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Assessment of reservoir conditions and engineering factors influencing coal bed methane recovery in the South Wales Coalfield

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Abstract. This paper investigates the sensitivity of methane recovery from a representative deep coal bed in the South Wales Coalfield, UK, considering the influence of reservoir conditions and engineering factors. A data set of reservoir conditions is used to establish the expected ranges of coal permeability and methane content in the region. By applying a numerical model for high pressure gas transport with kinetically controlled desorption and permeability evolution, the sensitivity of methane recovery to the different reservoir conditions is studied. The role of key engineering factors, namely the well pattern and spacing, is also considered. This is achieved by comparing the results for methane recovery predicted by the model, firstly under a series of reservoir conditions for single production well recovery, and subsequently for four-spot well patterns with different spacing. From the results analysis, it is demonstrated that the permeability influences the rate of methane recovery more than the methane content, thereby presenting an engineering challenge to widespread exploration in the generally gassy yet low permeability seams found in the region. The study of a four-spot well pattern at 150 m spacing clearly demonstrated the adverse effects of well interference. In contrast, a spacing of 250 m resulted in very little interference for the 1 year simulation period considered. To the authors' knowledge, this study represents the first application of numerical simulations to assess the potential performance of coal bed methane recovery in the South Wales Coalfield. Thus, the results of this study provide a meaningful reference for both further research and potential developers of coal bed methane installations in the region.

Keywords. coal bed methane recovery, engineering factors, numerical simulations, reservoir conditions, sensitivity analysis, South Wales Coalfield

1. Introduction

Meeting the challenges of maintaining a secure and affordable energy supply is more important than ever, especially in the context of the transition to a less carbon intensive energy mix over the coming decades. According to the IEA [1], global energy consumption is increasing and around 81% of this demand is fulfilled by fossil fuels,

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with oil (32.3%) and coal (27.3%) being the major sources. Although the conventional use of these resources looks set to continue for some time, there is also a growing demand for newer unconventional exploration technologies to enhance energy security and provide economic growth in the transition to the low carbon future [2]. Coal bed methane (CBM) recovery is an example of such an unconventional exploration technology.

In CBM recovery, a well is drilled into the coal seam and water is pumped out to lower the pressure in the seam. This allows methane to desorb from the internal surfaces of the coal and diffuse into the cleats, where it is able to flow, either as a free gas or dissolved in water, towards the production well [3]. The desorption area expands outward with pressure propagation and by controlling the release of pressure it is possible to capture the released natural gas (i.e. methane). The captured gas can then be treated and used in a variety of applications including electricity generation for supply to the national grid. CBM recovery projects are currently developed commercially around the world, most notably in Australia, China and the United States, although exploration is also ongoing in Europe [4].

A key task in a CBM field development plan is the recovery forecasting. The permeability and gas content of the target coal bed and the well spacing are important factors in well performance and recovery estimation. The South Wales Coalfield features relatively high gas contents (i.e. “charge”) but low permeability [5]. It is therefore important to understand how these conditions and well patterns influence the gas recovery rate and thus how commercially viable an installation may be.

Computational modeling is a useful tool for calculating the drainage area and well deliverability of unconventional hydrocarbon reservoirs. The objective of this paper is to investigate the sensitivity of CBM recovery to the different reservoir conditions found in the South Wales Coalfield, UK. A series of numerical simulations have been performed to assess how the recovery of South Wales’ CBM varies with the reservoir conditions, i.e. coal permeability and methane content, and engineering factors, i.e. well pattern and spacing. The numerical simulations were carried out using 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 for reactive gas transport in coal

A coupled THCM model, developed by Thomas and co-workers [e.g. 6,7], forms the basis for the numerical simulations presented in this work. The model employs a mechanistic approach to solving for heat transfer, moisture and chemical/gas transport, and mechanical behavior. The model has been extensively verified and applied to simulate the reactive transport of multicomponent chemicals and gas in a range of geological media [e.g. 7,8]. The numerical simulations presented in this work have been performed using the reactive gas transport module of the model with the following assumptions:

a) Pore fluid in the coal bed is single phase and single component, i.e. methane gas.
b) Coal is a homogenous, isotropic and elastic material.
c) A single porosity, equivalent continuum approach is valid.

d) Isothermal conditions prevail.

