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Investigation of CO_2 storage capacity in open saline aquifers with numerical models

Yang Wang[a*], Yaqin Xu[a], Keni Zhang[a]

[a]College of Water Sciences, Beijing Normal University, 19 Xinjiekouwai St., Haidian District, Beijing 100875, P. R. China

Abstract

Accurate calculation of carbon dioxide (CO2) storage capacity in deep saline aquifers is a challenging task. However an assessment must be performed to determine whether there is sufficient capacity in a storage site for any CO2 sequestration project. We evaluated the CO2 storage capacity for a simplified reservoir system, which the layered potential storage formations are overlaid by sealing cap rock. This study aims at determining CO2 storage capacity for the injection of CO2 in opened saline formations using numerical simulation method. In this study, a 3D numerical model was developed for the investigation. Detailed processes for the storage capacity estimation are derived. The impact of injection strategy and the residual gas saturation on storage capacity was investigated. It is shown that both of the injection strategy and the residual gas saturation have a great impact on the spatial distribution of CO2 plume and the effective storage of CO2 in the reservoir. Simulation results also indicate that the injection well distribution may significantly influence the use of the formation porous space for CO2 storage. From this study, we may conclude that the most accurate way to estimate storage capacity is through construction of a basin scale three-dimensional numerical model for specific storage site by incorporating detailed geological information of the site and injection scheme used.

Keywords: Geological CO_2 sequestration, Saline aquifer, Storage capacity; Numerical simulation;

* Corresponding author. Tel.: +86-15210631560; Fax: +86-10-58802738.
E-mail address: wangyang.cool.cool@163.com

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1. Introduction

Geological carbon dioxide sequestration in deep formations (e.g., saline aquifers, gas and oil reservoirs, and coal beds) is a promising measure for mitigating the impact of climate change [1-2]. The greatest storage potential of all the geological CO_2 storage options is in saline aquifers [3]. However, for implementation of this technology at the scale needed to achieve a significant and meaningful reduction in CO_2 emissions, governments and industry need to know more about CO_2 storage capacity in deep geologic formations. However, evaluation of the CO_2 storage capacity in deep saline aquifers is not a straightforward or simple process. There are many levels of uncertainty within any assessment [4-5].

In this study, we use generic numerical simulations to investigate the capacity of deep brine-saturated formations to sequester CO_2 that has been compressed to a supercritical state and injected. The three-dimensional (3D) model simulates flow and transport processes of a two-phase (liquid and gas), three-component (CO_2, water, dissolved NaCl) system. This study aims at development of a numerical simulation method for assessment of CO_2 storage capacity in deep open saline formations typical in north-east China. A base-case model is constructed to investigate the system performance for a general parameter set and injection strategy. The simulation results of variations with different parameters and injection strategies are compared against the base-case model to identify their impact on the CO_2 storage capacity, spatial distribution of CO_2 plume and the pressure buildup. Therefore, effective strategies or technologies for increasing CO_2 storage efficiency may allow us to significantly increase the overall capacity for CO_2 storage in deep saline aquifers. This work may help in identifying the key factors for increasing the storage capacity. Even though this study is based on the simplified aquifer system, the approach can apply to any complicated CO_2 storage reservoir. In addition, we can show the procedures for estimation of storage capacity for a typical layered saline aquifer and come to some conclusions about the effectiveness of the approach over a large regional extent. The numerical simulations were conducted using the TOUGH2-MP/ECO2N code [6-7].

2. Model setup and parameters

2.1. Conceptual model and model setup

A model domain was chosen to represent a deep saline aquifer underlying a typical aquifer/aquitard (e.g., sandstone/shale) stratigraphy—Songliao Basin. The basin, located in northeastern China, is approximately 750 km in length, 330-370 km wide, with a total area of 26×10^4 km^2. The storage formation into which CO_2 is injected, located at a depth of approximately 1200 m below the ground surface, is 20 m thick and bounded at the top by a sealing layer 10 m thick, see Fig.1. The bottom of the storage formation is formed by impermeable base rock. Altogether, the model domain includes one storage layer and one sealing layer. The modeled domain covers an area of 10 km×10 km with a thickness of 30 m. Carbon dioxide is injected at 150% of the initial hydrostatic pressure at the top of the hypothetical storage formation. For the ideal situation, CO_2 is expected to occupy the entire aquifer layer.

