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COUNTER-CURRENT RELATIVE PERMEABILITY AND IMMOBILIZATION OF CO_2 IN SALINE AQUIFERS

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Summary. *Relative permeability measurements for two- and three-phase systems have shown that counter-current relative permeability of all phases is less than the corresponding co-current values. However, in numerical simulation of CO_2 injection into saline aquifers, one set of relative permeability functions (drainage–imbibition) is commonly assigned to each phase that is based on co-current flow observations. In this study, we combine displacement calculations and experimental observations to investigate the impact of relative permeability reductions during counter-current flow on the migration dynamics of CO_2 that is injected into saline aquifers. Our study indicates that both co-current and counter-current relative permeability functions should be used in the prediction of CO_2-Brine displacement processes to properly delineate the migration of a CO_2 plume in effective design and risk assessment frameworks.*

1 INTRODUCTION

Existing numerical simulators that are currently used in modeling of CO_2 injection into saline aquifers assume, implicitly, that co-current and counter-current saturation functions (e.g. relative permeability) are similar. However, the migration of the injected CO_2 in an aquifer occurs in both co- and counter-current flow settings, especially in its vertical migration where counter-current flow is the dominant flow regime. The difference between co- and counter-current flow and its impact on CO_2 migration and entrapment was addressed by Javaheri and Jessen (2011).

Previous experimental studies have demonstrated a reduction in the relative permeability functions of counter-current flows relative to co-current values (Lelievre, 1966; Bentsen & Manai, 1993; Bourbiaux & Kalaydjian, 1990). These experiments were carried out with two-phase brine/oil fluid systems. Theoretical studies (Whitaker, 1986; de la Cruz & Spanos, 1983) show that multiphase flow in porous media is affected by the viscous effect at the fluid/fluid interface. Eastwood & Spanos (1991) and Spanos *et al.* (1986) used this analysis and demonstrated that the relative permeability does not only depend on the saturation. In addition, Javaheri and Jessen (2011) applied the dependency of relative permeability on flow regime and demonstrated that a reduction in relative permeability functions due to transition from co-current to counter-current flow (in the vertical direction) increases the residual entrapment of CO_2 and retards its upward migration.

To validate the applicability and accuracy of co-current relative permeability in settings where fluid displacements occur in a counter-current setting, as is the case for CO_2 injection into saline aquifers, we have designed counter-flow experiments that attempt to minimize the effect of boundary conditions. The experiment shows that the relative permeability in the counter-current setting should be decreased from the co-current values (where relative permeability was measured). We also address the implication of these changes in the injection of CO_2 into an aquifer and its effect on the fraction of the CO_2 that is trapped.

2 EXPERIMENTAL STUDY OF GRAVITY SEGREGATION

In this section we briefly describe the apparatus for our experimental study of gravity segregation and two-phase flow. The saturations were measured along a packed column and compared with numerical calculations: The relative permeability of both phases was adjusted to obtain a good agreement between experiments and simulation.

2.1 Segregation experiment

A glass column packed with glass beads served as porous media in this work with emphasis on water-wet systems. Four-electrode resistivity measurements were used to estimate the wetting-phase saturation along the porous column as a function of time. The porous media consists of a borosilicate glass column with adjustable plungers at both ends. The glass column has an inner diameter of 50 mm and a height of 500 mm. Stainless steel frits (type 316) with an average pore size of 10 μm were attached to the end of each plunger. The glass column was further modified by drilling holes along the length to insert the potential electrodes. In each selected interval, three holes were drilled on the perimeter of the column with a spacing of 120 degrees. A total of 36 holes were drilled along the glass column to establish a total of 11 sections.

To represent and study the migration of a supercritical CO_2 plume in a saline aquifer, we conducted a series of segregation experiments at low-pressure using the synthetic porous material and analog fluids. We used BT13 (170 Mesh) glass beads with an average particle diameter of 88 μm to represent the porous media while the immiscible two-phase brine/iso-octane (iC_8) fluid system was used to represent brine/supercritical CO_2 at reservoir conditions. Brine was prepared from deionized water and NaCl with a concentration of 20,000 ppm resulting in a density of 1013 kg/m^3 at 70°F while the non-wetting phase (iC_8) has a density of 692 kg/m^3 at 70°F. To visualize the propagation of iC_8 in the column we used an oil soluble dye (Sudan Red 7B). The viscosity of brine and iC_8 were 1.0 and 0.48 mPa.s, respectively. Pendant drop measurement was performed to determine the interfacial tension of the brine/iC_8 system and a value of 47.3 mN/m was observed from repeated measurements.