2.1. Governing equation

Based on the principle of conservation of mass, the theoretical formulation of the gas transport module incorporates flux components due to advection and diffusion, real gas behaviour, kinetically controlled adsorption/desorption reactions, and porosity and permeability evolution. Thus, the governing equation describing the reactive transport of a gas component can be expressed as:

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

where θ_g is the volumetric gas content equal to the porosity n is a fully dry system, c_g and s_g 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 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:

$$\mathbf{v_g} = \frac{K}{\mu_g} \nabla u_g = \frac{KZRT}{\mu_g} \nabla \mathrm{c}_g \tag{2}$$

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 can be included as an equilibrium process via a retardation factor or as a kinetically controlled reaction formulated using an appropriate rate model. The latter approach has been adopted in this work and a first-order kinetics model has been selected, which takes the following form [9]:

$$\frac{\partial s_g}{\partial t} = k_r \left(\mathrm{s}_{g,\infty} - \mathrm{s}_g\right) \tag{3}$$

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

$$\mathrm{s}_{g,\infty} = \frac{n_L b_L ZRT \mathrm{c}_g}{1 + ZRT b_L \mathrm{c}_g} \tag{4}$$

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

2.2. Constitutive relationships for gas and coal properties

Appropriate constitutive relationships have been employed in the model to accurately describe the evolution of the key gas transport properties as the pressure, temperature and composition vary. In relation to the formulation described above, these properties are: i) real gas compressibility, ii) viscosity, and iii) diffusivity. Real gas compressibility has been considered using the Peng and Robinson [10] equation of state (EoS). The resulting relationship between the pressure, volume and temperature of a gas is solved for the compressibility factor, Z. The gas viscosity is calculated via the dense gas model of Chung et al. [11]. Finally, the influence of pressure on gas diffusivity is described by the simple empirical model suggested by Reid et al [12].

Coal matrix shrinkage caused by methane desorption is an important phenomena influencing coal porosity and permeability [13], and therefore methane mobility. In this work, the permeability model of Palmer and Mansoori [14] has been used to relate changes in the effective stress and matrix shrinkage to changes in porosity and permeability:

$$\frac{n}{n_0} = 1 + \frac{1}{n_0 M}\left(ZRTc_g - ZRTc_{g0}\right) + \frac{\varepsilon_L}{n_0}\left(\frac{K}{M} - 1\right)\left(\frac{b_L ZRTc_g}{1+ZRTb_L c_g} - \frac{b_L ZRTc_{g0}}{1+ZRTb_L c_{g0}}\right) \tag{5}$$

$$\frac{K}{K_0} = \left(\frac{n}{n_0}\right)^3 \tag{6}$$

where the subscript 0 is used to denote the initial condition, M is the axial modulus, K is the bulk modulus, and ε_L is the Langmuir strain.

2.3. Numerical solution

A numerical solution of the governing equation for gas transport is achieved by applying the finite element method with Galerkin weighted residuals for spatial discretisation and an implicit mid-interval backward-difference scheme for temporal discretisation. An operator splitting approach is used to couple the gas transport and kinetically controlled adsorption/desorption terms. The sequential non-iterative approach (SNIA) is adopted, whereby each time step involves first solving the transport equations with no reactions. Once the transport equations have converged, the solution is passed to the reactions module to be modified accordingly before the start of the next time step.

3. Numerical simulations

All simulations have been performed for methane recovery from a 600 m deep axisymmetric, hypothetically isolated coal bed of 500 m radius and 1 m thickness, as shown in Figure 1a. Of the eight simulations performed, six were for the single well domain shown in Figure 1b to study how the ranges of coal permeability and methane content typical of the South Wales Coalfield affect methane recovery. The two remaining simulations assessed the importance of well spacing for four-spot well patterns, using domains based on Figure 1b.

As mentioned in section 2, the pore fluid in the coal bed was assumed to be pure methane under an isothermal condition. The initial gas pressure in all simulations was uniform at 6 MPa and the production well boundary conditions were fixed for a bottomhole pressure of 1 MPa for the 1 year simulation period. Since the coal bed is axisymmetric and isolated, no flow boundaries conditions were prescribed at all other boundaries.

A material properties data set was formed through a combination of laboratory characterisation and literature survey, allowing representative ranges of coal permeability and methane content to be identified. Table 1 provides a summary of the material parameters used in the sensitivity study along with the data sources which have been used.

