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CO_2 injectivity in a multi-lateral horizontal well in a low permeability coal seam: results from a field trial

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Abstract

Enhanced coalbed methane (ECBM) production by CO_2 injection offers the potential of increasing recovery of the gas in place over primary recovery methods and at the same time storing CO_2. A field ECBM trial via CO_2 storage has been carried out in the east margin of the Ordos Basin, Shanxi province, China. A unique aspect of the trial was using a multi-lateral horizontal well, which was clearly beneficial for production or injection for low permeability formations. This paper described a reservoir model constructed to simulate the CO_2 injection behaviour using the coal seam reservoir simulator SIMED II. The simulation work included history matching the bottomhole pressure while using injection rate as control. A complexity in the modelling was representation of the multi-lateral horizontal well as its branches were not aligned with x or y coordinates. Thus approximation was taken to represent the well in the model. The simulation result showed good match for some data but could not match well the whole range of data, suggesting possible well opening or closing to flow during injection and shut-in periods. It has been suggested that the permeability decrease due to gas adsorption induced coal swelling may play an important role in the gas flow behaviour, especially near the wellbore where the amount of CO_2 adsorbed was highest. However, due to the coarse grid size applied in this finite difference model and the difficulty to refine them near the well branches while maintaining overall size of the model, the permeability loss due to adsorption induced coal swelling was diluted by the relatively large grid size. Thus this may not accurately reflect the permeability change and the quality of the history matching results are affected. A suggestion is to use refined grid blocks near wellbore to examine the impact of swelling on the overall CO_2 flow behaviour for this project.

Keywords: coalbed methane, enhanced coalbed methane recovery (ECBM), reservoir simulation, CO_2 storage;

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1. Introduction

Coalbed methane is an important resource of energy. Meanwhile CO_2 sequestration in coal is a potential management option for greenhouse gas emissions. An attractive aspect to this process is that CO_2 is adsorbed to the coal, reducing the risk of CO_2 migration to the surface; another aspect to this is that the injected CO_2 could displace adsorbed methane leading to enhanced coalbed methane recovery (ECBM) [1]. A few ECBM field experiments have been carried out in the past and an important challenge for CO_2-ECBM is permeability decline due to coal swelling with CO_2 adsorption [2]. Significant decline in permeability would be exhibited by decreases in the rates of CO_2 injection and this has been shown in the previous field trials. Since most of the previous ECBM field trials used vertical wells to inject CO_2 in low permeability coal seams, this often led to low initial injectivity and further declined injectivity over time due to coal swelling induced permeability decrease. Thus to increase CO_2 injectivity in low permeability coal seams, advanced well technology is required. A good option is horizontal well since it provides a much larger contact area than horizontal well for CO_2 to flow into the coal reservoir.

To investigate the CO_2 injection and storage behaviour using a horizontal well, a project using a multi-lateral horizontal well for injection was carried out in the east margin of the Ordos Basin, Shanxi Province, China [3]. The multi-lateral well was drilled in the #3 coal seam in the Permian Shanxi formation with two main branches and two sub-branches. The total well length was about 2600 m with about 2200 m in the coal seam. This well was not cased or lined in any fashion within the coal seam being left open hole.

The CO_2 was sourced from a commercial gas supply company located at the city of Changzhi, approximately 500 km from the site. The CO_2 was transported by tanker truck in liquid form to the field site where it was pumped into the injection well using the booster pump via the flow skid. The first two truckloads of liquid CO_2 of about 20 metric tonnes were injected in mid-September 2011. CO_2 injection was paused due to a CO_2 injection pump problem and resumed in mid-October 2010. Due to the local weather and road conditions CO_2 injection was discontinuous. Nevertheless, from January and March 2012, there were two periods with more continuous injection. In total about 460 tonnes of CO_2 was injected during the trial; Fig. 1 presents a graph of the cumulative quantity injected with time and the rates for each injection.

Due to the transport of CO_2 by trucks, the injection is cyclic with each cycle involving a CO_2 injection period during which the bottomhole pressure increased followed by a period of pressure decay after injection had ceased. The CO_2 injection rate was usually around 5 to 10 tonnes per hour with the injection lasting a few hours until the tanker truck was empty. A maximum limit for the bottomhole pressure was 5MPa; if this was reached the injection was paused until the pressure had decayed sufficiently for it to resume. In between injections the bottomhole pressure decayed and often recovered close to the initial reservoir pressure of about 2.1 MPa.

In this project, a monitoring well was also drilled about 20 m away from the vertical section of the injection well. A u-tube sampling system was installed in the monitoring well and automated to allow reservoir gas to be sampled and retrieved for analysis in an onsite field laboratory. Two injections of tracer gas, SF_6, were carried out at the early and final stages of CO_2 injection. This was to identify the flow pathways and rates within the reservoirs and provided data on storage assurance.