Figure 1 shows a schematic diagram of the dynamic segregation experiment including connections to the source and acquisition systems. We used a dry-packing approach where glass beads were slowly loaded into the glass column with one plunger in place while resting on a shaker to ensure an effective packing. The top plunger was then firmly tightened to provide a good support for the beads. The column was then evacuated by a vacuum pump to remove air from the packed column. Under continued evacuation, brine was then loaded into the column from the bottom to fully saturate the packed column. The porosity and permeability of the packed column were measured to 38.6% and 4.8 Darcy, respectively. At fully saturated conditions, the porosity at each section of the column was calculated from the resistance and found to be in good agreement with the overall porosity.

Relative permeability functions for primary drainage and imbibition processes were measured from steady-state flow experiments. The relative permeabilities were measured in a co-current setting and provide the initial input to the numerical calculations. Drainage capillary pressure was measured on a small sample and was smoothed by the van Genuchten (van Genuchten, 1980) capillary pressure function.

A Teledyne 260D syringe pump was used to inject iC_8 at the top of the column at a rate below the critical velocity. The dyed iC_8 was then injected into the column to create an initial non-wetting saturation distribution as uniform as possible. After the desired amount of iC_8 was injected (0.31 PV for this experiment), the packed column was inverted and the segregation experiment initiated. The potential differences at each section of the packed column were continuously recorded allowing for subsequent calculation of the wetting phase saturation.

The electric current through the column at any given time was calculated from the potential drop across the shunt resistor. From the potential differences across the column sections, the resistances of the sections of the column were then calculated. The brine saturation in each section of the packed column was then calculated based on the resistivity index (RI) with a saturation exponent, *n*, that was obtained from Archie's equation (Archie, 1942) knowing the total volume of the injected iC_8. This approach allows us to determine the brine saturations at each section of the packed column as a function of time. The saturation of iC_8 is depicted in Figure 2 as a function of time.

2.2 Simulation

To simulate and interpret the experimental observations, we assume a 1D fluid flow and the physical properties of brine and iC_8 (viscosity and density) are assumed to be constants. An IMPES formulation was used to solve the incompressible two-phase flow problem. In the numerical calculations we use a spatially refined model to reduce numerical diffusion and upscale (average) the calculation results to compare with the iC_8 saturations from the experiments. The permeability is assumed to be a constant (4.8 Darcy) in all cells, while the porosity in each cell of the refined model is set equal to the porosity of relevant section in the experimental setup.

Corey-type relative permeability functions were used in the simulation where the exponents and endpoints were calculated by fitting the best curve to the relative-permeability data. Killough's model (Killough, 1976) was used to represent hysteresis in both capillary pressure and relative permeability for both phases.

To match our experimental observations, model input parameters were changed by optimization. We attempt to match our experimental observations by adjusting three parameters: the saturation exponents of brine and iC_8, and the endpoint relative permeability of iC_8.

2.2.1 Adjustment of model parameters

In the numerical calculations based on the co-current inputs, the iC_8 is predicted to reach the top of the column after five hours, while it takes about one day in the experiment. Therefore, the input parameters should be adjusted to match the experiment.

Phase relative permeabilities were measured in a co-current setting. However, the segregation experiment with brine and iC_8 occurs in a counter-current flow setting. We assume that the model parameters other than the relative permeability (e.g. capillary pressure) do not depend on the flow regime and focus on modifying the relative permeabilities to match the observations of the counter-current flow experiments.

Two approaches were used for tuning the relative permeability functions: A) adjustment of saturation exponents, and B) adjustment of saturation exponents as well as the endpoint relative permeability of iC_8. The second approach is based on the experimental measurement of counter-current relative permeability in the brine/oil system (Benstsen and Manai, 1993; Lelievre, 1966) where a distinct reduction in the endpoint relative permeability of the non-wetting phases was observed. We note that it is not documented whether this reduction is related to the boundary conditions of the experiments or other effects, e.g. a change in fluid distribution in the counter-current displacement compared to the co-current displacement experiment.

