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Relative permeability and non-wetting phase plume migration in vertical counter-current flow settings

Mohammad Javaheri, Dalad Nattwongasem, Kristian Jessen*

Department of Chemical Engineering and Materials Sciences, University of Southern California, Los Angeles, CA 90089, United States

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ABSTRACT

In this work, we investigate the impact of co-current to counter-current flow reversals on the migration dynamics of a non-wetting phase plume in a porous medium. The presented results and observations have direct application to CO_2 injection into saline aquifers where a less dense CO_2-rich plume migrates during and following the injection period. Counter-current gravity segregation experiments were performed in a vertical glass-bead pack with brine and iC_8 as analog fluids to mimic the behavior of a CO_2/brine system of relevance to CO_2 sequestration processes. Four-electrode resistivity measurements were used to monitor the migration of the non-wetting phase (iC_8) by relating the resistivity index (RI) to the brine saturation. The observations are compared with numerical calculations to demonstrate that standard co-current relative permeability measurements are inadequate to reproduce the experimental observations. A reduction in the relative permeability of both phases, in particular for the non-wetting phase, is required to improve the agreement between experimental observations and numerical calculations. Numerical calculations based on co-current input data predicts a much faster migration of the non-wetting phase to the top of the column than what is observed in the segregation experiments. Our findings demonstrate that counter-current flow affects the phase's mobilities, because of interfacial coupling, and should therefore be considered in the modeling of injection/storage of CO_2 in saline aquifers: simulation of CO_2/brine dynamics based on co-current relative permeability measurements is likely to render estimates of migration time/distance in significant error.

1. Introduction

Increased concentration of CO_2 in the earth's atmosphere has initiated a wide range of efforts to reduce the emissions as well as to research/implement capture and sequestration strategies. Deep saline aquifers with an impermeable cap-rock provide potential sites for long-term storage of large amounts of CO_2. Accurate modeling/simulation of the CO_2 distribution over time is required to assess the storage capacity of a given aquifer and to predict the CO_2 migration paths (and time scales) that, in turn, will play an important role in monitoring, verification and risk assessment work flows.

The migration of CO_2 after injection into an aquifer is governed by multiphase flow phenomena in porous media. Reservoir parameters (such as pressure, temperature and absolute permeability) are not the only factors that affect the paths and time scale for CO_2 migration. Saturation functions, such as relative permeability and capillarity, are also important in dictating feasible injection rates and subsequent plume migration (Juanes et al., 2006; Burton et al., 2009; Saadatpoor et al., 2010).

Relative permeability and the parameters that affect it have been researched extensively, especially in the petroleum industry (Honarpour et al., 1986). In the context of CO_2/brine systems, Flett et al. (2004) and Juanes et al. (2006) demonstrated that hysteresis in relevant saturation functions can have a significant impact on the long-term immobilization of CO_2. Bennion and Bachu (2008, 2010) summarized the characteristics of co-current drainage and imbibition relative permeabilities of CO_2/brine and H_2S/brine systems for various rock types. Krevor et al. (2012) measured the relative permeability of four rock samples and confirmed that the residual/trapped CO_2 saturation of all four samples depend on the maximum CO_2 saturation before imbibition.

The relationship between the initial and residual non-wetting phase saturation of CO_2 in saline aquifers was investigated by Pentland et al. (2010) and Al Mansoori et al. (2010). To represent CO_2 at aquifer conditions, they performed a series of laboratory experiments using analog fluids (brine/*n*-octane) in unconsolidated sand packs. Results obtained from analysis of the equilibrium (final) saturation distribution indicate that the trapped non-wetting phase saturation increases linearly with its initial saturation up to a

* Corresponding author. Tel.: +1 213 740 2073; fax: +1 213 740 0324.
E-mail address: jessen@usc.edu (K. Jessen).

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Nomenclature

c	coefficients of the generalized Darcy's equation
f	objective function
g	gravitational acceleration [$\mathrm{L\,T^{-2}}$]
K	Darcy permeability [$\mathrm{L^2}$]
k_r	relative permeability
k_{re}	endpoint relative permeability of the non-wetting phase
l	length of the glass bead column [L]
p	pressure [$\mathrm{M\,L^{-1}\,T^{-2}}$]
Q	flow rate [$\mathrm{L^3\,T^{-1}}$]
r	internal radius of the glass bead column [L]
r_1	contact radius of wetting and non-wetting phases inside a pore [L]
R	pore radius [L]
R	resistivity [$\mathrm{M\,L^2\,T^{-3}\,A^{-2}}$]
$\bar{s}$	dimensionless saturation
S	saturation
v	Darcy velocity [$\mathrm{L\,T^{-1}}$]
V	volume [$\mathrm{L^3}$]
w	weight factor
z	vertical distance [L]

Greek letters

α, β	relative permeability exponents
$\in$	adjusting parameter for saturation objective function
μ	viscosity [$\mathrm{ML^{-1}\,T^{-1}}$]
ρ	density [$\mathrm{ML^{-3}}$]
ϕ	porosity
∇	gradient

Subscripts

sim	simulation
exp	experiment
j	segments along the column
nw	non-wetting
r	residual
t	total
w	wetting
wc	connate water

Superscripts

n	cementation factor

certain trapped saturation and remains constant as the initial saturation increases beyond this point.

