Analytical Solutions For Mixed Gas Injection in CO_2 Sequestration and Enhanced Coalbed Methane Recovery

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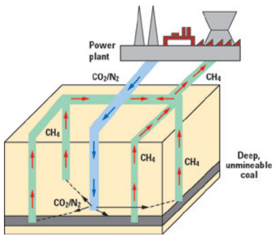
Coal Reservoirs

Motivation

Injection of CO_2 into deep unminable coal seams is an option for geological sequestration of CO_2. In these systems, adsorption of gas on the internal surfaces of the coal is the storage mechanism. In many of these reservoirs, large amounts of CH_4 are adsorbed onto the coal. CO_2 is preferentially adsorbed compared to CH_4, which offers the possibility of desorption and increased recovery of CH_4 from coal without lowering pressure in the coal bed. The interaction between CO_2 sequestration and enhanced CH_4 production make coal reservoirs interesting candidates for sequestration.



Concept of integrated sequestration and electricity generation scheme (SPE 71749). Flue gas sequestered from gas burning power plant are used to enhance CH_4 recovery for power generation.

Understanding the complex interplay between adsorption, phase behaviour and convection is important in creating efficient and physically accurate techniques for predicting the fate of injected CO_2 in the subsurface.

Mixed Gas Injection

Flue gases from industrial power generation activities are significant point sources of anthropogenic CO_2. In some settings, it is expensive to obtain high purity CO_2 streams, and it is possible that mixtures of CO_2, N_2 and sulphur oxides may be injected. However, additional costs associated with compression of impurities may negate the expense of separation prior to injection. Understanding the effect of these other gas species in the injection gas stream on recovery efficiency and timing is important for engineering sequestration projects that maximise recovery and CO_2 storage while minimising costs.

Mathematical Model

For convection-dominated flows, 1D analytical solutions can be used to model multicomponent, multiphase flow in coal reservoirs.

$$\frac{\partial G_i}{\partial \tau} + \frac{\partial H_i}{\partial \xi} = 0 \qquad z_i(\xi,0) = \begin{cases} z_i^{inj} & \xi = 0 \\ z_i^{init} & \xi > 0 \end{cases}$$

$$i = 1 \ldots N_c \quad j = 1 \ldots N_p \qquad u(\xi = 0) = 1 \quad \tau > 0$$

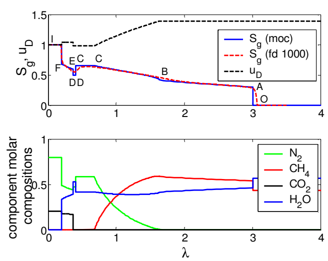
$$G_i = \sum_{i=1}^{N_c} x_{i,j}\rho_j S_j + \frac{1-\phi}{\phi} a_i \qquad H_i = u_D \sum_{i=1}^{N_c} x_{i,j}\rho_j f_j$$

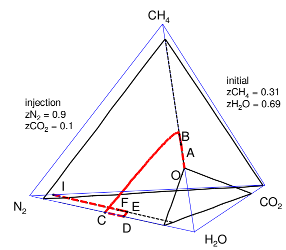
For a multicomponent system, a system of coupled transport equations results, which can be decomposed into an eigenvalue problem. In such an analysis, the eigenvalues represent wave velocities at which the composition propagates. The corresponding eigenvectors represent the directions of variation in composition space. Solutions connecting initial and injection conditions can consist of segments of continuous variation, discontinuous variation and zones of constant state. Unique physical solutions are constructed by applying a velocity rule and entropy conditions.

Mixed Gas Injection Solutions

Solution structures for injection gas mixtures have shock and spreading features of pure gas injection solutions (Seto *et al.*, 2006). More strongly adsorbing gases displace less strongly adsorbing gases through a self sharpening displacement or shock (CO_2 displacing CH_4). Less strongly adsorbing gases displace more strongly adsorbing gases by means of a continuous variation or rarefaction (N_2 displacing CH_4).