A key step to evaluate the injection data is using reservoir simulation to better understand the CO_2 flow behaviour in the reservoir. Reservoir simulation will also provide information such as how the permeability changes during CO_2 injection. Due to the complexity of the well, as a first step, this paper is focused on simulating the CO_2 injection behaviour for the multi-component well. Simulation of trace gas is considered as the second step and is not included in this paper.

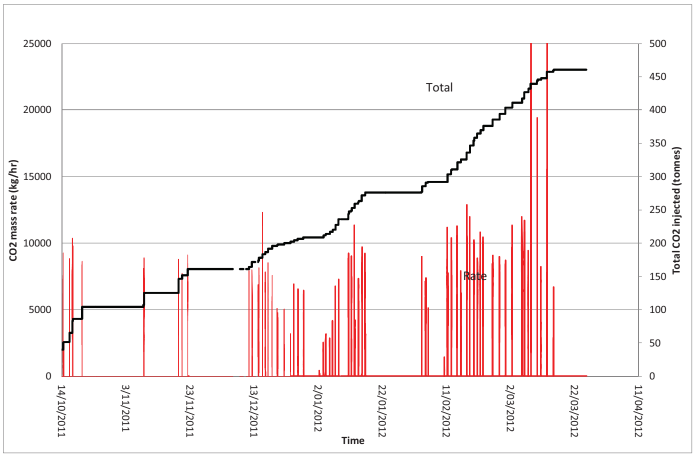

Fig. 1 CO_2 injection rates and total mass injected [3]

2. Reservoir model

A reservoir model was constructed to simulate the CO_2 injection behaviour using the coal seam reservoir simulator SIMED II. SIMED II is a two-phase multi-component coal gas reservoir simulator, which can be applied for CO_2 storage in coal seams or other gas migration problems [1][4]. It has been validated with other coal reservoir simulators through a comparison work [5].

2.1. Permeability model

As one of the key parameters in coal reservoir simulation, one of the widely applied permeability model, Shi and Durucan model, is used in SIMED II. The Shi and Durucan model describes the permeability change from a stress approach [6]:

$$\sigma-\sigma_0=-\frac{\nu}{1-\nu}\left(P-P_0\right)+\frac{E\varepsilon_V}{3\left(1-\nu\right)} \tag{1}$$

where σ is the effective horizontal stress, σ_0 is the effective horizontal stress at the initial reservoir pressure, ε_V is the volumetric swelling/shrinkage strain. To relate the permeability with effective stress, the equation below is used [6]:

$$k=k_0e^{-3c_f(\sigma-\sigma_0)} \tag{2}$$

where c_f is referred to as the cleat volume compressibility with respect to changes in the effective horizontal stress normal to the cleats.

2.2. Reservoir properties

Key reservoir properties, including permeability, Langmuir isotherm, swelling ratio are summarized in Table 1. Permeability was measured on the field and Langmuir isotherms for CH_4 and CO_2 were measured in the laboratory. Other properties were reasonably assumed based on literature data [7]. Another key parameter, the relative permeability, is shown in Fig. 2.

Table 1. Reservoir properties

Key reservoir properties	
Permeability (md)	0.64
Langmuir volume CH_4 (m^3/tonne)	20.9
Langmuir pressure CH_4 (MPa)	3.52
Langmuir volume CO_2 (m^3/tonne)	46.9
Langmuir pressure CO_2 (MPa)	0.73
Cleat porosity	0.008
Cleat compressibility (MPa^{-1})	0.05
Maximum volumetric swelling ratio	0.03
Young's modulus (GPa)	3.0
Poison's ratio	0.3

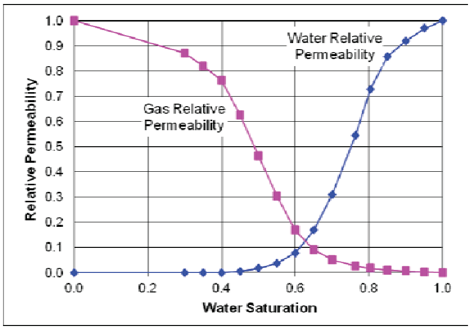

Fig. 2 coal seam depth and gird system

The depth of the coal seam is shown in Fig. 3. As can be seen from the figure, the depth of the seam various from about 510 to 565 m. The simulated area is 1000 m by 700 m. The grid system is 100 by 70 with each block 10 m by 10 m.

2.3. Well location

The multi-lateral horizontal well was drilled with entering depth at about 565 m. Four branches were drilled up-dip with a total length of about 2,600 m. The well branch locations are illustrated in Fig. 4. The vertical CBM production well was connected at the main branch close to the entering point. This helped to effectively pump out the water produced from the coal seam. This CBM production well was converted to CO_2 injection well by removing the pump and tubing. Tubing was reinstalled with two sets of pressure and temperature transducers attached at the end tubing.

