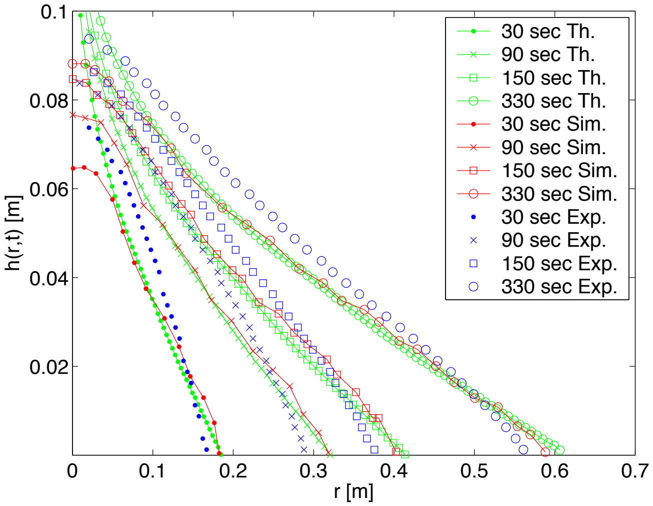
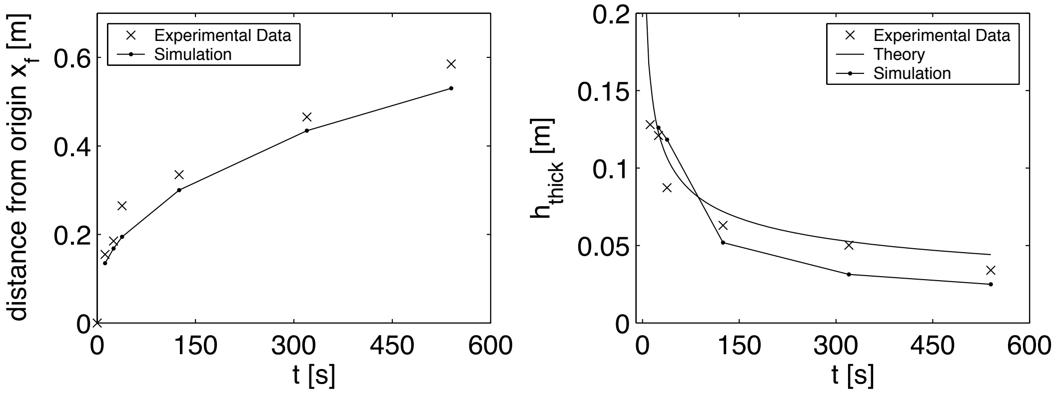


Figure 1 Comparison of simulated, theory and experimental h(r,t) [m] versus r [m], at four times (30, 90, 150, 330s). Theory function and experimental data from Lyle et al. [1].

2.2. Fixed volume 2D cartesian, homogeneous

Experiments were also performed with a fixed volume release of salt water. The tank was 1.2m long, filled with 2mm glass spheres, giving a permeability of 3.4 x 10^{-9} m^2 and a porosity of 37%. The glass spheres were a random close packing, and the permeability was determined by Carmen-Kozeny equation. The initial release was 0.09 m wide by 0.128 m deep and $g' = g\ \Delta\rho/\rho$ was 0.5 m s^{-2} (where ρ is the density of the in situ water, Δρ is the density increase in the gravity current, and g is the acceleration due to gravity). The results are compared with theory from Huppert [3], and with the simulation results. Figure 2a-b shows the vertical height thickness h_{thick} and leading edge x_f (distance from origin) versus time, and the agreement between theory, experimental data and simulation is fairly good.



(a) (b)

Figure 2 Theory, simulation and experimental data for a fixed volume release in an homogeneous porous medium, 2D Cartesian geometry.