The results of the second approach, where three parameters are adjusted (two saturation exponents and iC_8 endpoint relative permeability) are shown in Figure 3 that compares the iC_8 saturation along the column between the experiment and simulations. Both co-current and adjusted simulation results are shown to demonstrate that the co-current relative permeability input cannot accurately predict the migration of iC_8 to the top of the column. The adjusted simulation predicts the migration of iC_8 to the top of the column more accurately than the co-current model (compare the simulations after 5 hours). Finally, the measured and adjusted relative permeabilities (for both approaches) are compared in Figure 4. The relative permeability (especially the iC_8 relative permeability) in both approaches has to decrease significantly to match the experimental observations.

3 LARGE-SCALE CALCULATIONS

Next we present the implications of including a displacement-dependent relative permeability in the simulation of CO_2 injection into an aquifer from a single well. We report the fraction of the injected CO_2 that is trapped as a function of time and compare calculation results with simulations with a fixed relative permeability (independent of flow regime). The model is a 2D reservoir (a 2000×300 m cross-section of a 3D reservoir with a horizontal well), with an average horizontal permeability of 125 mD. Four different vertical permeabilities are used (k_v/k_h=0.1, 0.3, 0.5 and 1). CO_2 is injected from a well located at the bottom of the aquifer with an injection rate of 0.8 Kt/y/m. For further details refer to Javaheri and Jessen (2011). The trapped CO_2 in the co-current mode, counter-current mode and mixed mode (displacement-dependent) are presented in Figure 5. We infer that depending on the ratio of vertical to horizontal permeability and different correlation lengths in four aquifer settings (Figure 6), the trapped CO_2 calculations is increased by more than 20% when displacement-dependent relative permeability is used in the calculations.

4 CONCLUSIONS

While our parameter estimation does not result in a unique set of model parameters, the approach confirms that there is a considerable difference between the input parameters based on co-current observations and the adjusted parameters that provide an improved agreement between calculations and experiments. The reduction in the relative permeability that is required to match the experimental observations can be explained, in part, by the viscous effects at the brine/iC_8 interfaces. This viscous effect changes the velocity profile during counter-current flow, and therefore, the mobility of both phases is reduced relative to the co-current flow setting, where the relative permeabilities are measured.

This study can be applied to the simulation of CO_2 injection into saline aquifers where flow regime is different in vertical and horizontal directions (Javaheri & Jessen, 2011). The results of the experiment show that the mobility of the fluids is reduced in the counter-current flow setting as compared to the co-current flow setting. Applying the results of this study (as well as previous studies) to the analysis of CO_2 migration in aquifers, we infer that the mobility of CO_2 is different between horizontal migration (dominated by co-current flow) and vertical migration (dominated by counter-current flow). Therefore, we propose that it is necessary to use a displacement-dependent representation of relative permeability in the simulation of CO_2 injection into saline aquifers to model the migration of CO_2 accurately. This kind of relative permeability for the migration of CO_2 predicts that more fraction of CO_2 is trapped.

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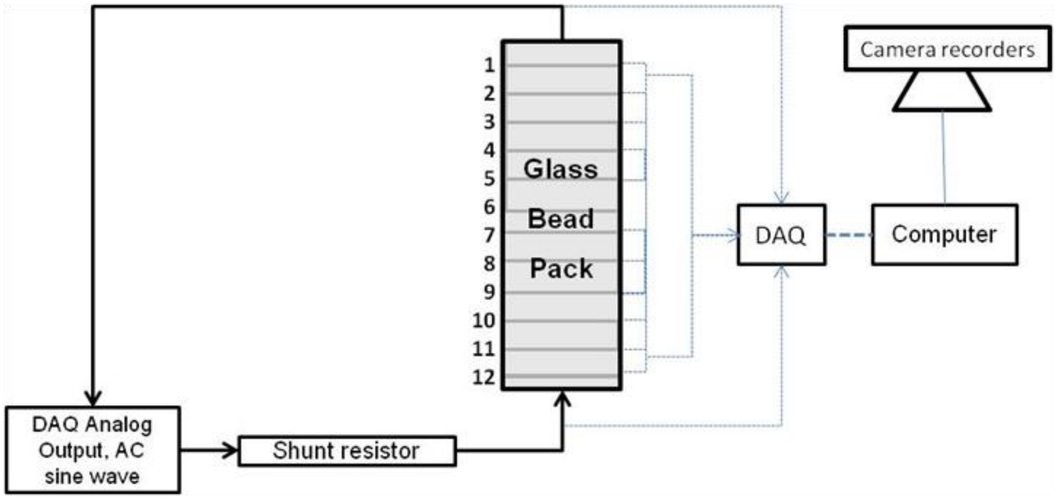