A complexity in the modelling was the representation of the multi-lateral horizontal well since SIMED II used finite difference method and the well branches were not aligned with x or y coordinates. Approximation was taken to represent the well in the reservoir model. For blocks where the well penetrated and the effective length was over the block grid size of 10 m, a horizontal well section was represented for this block. For blocks where the effective well length was less than 10 m, a well section was represented or not in this block was also determined with the effective well length in its adjacent blocks. The total represented well in the reservoir model matched the real total in coal seam length of 2200 m.

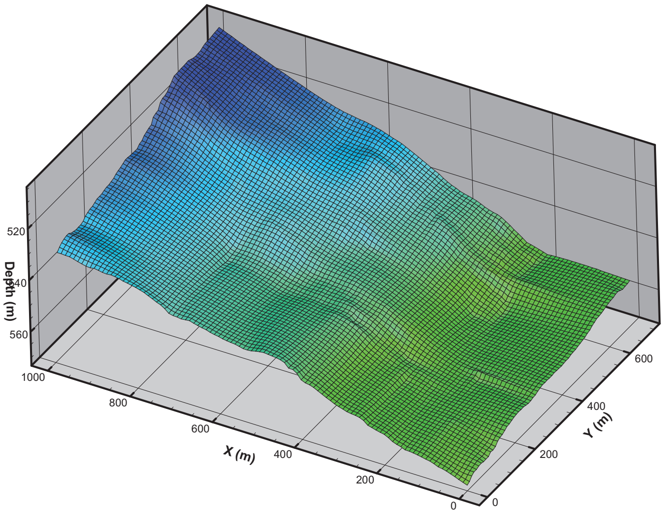

Fig. 3 Coal seam depth and grid system

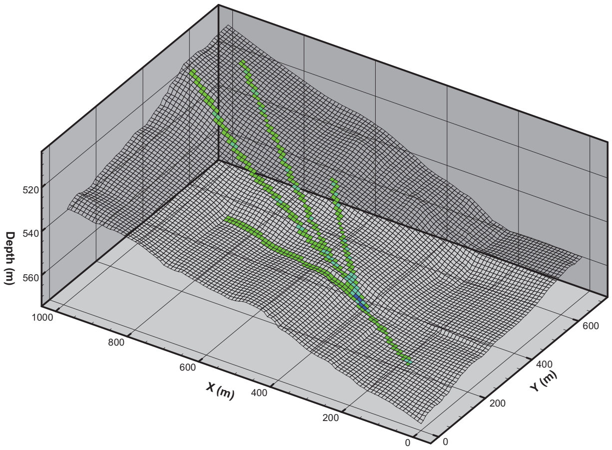

Fig. 4 Multi-lateral well location

3. Simulation results

In the simulation, injection rate was used as control. The bottomhole pressure was used as to examine the simulation results. Injection rate and bottomhole pressure used were averaged daily values.

Fig. 5 shows the bottomhole pressure for the field experiment and simulation. In general, the bottomhole pressure calculated from the simulation can represent the experimental data in the early and late stages of the injection. However, it was not able to represent the data in late December, 2011 till early January 2012. In this period, as can be seen from Fig. 1, the injection amount for each cycle was relatively low due to the quick increase of bottomhole pressure to reach the maximum pressure. One possibility of this was that the well may not be entirely open to flow due to the injection and shut-in cycles. This may attribute to the complex multi-phase flow behaviour in well and reservoir with possible plugs formed to close part of the well branches. Since the current reservoir model did not account for this behaviour, the simulated bottomhole pressure for this period was lower than the experiment.

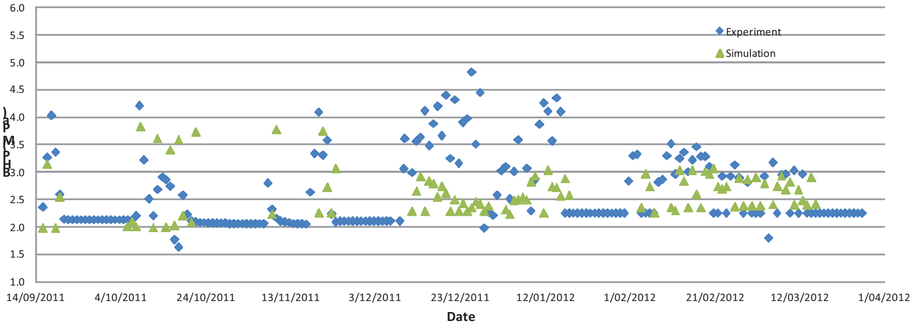

Fig. 5 Bottomhole pressure results

Fig. 6 shows the CO_2 concentration at the end of injection. CO_2 tended to accumulate at the up-dip branches where the coal seam is shallower. It can also been from the figure that CO_2 was only at the vicinity of the well branches. The adsorbed CO_2 concentration was relatively low at about 3 to 4 m^3/tonne. This was due to the relatively low injection pressure thus the adsorption amount was far below the coal's maximum adsorption capacity. Furthermore, since the block size was 10m by 10m, it was coarse to obtain a better CO_2 concentration distribution. However, it can be speculated that with finer grid blocks, CO_2 adsorbed concentration would be higher near wellbore.

