

Capillary effects increase salt precipitation during CO₂ injection in saline formations

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Extended abstract

Saline formations are attractive for CO₂ storage because high salinity renders their associated brines undesirable for future water resources. However, high salinity can lead to dissolved salt precipitating around injection wells resulting in significant loss of injectivity. Mathematical analysis reveals that the process is self-similar and strongly controlled by a dimensionless capillary number.

Consider a fluid mixture of two mutually soluble components: $i = 1$ and 2 . The two components can partition into a non-wetting and wetting phase, denoted hereafter as $j = 1$ and 2 , respectively. The densities of the two components are assumed to be constant properties. Let C_i [-] be the volume fraction of component i for the combined fluid mixture, defined by (Orr, 2007)

$$C_i = \sum_{j=1}^2 c_{ij} S_j, \quad C_1 \in (c_{12}, c_{11}) \quad (1)$$

where c_{ij} [-] is the constant equilibrium volume fraction of component i in phase j and S_j [-] is the volume fraction of phase j for the combined fluid mixture.

A homogenous, isotropic, cylindrical and porous reservoir is invoked with a thickness of H [L] and an infinite radial extent. The reservoir pore-space is initially filled with a uniform fluid mixture of $C_i = C_{iI}$. A fluid mixture of volume fraction, $C_i = C_{i0}$, is injected at a constant rate of Q_0 [L³T⁻¹] into the center of the reservoir via a fully penetrating injection well of infinitesimally small radius. Fluid flow is assumed to be one-dimensional such that the problem reduces to the following one-dimensional radially symmetric conservation equation

$$\frac{\partial C_i}{\partial \tau} + \frac{\partial F_i}{\partial \xi} = 0 \quad (2)$$

where

$$F_i = \alpha_i + 2\beta_i \xi \frac{\partial C_1}{\partial \xi} \quad (3)$$

$$\tau = \frac{Q_0 t}{\pi \phi H r_e^2} \quad (4)$$

$$\xi = \frac{r^2}{r_e^2} \quad (5)$$

and

$$\alpha_i = \begin{cases} C_i, & C_1 \notin [c_{12}, c_{11}] \\ \sum_{j=1}^2 c_{ij} f_j & C_1 \in (c_{12}, c_{11}) \end{cases} \quad (6)$$

$$\beta_i = \begin{cases} 0, & C_1 \notin [c_{12}, c_{11}] \\ \sum_{j=1}^2 (-1)^j c_{ij} G & C_1 \in (c_{12}, c_{11}) \end{cases} \quad (7)$$

where

$$f_j = \frac{k_{rj}}{\mu_j} \left(\sum_{j=1}^2 \frac{k_{rj}}{\mu_j} \right)^{-1} \quad (8)$$

$$G = \kappa f_2 k_{r1} \frac{\partial \psi}{\partial C_1} \quad (9)$$

and r [L] is radial distance from the injection well, r_e [L] is an arbitrary reference length, t [T] is time, ϕ [-] is the reservoir porosity, k_{rj} [-] is the relative permeability of phase j , μ_j [ML⁻¹T⁻¹] is the dynamic viscosity of phase j , k [L²] is the reservoir permeability, and κ [-] and ψ [-] are a dimensionless capillary number and dimensionless capillary pressure, respectively, found from

$$\kappa = \frac{2\pi H k P_{c0}}{Q_0 \mu_1} \quad (10)$$

and

$$\psi = \frac{P_c}{P_{c0}} \quad (11)$$

where P_c [ML⁻¹T⁻²] is the capillary pressure (the difference between the non-wetting and wetting phase pressures) and P_{c0} [ML⁻¹T⁻²] is a reference ‘‘air-entry’’ pressure for the porous medium of concern.

When $\kappa = 0$, the above problem reduces to the hyperbolic problem solved by Orr (2007) using the method of characteristics. When $c_{11} = 1$ and $c_{12} = 0$, the above problem reduces to the immiscible two-phase flow problem with capillary pressure, previously solved by McWhorter and Sunda (1990) and Bjornara and Mathias (2013). The G term in Eq. (9) is analogous to the G term in Eq. (16) of Bjornara and Mathias (2013). The reader is referred to Bjornara and Mathias (2013) for further guidance with regards to the derivation of Eq. (9).

The above problem is shown to be self-similar and reduced to a non-linear ordinary differential equation. Following Bjornara and Mathias (2013), this is then solved using a pseudospectral method. Low injection rates lead to high capillary numbers, which in turn are found to lead to large volume fractions of precipitated salt around the injection well. For example, reducing a CO₂ injection rate from 15 kg s⁻¹ to 0.9 kg s⁻¹ can lead to a tenfold increase in the volume fraction of precipitated salt around the injection well.

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References

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