2.3. Constant rate, 2D cartesian, two layer permeability

Experiments and simulations were conducted on a porous medium composed of two layers of different permeability, the simplest form of a heterogeneity, with a constant rate injection of salt water in the lower layer (injection rate of $9.6 \times 10^{-7} m^3/s$, $k_L = 1.35 \times 10^{-9} m^2$, $k_U = 1.14 \times 10^{-8} m^2$). Figure 3a-e shows the contours of the salt mass fraction at five times, next to the photograph at the associated time. There is reasonable agreement in shape and vertical extent, although the simulations consistently over-predict the lateral extent. The position and timing of the fingers which form are not in good agreement. To improve this match, it would likely be necessary to model the small-scale permeability variations in the experimental system which will influence finger formation. For a random close packing of sphere, a representative elementary volume (on which the average porosity does not fluctuate markedly) is at least four or five sphere diameters, so given that the glass beads are around 2mm in diameter, this equates to a least 1 cm scale for porosity and permeability variations There is also the potential unevenness of the interface of permeabilities. An improved matching for fingering (in particular an earlier onset and coarser fingers) would remove material from the upper layer more quickly in the simulation, and should improve the matching of the lateral extent as well. There are no fitted parameters used in the simulation model, and the fact that the simulator can predict *a-priori* the experimental data with moderate accuracy is encouraging. This is also true of the comparisons made in section 2.1 and 2.2 for an homogeneous system with constant rate and fixed volume respectively. The results of a similar experiment with a lower injection rate of $1.1 \times 10^{-7} m^3/s$ is shown in Figure 4 as a line plot of the maximum extent of the gravity current in both the upper and lower layers. The agreement is fairly good for the shape and the timing, but again the lateral extent is over-predicted.

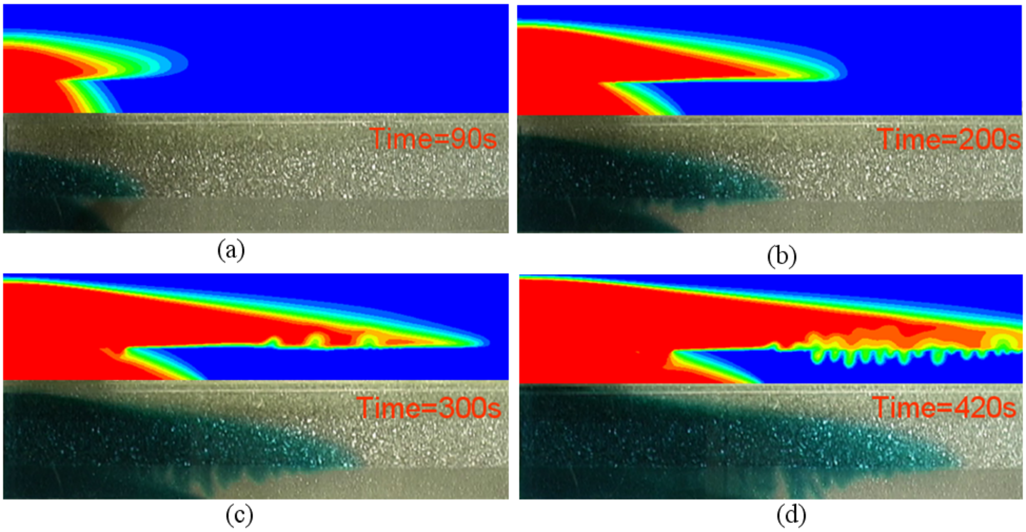


Figure 3 Experimental and simulation results for a constant rate injection in a 2D Cartesian geometry with two layers of differing permeability. Snapshots are at times (a) 90s, (b) 200s, (c) 300s and (d) 420s.