To examine the permeability change before and after the CO_2 injection, Fig. 7 shows the permeability change ratio at the end of CO_2 injection. Permeability change ratio is defined as:

$$\alpha = \frac{k - k_0}{k_0} \times 100\% \tag{3}$$

It can be seen from the figure that permeability decreased by more than 20% where the CO_2 adsorption was the highest. At the blocks where CO_2 adsorption was low and reservoir pressure was high the reservoir permeability was instead increased, with permeability in some blocks increased by more than 20%. Again due to the relatively coarse grid, it was not able to more accurately evaluate the impact of permeability loss due to swelling near wellbore. However, it can be speculated that CO_2 concentration near wellbore will be higher using a finer grid thus permeability loss would be even more significant at near wellbore.

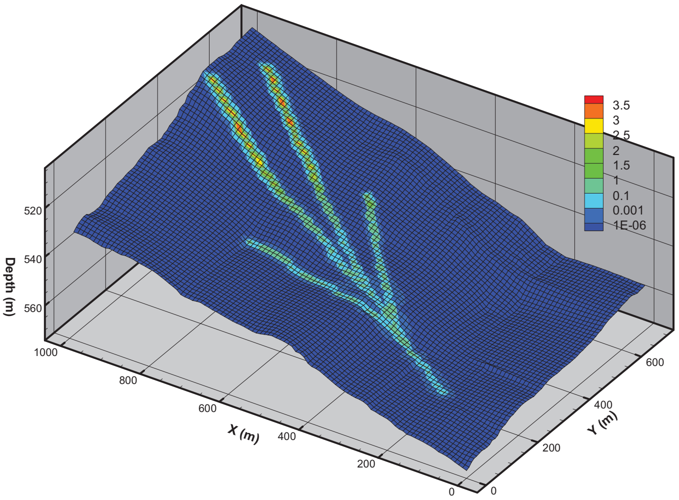

Fig. 6 CO_2 concentration at the end of injection

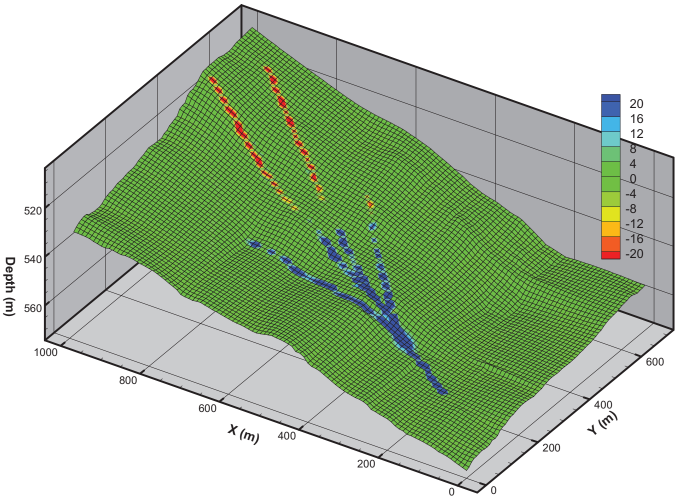

Fig. 7 Reservoir permeability change at the end of injection

4. Conclusions

This paper described a reservoir model constructed to simulate the CO_2 injection behaviour using the coal seam reservoir simulator SIMED II for a field CO_2-ECBM trial using a multi-lateral horizontal well in the east margin of the Ordos Basin, Shanxi province, China. The simulation work included history matching the bottomhole pressure while using injection rate as control. The simulation result showed good match for some data but could not match well the whole range of data, suggesting possible well opening or closing to flow during injection and shut-in periods. This made it more complex for history matching the injection data. Permeability loss due to swelling was also observed especially at near wellbore blocks. However, due to the coarse grid size applied in this finite difference model and the difficulty to refine them near the well branches while maintaining overall size of the model, the permeability loss due to adsorption induced coal swelling may be underestimated by the relatively large grid block size, because the CO_2 adsorption amount is averaged down by the large block size. Thus this may affect the quality of the history matching results. Due to the complexity of the well, the results presented in this work were still preliminary. However, the results were instructive and would serve a good insight to improve the simulation work in the future. Future work may include refining grid blocks near wellbore to better examine the impact of swelling on reservoir permeability near wellbore and overall flow behaviour for this CO_2-ECBM project.

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