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An improved simplified analytical model for CO_2 plume movement and pressure buildup in deep saline formations

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ABSTRACT

This study presents an evaluation of the three-region simplified analytical model of Burton et al. (2008) based on fractional flow and steady-state pressure gradient considerations for predicting CO_2 plume movement and pressure buildup in deep saline formations. The saturation and pressure profiles as well as injection-well pressure buildup predicted by the analytical model are benchmarked against those from the numerical simulator STOMP to suggest improvements as needed for the simplified modeling approach. Good agreement is observed between the two approaches for predicting CO_2 saturations. However, using a two-phase mobility based on average saturations as proposed by Burton et al. results in under-prediction of the pressure buildup. An improved method is presented for calculating a representative two-phase mobility based on the actual mobility profile in the two-phase region. This leads to a much better match between predictions of STOMP and the three-region model for both formation pressure profile and injection-well pressure buildup.

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1. Introduction and scope

CO_2 injection into the sub-surface is emerging as a viable technology for reducing anthropogenic CO_2 emissions into the atmosphere (Benson and Cook, 2005). Deep saline formations provide a particularly attractive target for this purpose, with potential storage capacity in such systems in North America estimated to be of the order of 3400 billion tons of CO_2, or the equivalent of emissions from hundreds of years (DOE/NETL, 2010). When large amounts of CO_2 are sequestered underground, excess pressure buildup in the storage formations and caprock is an associated risk, along with potential plume movement beyond the injected domain. In this context, simplified analytical or semi-analytical modeling tools can be valuable assets in preliminary CO_2 injection project screening and implementation phases. Such tools have minimal data and computational requirements compared to detailed multi-physics numerical simulators.

In recent years, there has been significant progress in developing simplified models for plume tracking and predicting formation overpressure. These models generally build on the work of Woods and Comer (1962) for obtaining saturation and pressure distributions in a radial gas-storage formation. The Woods–Comer model consists of: (1) a growing gas bubble, where two-phase flow occurs, and (2) the surrounding aquifer, with unsteady-state single-phase flow. A rapid semi-analytic computational scheme was proposed to solve for pressure and saturation as a function of time. Among the earliest efforts to develop a semi-analytical model specifically for the problem of CO_2 injection in deep saline formations was by Saripalli and McGrail (2002). They developed equations describing the radial injection of supercritical CO_2 into saline formations and showed that the formulation based on Buckley–Leverett theory of immiscible displacement (Lake, 1989) adequately describes the injection and migration of CO_2 around the well. Saripalli and McGrail did not explicitly discuss the issue of pressure buildup within the reservoir or at the injection well. Benson (2003) developed a pressure buildup solution based on the assumptions of Buckley–Leverett type displacement, vertical equilibrium, a homogeneous storage formation, and negligible capillary pressure. The solution consists of two components: (1) steady-state pressure buildup behind the CO_2 front and (2) transient pressure buildup outside of the front. Benson's model provides both pressure and saturation solutions, although it does not take into account the possibility of brine dry-out (and the creation of a dry CO_2-filled region) near the wellbore because of mutual solubility effects.

Noh et al. (2007) developed the modified Buckley–Leverett theory accounting for mutual solubility of CO_2 and brine, which explains the saturation evolution of the CO_2 in the formation. According to this solution two distinct fronts develop when CO_2 is injected (the drying front and the Buckley–Leverett front) separating the storage formation into three regions (the single-phase CO_2 region, the two-phase region comprising both brine and CO_2 phases, and the single-phase brine region). Burton et al. (2008)