Figure 1. Schematic diagram of the experimental setup for segregation experiment

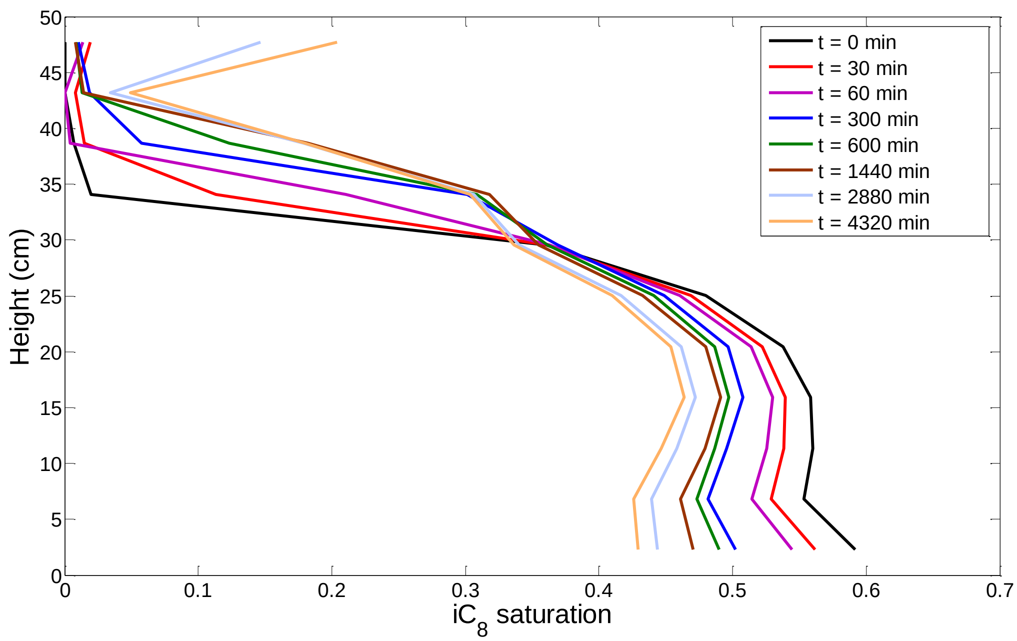

Figure 2. Saturation profiles of iC_8 in the column at various times

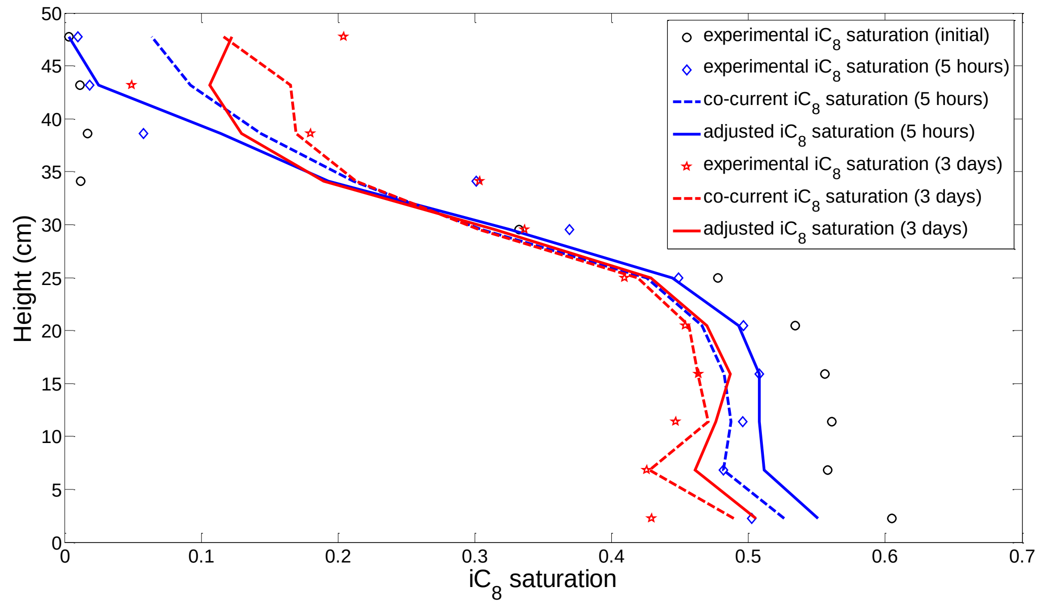

