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An Investigation of Different Borehole Layouts for Carbon Sequestration in Coalbeds

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ABSTRACT

This paper investigates how the layout of injection boreholes can influence the effectiveness of carbon sequestration and enhanced methane recovery in a coalbed. A numerical model for high pressure gas transport with kinetically-controlled adsorption and desorption is used to predict the carbon dioxide storage and methane displacement behaviour in two simulation scenarios. In the first scenario, carbon dioxide is injected using a single borehole located at the centre of the domain, whereas the second scenario considers a four-spot layout for the injection boreholes. Both simulations consider the same arrangement of boreholes for the recovery of the displaced methane. It is demonstrated that the four-spot layout increases the amounts of carbon dioxide stored and methane recovered in the simulation period, although the increase in carbon dioxide storage is somewhat offset by interference between the injection boreholes.

Keywords: *carbon sequestration; coalbed methane recovery; borehole layout; coupled modelling*

1. Introduction

Geological carbon sequestration is set to play an integral role in the transition to the low carbon future by preventing the atmospheric emission of carbon dioxide generated in the energy and industry sectors. Coalbeds are among the candidate storage reservoirs since coal typically has a strong preference to retain substantial amounts of gas in the adsorbed phase [1]. Moreover, the injection of carbon dioxide into a coalbed may also serve to enhance the displacement and recovery of in situ methane to provide a supply of unconventional gas.

Gas transport, storage and displacement in coal involves seepage flows through the network of naturally-occurring fractures as well as diffusive transport, adsorption and desorption in the porous rock matrix [1,2]. The injection and recovery of gas changes the effective stress and subsequently causes physico-mechanical coal deformation [2]. In addition, chemo-mechanical deformation caused by the adsorption-induced swelling or desorption-induced shrinking of the coal solids can have a considerable feedback on the gas transport behaviour. The coal-gas interactions described play an important role in governing carbon dioxide storage and methane displacement in coalbeds. However, it is also important to understand how the application of the technology is influenced by some of the key engineering factors involved. The present work therefore investigates the role of the injection borehole layout in determining the performance of carbon sequestration in coal with enhanced methane recovery.

The investigation is carried out by applying the reactive gas transport module of the coupled thermo-hydro-chemo-mechanical (THCM) model COMPASS. An overview of the theoretical formulation for reactive gas transport and its numerical implementation is provided below, followed by a description and discussion of the numerical simulations conducted as part of this work.

2. Theoretical formulation

The coupled THCM model, developed by Thomas and co-workers [e.g. 3], forms the basis for the numerical simulations presented in this work. The model applies a mechanistic approach to solving for heat transfer, moisture and chemical/gas transport, and mechanical behaviour and has been applied to

simulate the reactive transport of multicomponent chemicals and gas in a range of geoenvironmental applications. The application of the gas transport module in this work has been based on the assumption that: i) the coalbed is completely dry, ii) coal is a homogenous, isotropic and elastic material, iii) a single continuum, equivalent continuum approach is valid, and iv) the coalbed is isothermal.

The governing equation describing the reactive transport of the i^{th} gas component can be expressed as:

$$\frac{\partial n c_g^i}{\partial t} + \rho_s \frac{\partial s_g^i}{\partial t} = -\nabla \cdot \left[c_g^i \mathbf{v_g}\right] - \nabla \cdot \left[n \tau_g D_g^i \nabla c_g^i\right] \tag{1}$$

where n is the porosity, c_g^i and s_g^i are the concentrations in the free and adsorbed phases, respectively, t is time, ρ_s is the density of the solid phase, ∇ is the gradient operator, τ_g is the gas tortuosity factor, and D_g^i is the diffusion coefficient. Darcy's law is employed to calculate the bulk gas velocity, $\mathbf{v_g}$, which in combination with the real gas law gives:

$$\mathbf{v_g} = -\frac{K}{\mu_g} \nabla u_g = -\frac{KZRT}{\mu_g} \sum\nolimits_{j=1}^{n_g} \nabla c_g^j \tag{2}$$

where K is the intrinsic permeability, μ_g is the bulk gas viscosity, u_g is the bulk gas pressure, R is the universal gas constant, and T is the temperature. The compressibility factor, Z, is the ratio of the real and ideal molar volumes and expresses deviations of gas compressibility from the ideal gas law.