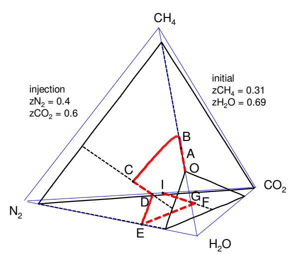
N_2-Rich Injection Gas





Relative to CH_4, N_2 is a less strongly adsorbing gas while CO_2 is more strongly adsorbing. Preferential adsorption of CO_2 from the flowing phase occurs as the displacement propagates through the coal. The injection gas is separated into a slow moving bank of CO_2 and faster moving bank of N_2. CO_2 is isolated from CH_4 production. As the N_2 bank propagates through the coal, N_2 desorbs CH_4 by reducing the partial pressure of CH_4. This results in a mixture of CH_4 and N_2 at the outlet, requiring separation of N_2 from the production stream.

CO_2-Rich Injection Gas

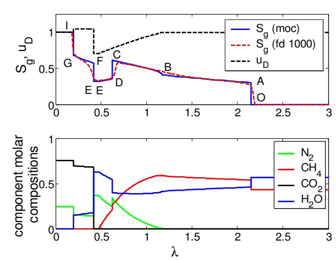


For CO_2-rich injection gas mixtures, a large fraction of injection gas is removed from the flowing phase, forcing a new composition route connecting initial and injection states.

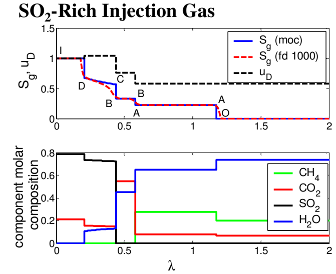
Once CO_2 is adsorbed onto the coal, gas phase saturations created by the remaining N_2 in the injection gas is sufficiently low that it is no longer the preferential flowing phase, resulting in a slow moving intermediate N_2-H_2O binary mixture.

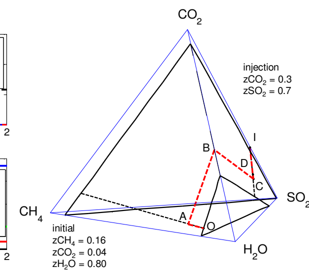
As N_2 propagates through the coal and desorbs CH_4, gas saturation rapidly increases to a maximum by means of a shock, making gas the preferentially flowing phase.

The volume increase from desorption of CH_4 is no longer sufficient to offset the volume decrease due to CO_2 adsorption, resulting in a slower displacement than the N_2-rich injection displacement.



SO_2-Rich Injection Gas

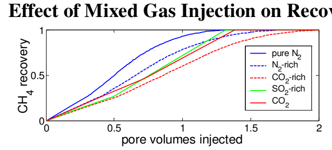




Both SO_2 and CO_2 are preferentially adsorbed relatively to CH_4. Displacement of CH_4 occurs through a series of shocks. Injection gas components are separated into banks based on their relative adsorption strength. The produced CH_4 is free of SO_2.

A significant decrease in local flow velocity occurs due to removal of all injection gas components from the flowing phase as they adsorb onto the coal surface, resulting in the latest breakthrough time for the injection gas scenarios presented.

Effect of Mixed Gas Injection on Recovery



Efficient recovery of CH_4 is achieved for both pure and mixed injection gas compositions. Total recovery times for mixed gas injection are comparable to those for pure gas injection.

The volume increase to the flowing phase caused by CH_4 desorption results in faster initial recovery in N_2-rich displacements, while the volume decrease caused by adsorption of CO_2 and SO_2 in acid gas injection mixtures results in slower initial recovery.

Conclusions and Summary

- Preferential adsorption of gases on the coal surface and differential partitioning of components between gas and liquid phases results in chromatographic separation of injection gas mixtures as they propagate through the reservoir. More strongly adsorbing, less volatile components travel through the coal slower than less strongly adsorbing, more volatile components.
- Efficient recovery of CH_4 is achieved for both pure gas injection and flue gas mixtures. Faster recovery is achieved with N_2-rich gases, but requires separation of the produced gas stream and compression of large volumes of N_2. Later breakthrough times are achieved with CO_2-rich injection gas.
- Injection gas mixture can be optimised to align with the goal of the project, be it accelerating CH_4 recovery or delaying CO_2 breakthrough.

References

Seto, C. J., Jessen, K., Orr, F. M., Jr. "A Four-Component, Two-Phase Flow Model for CO_2 Storage and Enhanced Coalbed Methane Recovery," SPE 102376, presented at the 2006 SPE Annual Technical Conference and Exhibition, San Antonio, TX., 24-27 September 2006.

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