Figure 3. Comparison of experiment and simulation when endpoint non-wetting phase relative permeability can change

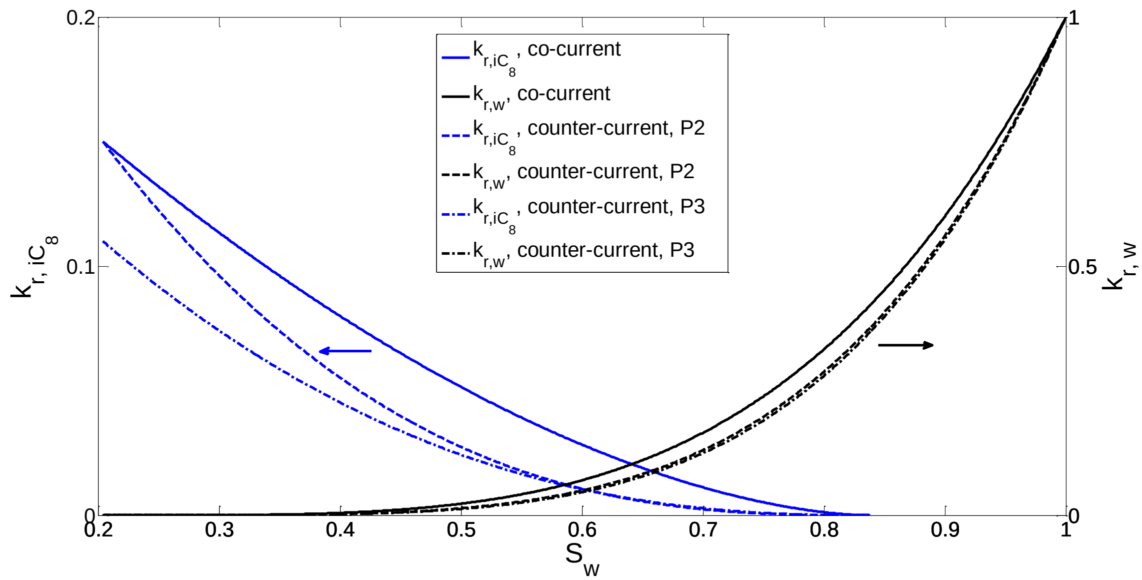

Figure 4. Measured and adjusted relative permeability for wetting (brine) and non-wetting (iC_8) phases