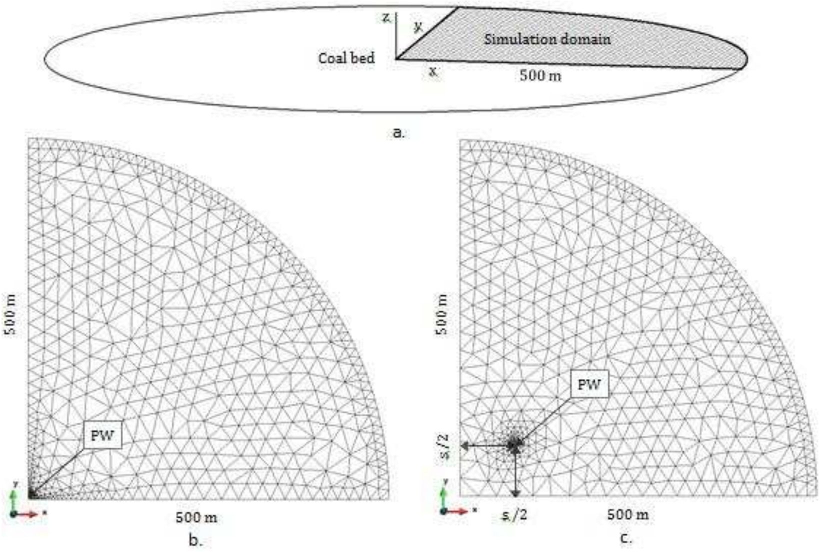


Figure 1 a. Coal bed geometry with highlighted simulation domain, and b. and c. spatially discretized domains for the single and four-spot well configurations, respectively. PW denotes a production well.

The methane content of South Wales' coal is well defined in the literature as a legacy of measurements related to methane management in the coal mines [e.g. 15]. This data has been supplemented by CBM exploration reports by Petroleum Exploration and Development Licence (PEDL) holders, as reported by DECC [16]. Laboratory testing of samples taken at 493 to 622 m deep at Aberpergwm Colliery has also been undertaken as part of the present work. Analysis of the methane content data gave 8.4, 13.3 and 16.5 m^3 t^{-1} as the 'lower', 'most likely' and 'upper' cases, respectively. By converting these values to mol kg^{-1} and back-calculating from the initial free gas content (assuming a fully dry pore volume), appropriate Langmuir capacities, n_L, were determined for each case (ref. Table 1).

Table 1. Summary of material parameters used in the sensitivity study for CBM in the South Wales Coalfield.

Parameter	**Value**			**Source**
Porosity, n (-)	0.025			[18]
Temperature, T (K)	298			[19]
Coal density, ρ_s (kg)	1495.9			Laboratory
Axial modulus, M (Pa)	4.16×10^9			Lit. survey
Bulk modulus, K (Pa)	2.81×10^9			Lit. survey
Sorption rate, k_r (s^{-1})	5.00×10^{-5}			Laboratory
Langmuir strain, ε_L (-)	0.01			Lit. survey
Langmuir constant, b_L (Pa^{-1})	0.45×10^6			Laboratory
Diffusion coefficient, D_g (m^2 s^{-1})	2.20×10^5			[20]
	Lower	**Most likely**	**Upper**	
Permeability, K (m^2)	1.0×10^{-16}	$-$	1.0×10^{-15}	Laboratory
Langmuir capacity, n_L (mol kg^{-1})	0.32	0.54	0.69	[15,16]

Permeability data for South Wales' coal is lacking in the literature, especially for seams greater than 300 m deep. The worst and best case values used in the sensitivity analysis were therefore derived from methane permeability tests conducted on a coal sample collected from 550 m deep at Unity Mine, near Glyn-Neath.

Two sets of simulations were performed. The first set of six simulations were for each combination of permeability and methane content for a single production well, and the second set of two simulations for assessing the effect of well pattern and spacing. This second set of simulations were performed for the 'lower' case permeability and the 'most likely' methane content in Table 1, with four wells at 150 m and 250 m spacing, respectively.

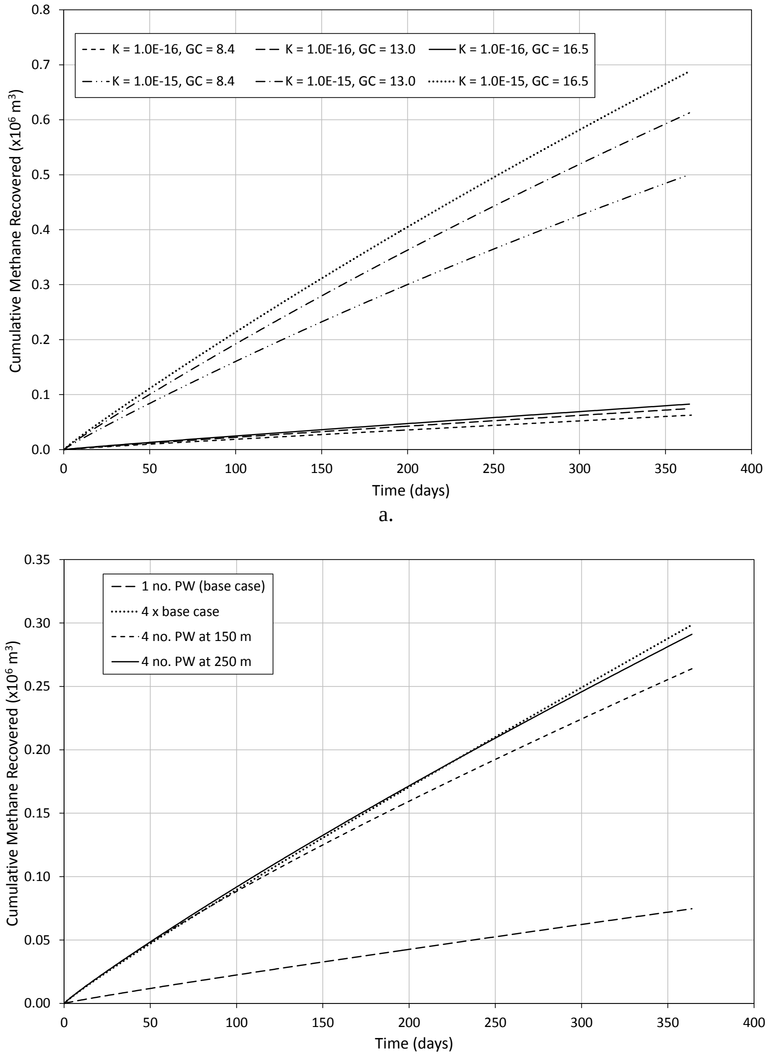
4. Sensitivity of CBM recovery in the South Wales Coalfield