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Nomenclature

a	coefficient in the linear relation
b	coefficient in the linear relation
A	term in Eq. (B5)
B	term in Eq. (B7)
c_f	formation compressibility, $M^{-1}\,L^{-1}\,T^2$ (Pa^{-1})
c_w	brine compressibility, $M^{-1}\,L^{-1}\,T^2$ (Pa^{-1})
$C^{dry}_{CO_2,g}$	concentration of CO_2 in the gas phase in the dry region, $M\,L^{-3}$ ($kg\,m^{-3}$)
$C^{BL}_{CO_2,g}$	concentration of CO_2 in the gas phase in the Buckley–Leverett region, $M\,L^{-3}$ ($kg\,m^{-3}$)
$C^{BL}_{CO_2,a}$	concentration of CO_2 in the aqueous phase in the Buckley–Leverett region, $M\,L^{-3}$ ($kg\,m^{-3}$)
$D_{BL\rightarrow dry}$	retardation factor for the drying front
$D_{brine\rightarrow BL}$	retardation factor for the Buckley–Leverett front
$f_{g,dry}$	fractional flow of gas immediately downstream of the drying front
$f_{g,BL}$	fraction flow of gas immediately upstream of the Buckley–Leverett front
H	formation thickness, L (m)
$I_{2\varphi}$	integral in the calculation of pressure buildup in two-phase region
k	absolute formation permeability, L^2 (m^2)
k_{rg}	relative permeability of gas
k_{rw}	relative permeability of brine
M_g	mass rate of CO_2 injected, MT^{-1} ($kg\,s^{-1}$)
M_{dry}	mobility of dry region, $M^{-1}\,L\,T\,(Pa\,s)^{-1}$
M_{brine}	mobility of brine region, $M^{-1}\,L\,T\,(Pa\,s)^{-1}$
M_{BL}	mobility of two-phase region calculated at $S_{g,avg}$, $M^{-1}\,L\,T\,(Pa\,s)^{-1}$
$M_{2\varphi,w}$	mobility of two-phase region calculated at S_{gw}, $M^{-1}\,L\,T\,(Pa\,s)^{-1}$
$M_{2\varphi}(r)$	mobility of two-phase region as a function of radial distance r, $M^{-1}\,L\,T\,(Pa\,s)^{-1}$
$M_{2\varphi,eff}$	effective mobility of two-phase region based on linear relation between $1/M_{2\varphi}(r)$ and r, $M^{-1}\,L\,T\,(Pa\,s)^{-1}$
$M_{2\varphi,dry+}$	mobility of two-phase region immediately downstream of drying front, $M^{-1}\,L\,T\,(Pa\,s)^{-1}$
$M_{2\varphi,BL}$	mobility of two-phase region immediately upstream of Buckley–Leverett front, $M^{-1}\,L\,T\,(Pa\,s)^{-1}$
ΔP_{tot}	total pressure buildup at the well, $M\,L\,T^{-2}$ (Pa)
$\Delta P_{2\varphi}$	pressure buildup in the two-phase region, $M\,L\,T^{-2}$ (Pa)
q_g	volumetric flow rate of CO_2, $L^3\,T^{-1}$ ($m^3\,s^{-1}$)
q_w	volumetric flow rate of brine, $L^3\,T^{-1}$ ($m^3\,s^{-1}$)
q	volumetric flow rate of CO_2, $L^3\,T^{-1}$ ($m^3\,s^{-1}$)
r	radial distance, L (m)
$r_{2\phi,avg}$	radial distance at which $S_{g,avg}$ occurs, L (m)
r_{BL}	Buckley–Leverett front position, L (m)
r_{dry}	drying front position, L (m)
r_e	formation drainage radius, L (m)
r_w	wellbore radius, L (m)
r_{inv}	radius of investigation, L (m)
$S_{g,dry}$	gas saturation immediately downstream of the drying front
$S_{g,BL}$	gas saturation immediately upstream of the Buckley–Leverett front
$S_{g,avg}$	average gas saturation in the two-phase region
S_{gw}	average gas saturation behind the two-phase front, from Welge tangent construction
t	time, T (s)
$v_{D,dry}$	dimensionless velocity of drying front
$v_{D,BL}$	dimensionless velocity of Buckley–Leverett front
φ	porosity
μ_g	gas viscosity, $M\,L^{-1}\,T^{-1}$ (Pa s)
μ_w	brine viscosity, $M\,L^{-1}\,T^{-1}$ (Pa s)
ρ_g	gas density, ML^{-3} ($kg\,m^{-3}$)

developed the pressure solution for the three-region model of Noh et al. (2007), for a constant pressure injection scenario, by calculating the pressure gradients at any instant, under the assumption of steady-state conditions for each value of the time-varying flow rate.

Nordbotten et al. (2005) developed a solution for space-time evolution of the CO_2 plume based on arguments of energy minimization. This solution reduces to a simple radial form of the Buckley–Leverett solution under viscous-dominated conditions with linear relative permeabilities. In their work, they show that there are two different time scales associated with the problem of supercritical CO_2 injection into a deep saline formation. The first is the transient pressure pulse that propagates at through the brine at a rate proportional to $\sqrt{t}$, which could be considered to be a representative outer boundary. The second time scale corresponds to the advancing CO_2 front, which for cases where buoyancy is negligible is also proportional to $\sqrt{t}$. CO_2 and brine are assumed to be separated by a sharp interface, with the vertical location of the interface being a function of both time and radial distance from the injection well. Mathias et al. (2008) built upon the Nordbotten et al. model, and prescribed a solution for the pressure distribution in the formation. A similarity solution was derived using the method of matched asymptotic expansions by solving the two coupled ordinary differential equations for continuity and Darcy's law.

The objective of this work is to evaluate the three-region model of Burton et al. (2008) by comparing its performance with results from the numerical simulator STOMP (White and Oostrom, 2006) which employs full physics of the CO_2-brine system. Specifically, our goals are: (a) to identify any limitations of the simplified modeling approach in predictions of CO_2 plume extent and formation pressure buildup, and (2) to propose modifications as needed for the model to achieve an improvement in performance. The rest of the paper is organized as follows. We first introduce and describe in brief the theory behind the three-region model. Next, for two different test problems, we compare the results of the model with corresponding results from STOMP and propose appropriate improvements to obtain a better match. Pressure buildup at the well and pressure and saturation profiles in the formation are used as performance metrics for this benchmarking exercise. Finally, we provide some concluding remarks and summarize the main findings from this study.

2. Description of the three-region model

The three-region model as described in Burton et al. (2008) is based on fractional flow theory accounting for inter-phase mass transfer during semi-miscible displacement (Noh et al., 2007). Fig. 1 shows a conceptualization of the CO_2 saturation profile and pressure profile following injection of supercritical CO_2 into a deep saline formation that leads to the development of three distinct regions, i.e., a single-phase CO_2 region nearest to the well, a two-phase region in between, and a single-phase brine region farther away from the well. These regions are delineated by two sharp fronts: (1) the drying front or the trailing shock, which separates the single-phase CO_2 region from the two-phase region

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