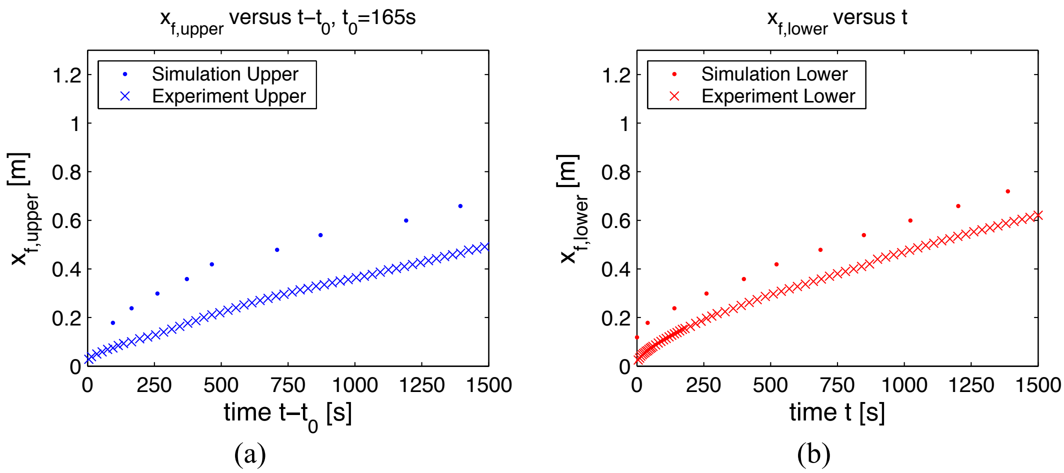


Figure 4 Lateral frontal position of plume in experiments and simulations for constant rate injection in a 2D Cartesian geometry with two layers of differing permeability. Lower injection rate of $1.1 \times 10^{-7} m^3/s$. (a) base of upper layer, (b) base of the lower layer.

2.4. Critical line for constant rate, 2D cartesian, two layer permeability

For practical and theoretical reasons, it is useful to delineate the boundary between the cases where the gravity current advances fastest in the upper layer (over-run) and when it advances fastest in the lower layer (under-run). A natural dimensionless rate is $Q_s = \nu Q/(k_L H\ g')$, where Q is the injection volumetric flow rate, ν is the dynamic viscosity, k_L is the lower layer permeability, H is the height of the lower layer. Dimensional analysis indicates that the boundary between over-run and under-run is described by $Q_s = f(k_L/k_U)$. Rearranging this, one can write $Q_2=\nu Q/(k_L H) = g'\ f_1$, so that plotting Q_2 against g′, the boundary between over-run and under-run should be a straight line. The experimental and simulation results plotted in Figure 5, for which k_L/k_U=0.1184, use the same geometry and general setup as discussed in section 2.3. Drawing the f_l boundary line between the over-run and under-run cases gives f_l approximately equal to 2/3, which is shown in Figure 5.

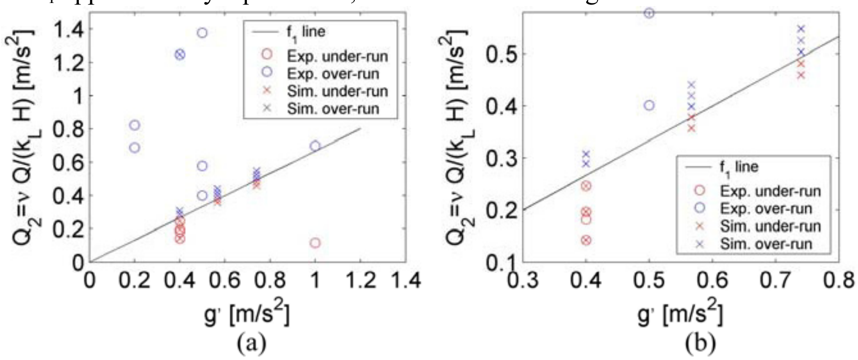


Figure 5 Delineation of the boundary between over-run and under-run in two layer permeability and constant rate injection. Q_2 is plotted against g, and both experiment and simulation results are shown (a) full range and (b) close up in region of interest.

3. Application to field scale CO_2 storage

The ultimate aim of this work is to apply the gravity current theory to a field-scale two-phase CO_2 storage case to gain a theoretical understanding of the spreading behavior of CO_2 in the gas phase, and the CO_2 dissolved in aqueous phase. The simplified model considered here has CO_2 injected into an homogeneous and horizontal reservoir unit via a vertical well completed across the full thickness of the reservoir, making use of radial symmetry. The gaseous CO_2 initially moves away from the well radially in all directions, but being less dense than the background saline water, the gas forms into an upwards moving gravity current. CO_2 also dissolves in the formation water that contacts the gas plume, slightly increasing the density of the formation water, and a weak gravity current in the aqueous phase develops moving downwards. The simulation results are compared to the theory of Lyle et al [1]. We assume constant isotropic permeability of $1x10^{-13}$ m^2 to allow the isotropic theory to be applied to the simulation.