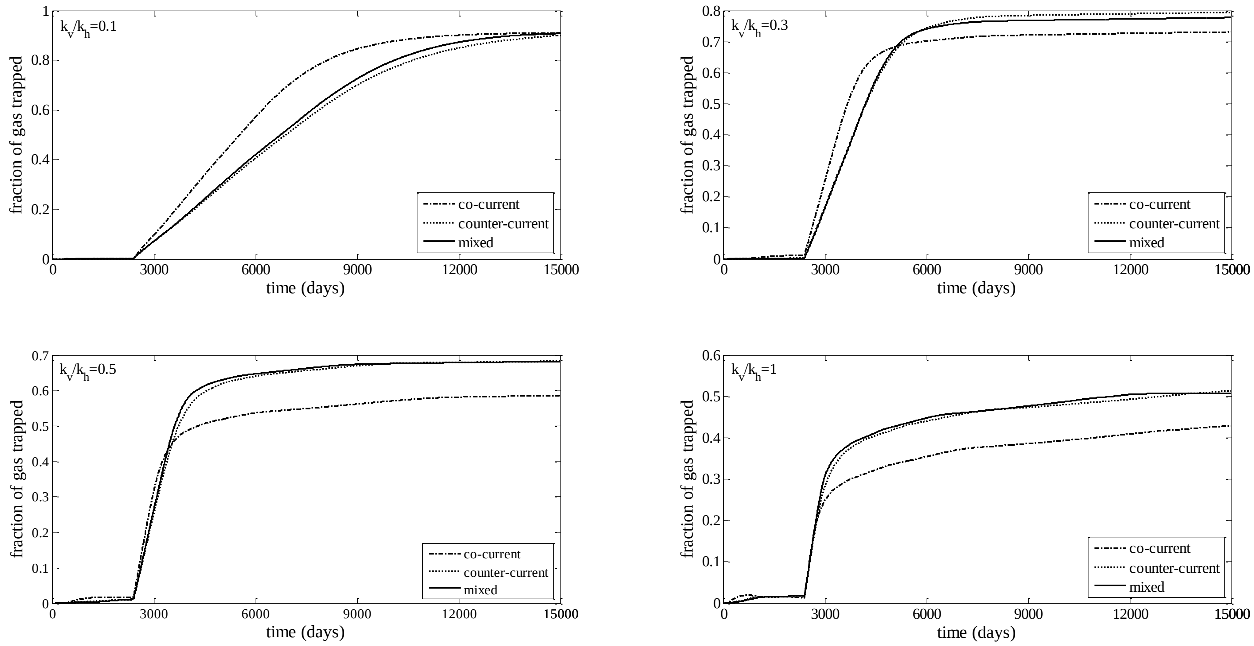

Figure 5. Residual entrapment of gas as a function of time in a heterogeneous aquifer (short correlation length)

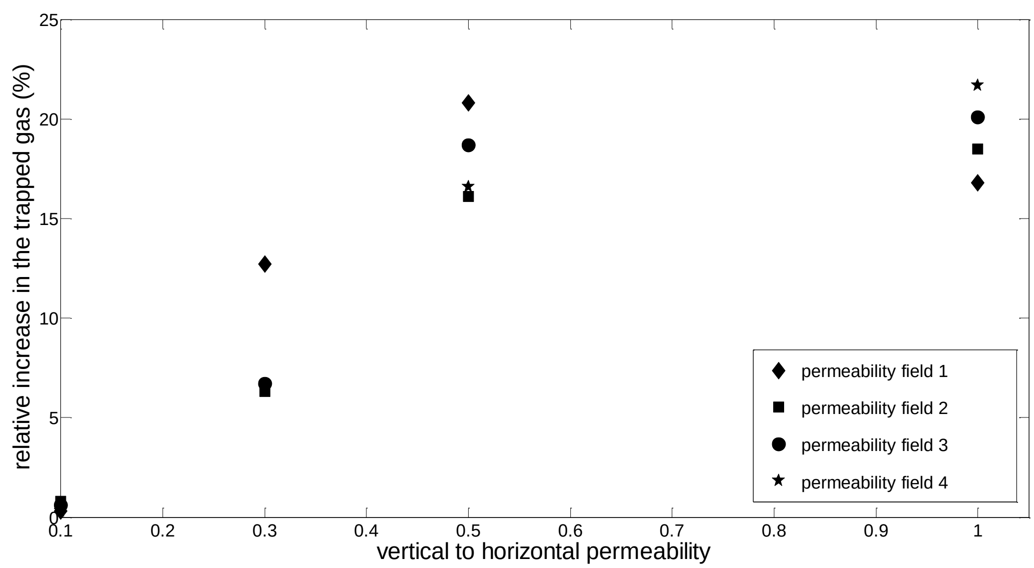

Figure 6. Relative change in the calculated residual entrapment of CO_2 between the co-current flow model and the mixed-flow model