Gas retention behaviour at the coal surface is included as a kinetically controlled reaction formulated using a first-order kinetics model, giving [4]:

$$\frac{\partial s_g^i}{\partial t} = k_r^i \left(s_{g,\infty}^i - s_g^i\right) \tag{3}$$

where k_r^i is the sorption rate. $s_{g,\infty}^i$ is the adsorbed amount at equilibrium with the free gas phase obtained using the extended Langmuir isotherm model, given by:

$$s_{g,\infty}^i = \frac{n_L^i b_L^i ZRT c_g^i}{1 + ZRT \sum_{j=1}^{n_g} b_L^j c_g^j} \tag{4}$$

where n_L^i is the Langmuir adsorption capacity and b_L^i is the reciprocal of the Langmuir pressure.

Appropriate constitutive relationships have been employed in the model to accurately describe the real gas compressibility and viscosity. The former is included using the Peng and Robinson [5] equation of state (EoS). The gas viscosity is calculated via the dense gas model of Chung et al. [6]. Coal deformation due to effective stress changes and adsorption/desorption-induced matrix swelling/shrinking has been described using the following model by Palmer and Mansoori [7]:

$$\begin{aligned} \frac{K}{K_0} = \left(\frac{n}{n_0}\right)^3 = \Bigg[1 + \frac{1}{n_0 M} \sum\nolimits_{j=1}^{n_g} \left(u_g - u_{g,0}\right) \\ + \frac{1}{n_0}\left(\frac{K}{M} - 1\right) \sum\nolimits_{j=1}^{n_g} \left(\frac{\varepsilon_L^j b_L^j X_g^j u_g}{1 + u_g \sum_{k=1}^{n_g} X_g^k b_L^k} - \frac{\varepsilon_L^j b_L^j X_{g,0}^j u_{g,0}}{1 + u_{g,0} \sum_{k=1}^{n_g} X_{g,0}^k b_L^k} \right) \Bigg]^3 \end{aligned} \tag{5}$$

where the subscript 0 refers to the initial condition, M is the axial modulus, K is the bulk modulus, ε_L^i is the Langmuir volumetric strain, and X_g^i is the free gas mole fraction.

A numerical solution of the governing gas transport equations is achieved by applying the finite element method with Galerkin weighted residuals for spatial discretisation and a mid-interval backward-difference scheme for temporal discretisation. The sequential non-iterative approach (SNIA) is adopted to couple the gas transport and kinetically-controlled adsorption/desorption terms.

3. Problem setup

The simulations have been performed for carbon dioxide injection and methane recovery from a 500 m deep, hypothetically isolated coalbed of 200 m long by 200 m wide and 1 m thick. Two arrangements were considered for the injection of carbon dioxide, namely: i) a single injection borehole (Test A), and ii) a four-spot layout with a spacing of 50 m (Test B). The 0.1 m radius injection boreholes were located symmetrically at the centre of the coalbed. The recovery of methane was considered in both Tests with a borehole in each corner of the coalbed. Owing to the symmetry of the problem, the simulation domain represented one of the four 100 m by 100 m quadrants of the coalbed. The domain was discretised using around 500 triangular elements in Test A and around 600 elements in Test B, with elements concentrated around the boreholes. The initial condition in both Tests was pure methane at a uniform pore gas pressure of 5 MPa and an isothermal temperature of 298 K. The injection of carbon dioxide at 5 MPa was prescribed at the injection boundary (borehole) with the gas recovery boundary (borehole) fixed at 1 MPa. Since the coalbed was assumed to be isolated, all other boundaries were closed. A 3 year simulation period was considered. The set of material parameters applied, presented in Table 1, was formed through a combination of laboratory characterisation [8] and literature survey [e.g. 2,9].

Table 1 Summary of material parameters used in the numerical simulations.

Parameter	**Value**		**Source**
Initial porosity, n_0 (-)	0.1		[9]
Initial permeability, K_0 (m^2)	1.0×10^{-16}		[8]
Coal density, ρ_s (kg)	1495.9		[8]
Axial modulus, M (Pa)	4.16×10^9		[2]
Bulk modulus, K (Pa)	2.81×10^9		[2]
	CO_2	**CH_4**	
Sorption rate, k_r^i (s^{-1})	3.60×10^{-4}	5.00×10^{-5}	[8]
Langmuir constant, b_L^i (Pa^{-1})	0.20×10^6	0.45×10^6	[8]
Langmuir capacity, n_L^i (mol kg^{-1})	1.26	1.09	[8]
Langmuir volumetric strain, ε_L^i (-)	0.021	0.009	[8]