3.1. Axisymmetric aqueous gravity current

CO_2 is injected into a homogeneous saline aquifer at a total flow rate of 30kg/s for a period of 20 years, and the simulation is continued into the post-injection period to about 50,000 years. The contours of the dissolved CO_2 are shown in Figure 6. A difficulty arises in defining the position of the front from the simulation, since as shown in Figure 6, the front is fairly smeared out. A cutoff of either 20% or 40% of the total concentration was used to determine the position of the front. Part of the problem in defining this position is the dissolved CO_2 that arrives from fingers forming from above: this additional CO_2 causes the simulated leading edge to be further along than it would otherwise be without fingering, as can be seen in Figure 6. This CO_2 from above becomes part of the gravity current. The theory of Lyle et al. [1] for a fixed volume release in a radial geometry is used to compare with the simulated axisymmetric spread of the aqueous CO_2 along the bottom part of the reservoir, as shown in Figure 7. The theory requires the initial volume of the gravity current, and Figure 7 shows the theory for two different volumes Q_0: (1) a low volume corresponding to the simulated volume at the end of injection (when there is more potential for

CO_2 to dissolve from residual gas CO_2), and (2) a high volume at the start of the gravity current development. For both cases of theory and simulation, a fairly good agreement is indicated in both the shape and quantitative predicted position of the front of the CO_2. The high volume theory overshoots the simulated radial front position for both c_i simulated cases, potentially because the initial volume Q_0 includes all aqueous CO_2 which is larger than actually available for the gravity current. The low volume case undershoots both c_i simulation cases but is fairly close to the simulated values with c_2=40%. Using a higher criteria (c_2=40%) in CO_2 mass fraction gives a better estimate of the leading edge the simulation predicts because it disregards the CO_2 coming down from fingering. It is likely that some intermediate volume Q_0 which reflects the actual volume available for the gravity current will provide the best agreement for the simulation case (case c_2). The overall agreement of theory and simulation is reasonable, given that the conditions of the fixed volume release are not precisely met, since the volume of dissolved CO_2 in the simulation increases over time due to convective mixing and continuing dissolution from the residual gas phase.

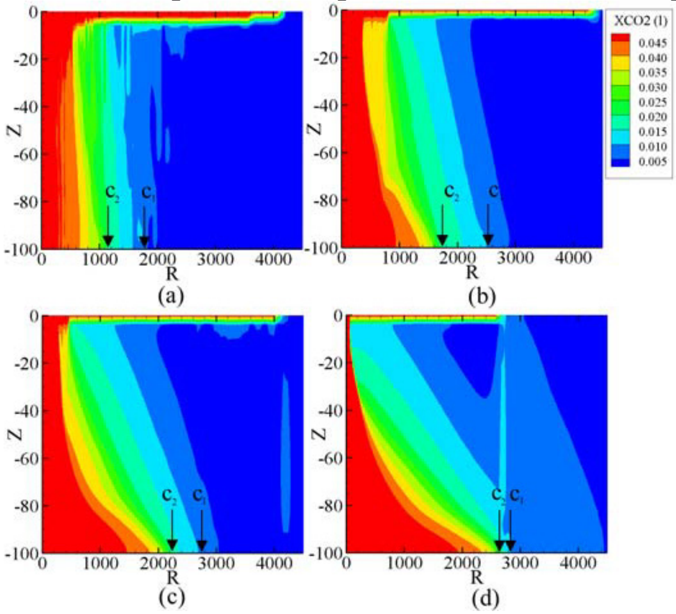


Figure 6 Simulation filled contours of mass fraction of dissolved CO_2 after CO_2 injection, where a gravity current occurs, depth Z (m) below cap rock versus distance from well R (m). Shown at times: (a) 1E11 sec (3171y), (b) 5.12E11 sec (16235y), (c) 1.4E12 sec (44378y) and (d) 1.61E12 sec (51081y). Two critical points defining the gravity current front position r_N as plotted in Figure 7 is indicated.