Numerical simulators that are currently used in the modeling of CO_2 injection into saline aquifers assume, implicitly, that saturation functions (e.g. relative permeability) do not depend on flow direction. However, the migration of the injected CO_2 in an aquifer occurs in both co- and counter-current flow settings. The lateral flow of CO_2 and brine is in the same direction away from the injection zone (co-current flow), while the upward flow of CO_2 due to buoyancy and the corresponding downward flow of brine are in opposite directions (counter-current flow). The vertical counter-current flow is especially dominant when the viscous force is smaller than gravity (e.g. after injection). The difference between co- and counter-current flow and its impact on CO_2 migration and entrapment was addressed through numerical calculations by Javaheri and Jessen (2011). They applied the dependency of flow directions on relative permeability 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.

The assumption that the relative permeability is the same in co- and counter-current flows is not supported by other experimental and theoretical studies that have demonstrated a reduction in the relative permeability functions of counter-current flows relative to the co-current values (Lelievre, 1966; Bentsen and Manai, 1993). These experiments were performed with two-phase brine/oil fluid systems in the context of oil recovery operations. To the best of our knowledge, no publicly available data exists that demonstrate the difference between co-current and counter-current relative permeability in CO_2/brine systems.

Indirect measurements of counter-current relative permeability have also been presented that support the idea of a reduction in relative permeability for counter-current flow settings (Bourbiaux and Kalaydjian, 1990; Langaas and Papatzacos, 2001; Li et al., 2005a). Theoretical studies (de la Cruz and Spanos, 1983; Kalaydjian, 1987; Whitaker, 1986) show that multiphase flow in porous media is affected by viscous effect at the fluid/fluid interface. Spanos et al. (1986) and Eastwood and Spanos (1991) demonstrated that the relative permeability does not only depend on the saturation (or saturation history) but also on the flow direction. Theoretical studies of two-phase flow in porous media using generalized permeabilities (de la Cruz and Spanos, 1983; Spanos et al., 1986; Whitaker, 1986; Eastwood and Spanos, 1991) can be used to explain the effect of drag on fluid mobility. These studies are based on volume averaging of Navier–Stokes equations for porous materials that leads to a general form of Darcy's equation (Li et al., 2005b):

$$\begin{bmatrix} v_w \\ v_n \end{bmatrix} = -\begin{bmatrix} \dfrac{Kk_{r,ww}}{\mu_w} & \dfrac{Kk_{r,wn}}{\mu_n} \\ \dfrac{Kk_{r,nw}}{\mu_w} & \dfrac{Kk_{r,nn}}{\mu_n} \end{bmatrix} \begin{bmatrix} \nabla p_w - p_w g \\ \nabla p_n - p_n g \end{bmatrix} \tag{1}$$

where K is the absolute permeability, $k_{r,ij}$ are the generalized relative permeabilities, μ is the viscosity, p is the pressure, ρ is the density and subscripts w and n refer to wetting and non-wetting phases. The diagonal terms account for flow of the two phases in the absence of the other phase, while the off-diagonal terms represent the coupling (or interaction) of the two phases during flow. Muskat's extension of Darcy's equation is obtained by ignoring the off-diagonal terms in Eq. (1) and do, accordingly, not represent the influence of the flow direction on the phase permeabilities explicitly.

Kalaydjian (1990) estimated the generalized phase permeabilities for flow in capillary tubes as well as from co-current and counter-current flow experiments in real porous materials and demonstrated that the off-diagonal terms are smaller in real porous materials than for flow in capillary tubes. However, even in a realistic porous material, the off-diagonal terms can assume values that are approximately 20% of the diagonal terms and should hence not be ignored. A similar observation was presented by Li et al. (2005b) based on Lattice–Boltzmann modeling of flow in 3D images of porous media.

Although the effects of viscous coupling in two-phase flow are well documented in the litterature, commercial and research simulators do commonly not allow for the use of a relative permeability tensor as dictated by Eq. (1). Furthermore, standardized experimental protocols for measurement of the generalized relative permeabilities have to our best knowledge not been established. Accordingly, most flow simulations in subsurface settings are based on implementations of Muskat's extension of Darcy's equation that do not destinguish between co-current and counter-current flow.