4. Numerical results

Figure 1 presents the results of the numerical simulations in terms of the distributions of carbon dioxide and methane in the gas phase at the end of the 3 year simulation period. The results are given for a cross section of the domain taken along the diagonal passing through the gas injection and recovery boreholes. The steep decline in the concentration of carbon dioxide in the vicinity of the gas injection boreholes, predicted in both Tests, is attributed to the dissipation of the injected gas away from the borehole boundary. Similarly, it can be seen that a steep decline in the methane concentration developed in the vicinity of the gas recovery boreholes. As expected, the displacement of methane by carbon dioxide followed a similar trend in both Tests due to the seepage-driven displacement of free gas in the pores and the preferential adsorption of carbon dioxide ahead of methane. As the carbon dioxide advanced into the coalbed, the kinetically-controlled displacement of the adsorbed phase resulted in the mixing front of the gases gradually widening.

By the end of the simulation period, 8.44×10^6 mol of carbon dioxide had been stored in Test B compared to 3.52×10^6 mol in Test A. Likewise, 6.96×10^6 mol of methane had been recovered in Test B compared to 3.57×10^6 mol in Test A. The respective amounts of carbon dioxide stored and methane recovered were therefore 140% and 95% higher for four injection boreholes compared to a single borehole. Interference between the injection boreholes can be seen towards $x = 0$ m in Figure 1b and restricted the carbon dioxide storage to considerably less than a four-time increase (i.e. an increase of 300%). Moreover, Figure 1 shows that an earlier breakthrough of carbon dioxide in the recovered gas would occur in Test B. This would necessitate an earlier termination of methane recovery and may result in a lower overall displacement, or 'sweep', efficiency compared to that at the time of breakthrough in Test A. This premise will be studied in future work.

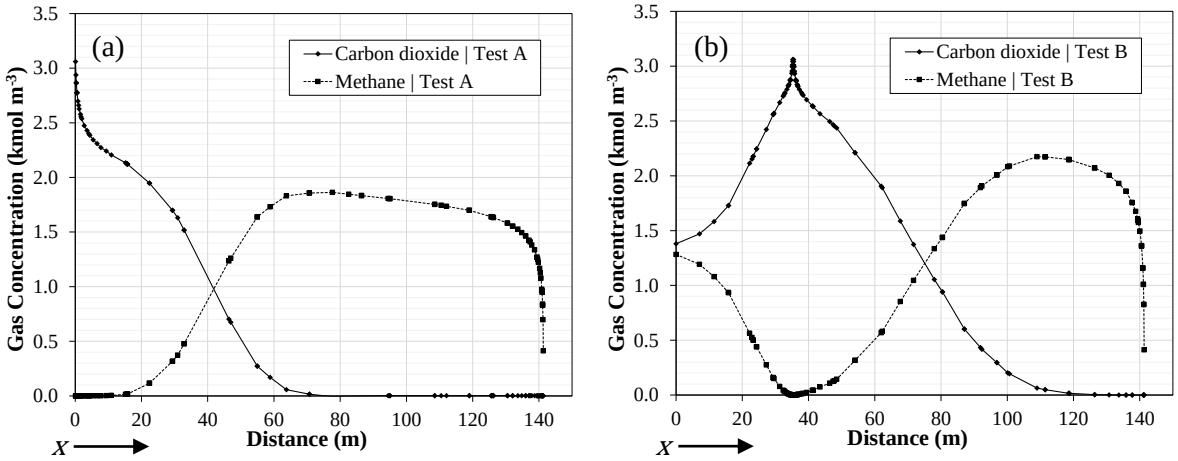

Figure 1 Distributions of carbon dioxide and methane taken along the diagonal of the domain passing through the gas injection and recovery boreholes after 3 years for: (a) Test A, and (b) Test B.

5. Conclusion

This paper has presented a numerical investigation of carbon sequestration in coal using different injection borehole layouts. In addition, some of the main physical and chemical phenomena responsible for the observed gas storage and displacement behaviour have been discussed. Based on the observations made, it can be concluded that the layout of the injection boreholes is a key engineering factor influencing the performance of carbon sequestration in coal with enhanced methane recovery. The four-spot layout delivered significant increases in the amounts of carbon dioxide stored and methane recovered, although the increase in carbon dioxide storage was somewhat offset by interference between the injection boreholes. The next step will be to expand the study to consider a number of different borehole spacings and different reservoir conditions.

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