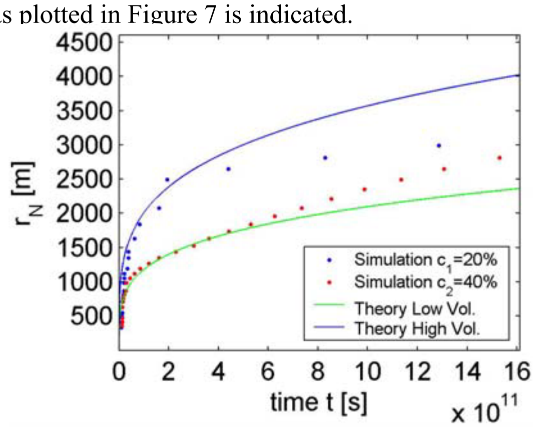
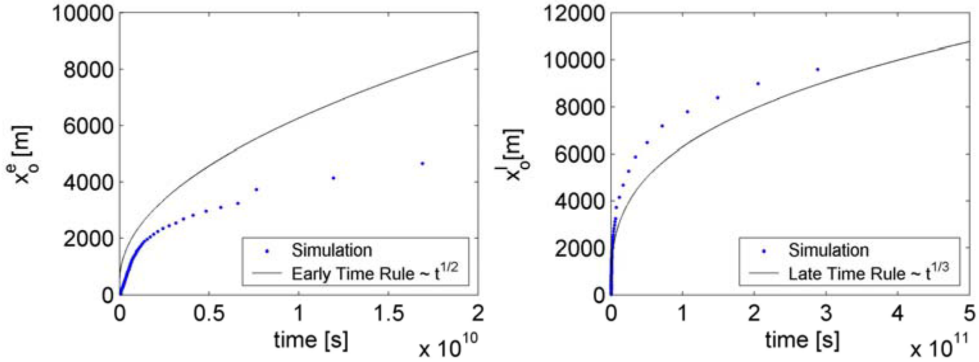


Figure 7 Simulation results for the spreading of dissolved CO_2 after injection, compared to theory of Lyle et al [1] for a fixed volume release in a radial geometry. A cutoff of either 20% or 40% was used to determine the front position. Two theory curves are shown for the volume Q_0: green line is low total volume Q_0 (total volume at initial development of gravity current) of CO_2 in system, blue line is high total volume Q_0 of CO_2 in system (total volume at end of injection).

3.2. Gas phase gravity current

Hesse et al [7] developed a two-phase theory for predicting the maximum extent of the gas phase CO_2 plume at early and late times, also predicting a transition between these times. The theory is used to compare with the simulated spread of the gaseous CO_2 along the top cap rock in a 2D Cartesian geometry, as shown in Figure 8. The agreement is not quantitatively good in early times in Figure 8(a), but is better for late times as shown in Fig. 8(b).



(a) (b)

Figure 8 Simulated spread of gas phase CO_2 after injection (where plume rises to cap rock) versus time (sec), compared with (a) early time Hesse theory ~ $t^{1/2}$, and (b) late time Hesse theory ~ $t^{1/3}$.