Figure 2a presents the results from the first set of six numerical simulations for the different combinations of permeability and methane content in terms of the predicted cumulative methane produced. Since the simulation domain represented one quarter of the axisymmetric drainage area, the model predictions were multiplied by 4 to give the results shown. The results indicate that the methane recovery rate in the South Wales Coalfield is considerably more sensitive to the coal bed permeability than the methane content. Approximately 8.2 times more methane was recovered for the 'upper' case permeability scenarios compared to the 'lower' case permeability scenarios. By comparison, only 1.4 times more methane was recovered for the 'upper' case methane content scenarios compared to the 'lower' methane content scenarios.

The greater dependence of CBM recovery on the permeabilities studied presents an engineering challenge to the exploration of the resource in the South Wales Coalfield. This is because the high methane contents found across a large portion of the Coalfield indicate a very good potential for the technology, whereas the simulations in this work have demonstrated the constraints imposed by the low natural permeabilities typical of the region and the UK in general. This follows the overall conclusion of Jones et al.[17] regarding the prospects for CBM recovery in the UK.

From the second set of simulation results presented in Figure 2b, it can be seen that a four-spot well configuration at 250 m spacing yielded a slightly higher methane recovery compared to a spacing of 150 m. A base case for the equivalent single production well recovery has also been included and a factor of 4 applied in effect to project the recovery curve for a four-spot well configuration with no interference. The curves show that there is considerably less interference for the 250 m spacing than for the 150 m spacing over the 1 year simulation period.

These findings represent one step towards the more accurate quantification of the practical (i.e. recoverable) CBM resource in the South Wales Coalfield. This work therefore provides a meaningful reference for those wishing to conduct techno-economic analyses for CBM recovery in the region. Nonetheless, further work is required before definitive conclusions can be drawn, perhaps with a focus on: i) a more comprehensive sensitivity analysis considering additional theoretical features in the numerical modelling, for example formation water, ii) regional scale resource assessments, iii) site specific techno-economic analyses, iv) instrumented field scale pilot installations, and v) continued laboratory characterisation of South Wales' coal.



a.

b.

Figure 2 Predicted cumulative methane recovery curves for: a. the six different combinations of permeability, K (m^2), and methane gas content, GC (m^3), and b. the two four-spot well configurations.

5. Conclusions

A sensitivity analysis via a series of numerical simulations for methane recovery from a representative coal bed in the South Wales Coalfield has been presented in this paper. Expected 'lower', 'most likely' and 'upper' values of coal permeability and methane content were identified through a literature review and laboratory characterisation, allowing the sensitivity of methane recovery to these key reservoir conditions to be examined. It has been demonstrated that coal bed methane recovery in the South Wales Coalfield is considerably more sensitive to the permeability than the initial methane content. Although the high methane content of the regions coal implies a very good theoretical resource, it is therefore likely that the practically recoverable resource is much smaller due to the characteristically low permeability of the UK's coal resources, including the South Wales Coalfield. Additional numerical simulations performed to assess the effects of well layout and spacing showed considerably more well interference for 150 m spacing than for 250 m spacing over the 1 year simulation period.

These findings are important since to the authors' knowledge they are the first that relate directly to some of the key reservoir conditions encountered in the South Wales Coalfield. As a result, they are useful for the development of accurate techno-economic analyses for coal bed methane recovery proposals in the region. Continued research and development is required at both the Coalfield and local scales to further reduce the uncertainties involved and allow better informed decisions on the viability of the technology to be made.

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