3.3. Gas phase two layer gravity current

We now apply the two layer theory from section 2.4 to the simulation of 2D field scale injection of CO_2 into two layers of different permeability, considering the gas phase gravity current rather than the aqueous phase (note that upper and lower are now relative to the direction of the gravity current). The function Q_2 is given by $Q_2 = \nu Q/(k_L H)$ where the parameters considered are as follows: $Q=4.11\text{x}10^{-5}\text{m}^2/\text{s}$ is the injection volumetric flow rate per unit width, $\nu=\mu_{gas}/\rho_{gas}=8.01\text{x}10^{-8}$ m^2/s (ρ_{gas}=730 kg/m^3), k_L =0.25x10^{-12} m^2 (note k_U=1x10^{-12} m^2) and H=20m (total height 100m), giving Q_2=1.44 m/s^2. Given g'=2.74m/s^2, and from section 2.4 $f_l(k_L/k_U=0.1184)=2/3$ so that the critical Q_2 is given by $Q_{2line}=f_l\ g'$ =2/3x2.74=1.83. Since Q_2=1.44< Q_{2crit}=1.83, under-run should be apparent; however as shown in Figure 9 neither under-run or over-run of the gas phase occurs i.e. the gas phase moves at the same pace in the both k_L and k_U layers. Note that because gas rises rather than sinking as the aqueous phase does, under-run occurs in the upper reservoir k_L layer. The theory may need to be adjusted to account for the viscosity of the gas phase CO_2. It is important to note that in these simulations we are not scaling the capillary pressure with permeability, which would further retard entry of CO_2 into the top layer. These results suggest that inject of CO_2 into a high permeability formation overlain by one of lower permeability could retard the overall rate of spreading of the gas plume.

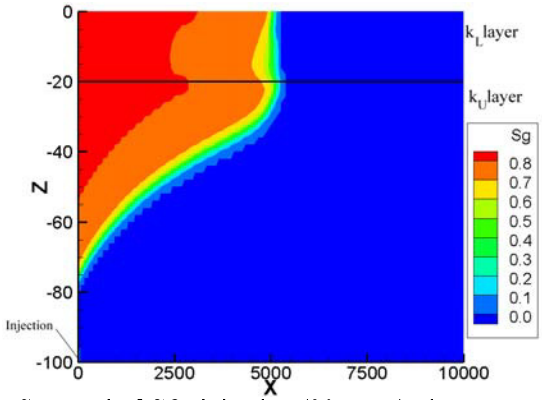


Figure 9 Simulated gas saturation S_g at end of CO_2 injection (20 years): the upper reservoir layer (k_L) and lower reservoir layer (k_U) are shown, along with the injection point.

4. Conclusions

Theory, experiments and simulations (with no adjustable parameters) of gravity currents in porous media have been compared, and applied to the spreading of both gas phase CO_2 and dissolved CO_2 under the influence of gravity in deep saline aquifers. Both constant rate injection and fixed volume release were considered in both homogeneous and heterogeneous media (the heterogeneity here consisting of two horizontal layers with contrasting permeabilities). In general, we found good agreement between experiment, theory and simulation of gravity currents in both single layer and two layer porous media. However the width and timing of fingering instabilities in some of the experiments has not been well matched in simulations, and a better characterization of the small-scale permeability variations in the experimental porous medium will probably be needed in order to improve this match.

We also linked the gravity current theory with a radial two-phase CO_2 injection into a generic homogenous saline reservoir, using two forms of gravity currents: at the top cap rock in regard to spread of the gas phase, and at the bottom of the reservoir with respect to the dissolved CO_2 in the aqueous phase. We compared the gravity current theory for the leading edge ($t^{1/4}$) for a fixed volume release with simulation predictions for the dissolved phase CO_2. The simulated leading edge is less than that predicted by the theory by up to 25%, which could be because the conditions do not precisely match the fixed volume release, since the amount of dissolved CO_2 in the simulation is increasing, as more is continually dissolving from the residual gas phase. We also used a two-phase gravity current theory to compare with the simulated spread of the gaseous CO_2 along the top cap rock in a 2D Cartesian geometry. For this case the agreement with theory is reasonable for the late times. Finally, we showed the two layer theory, which delineates the occurrence of over-run and under-run, was not yet able to be applied to the spreading of gas phase CO_2 for field scale injection. Further theoretical is required to incorporate the effect of viscosity, and to include capillary pressure variations between the two layers.

The theory of gravity currents thus has useful applications in predicting the spread of gas phase CO_2 and dissolved CO_2 in both homogeneous and heterogeneous porous media. Further theoretical developments, such as extensions to anisotropic porous media, are needed for field-scale applications.

5. Acknowledgements

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6. References

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