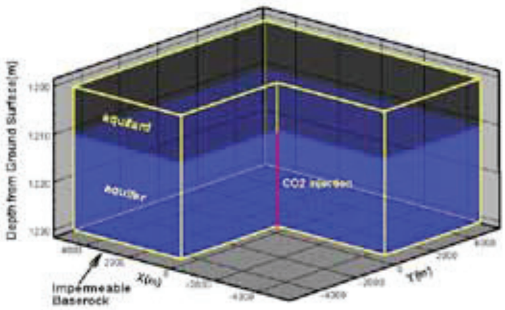


Fig. 1 Schematic showing the 3D model domain of a deep brine formation for CO_2 storage

Initial hydrostatic pressures vary linearly with depth from 120 bar at the top to 122.943 bar at the bottom. There is no lateral variation. Temperature varies linearly with depth from 38.6 ℃ at the top to 39.2 ℃ at the bottom with a geothermal gradient of 20 ℃/km. The groundwater has a salinity of 3%. At these conditions, the average density of CO_2 within the reservoir is about 730 kg/m^3. The system has an overlying seal with the permeability of 10^{-20} m^2, but open laterally (a constant pressure applied at the horizontal boundaries).

2.2. Model parameters

The hydrogeologic properties chosen for the aquifer–aquitard sequence are given in Table 1. For simplification, in all simulation cases, the aquifer and aquitard are considered as homogeneous and have been assigned the same set of hydrogeologic properties, respectively. The homogeneous properties of the aquifer are typical of sedimentary formations suitable for CO_2 storage, with high-enough permeability and porosity. The van Genuchten model was used to calculate the capillary pressure and the relative permeabilities for the two-phase flow in all the simulation cases [8].

Table 1 Hydrogeologic properties of the storage formation used in the base-case simulations

Properties	Values for aquifer	Values for aquitard
Permeability, k (m^2)	1.0×10^{-13}	1.0×10^{-20}
Pore compressibility, βp (Pa^{-1})	4.5×10^{-10}	9.0×10^{-10}
Porosity, Φ	0.35	0.1025
van Genuchten m	0.46	0.46
van Genuchten α (Pa^{-1})	5.0×10^{-5}	5.0×10^{-7}
Residual CO_2 saturation	0.25	0.35
Residual water saturation	0.30	0.30

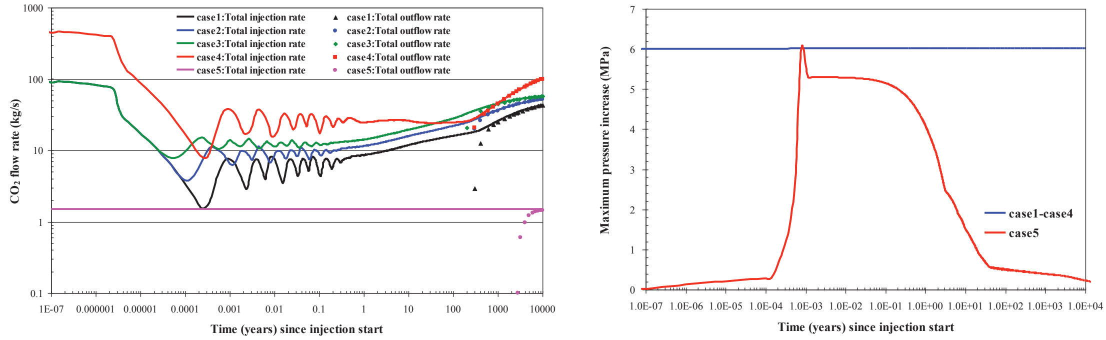
The sensitivity simulations conducted in this study are listed in Table 2. In each sensitivity case, only one parameter of interest was changed from the base-case value.

Table 2 Numerical simulation runs for different cases

	Case number	Number of injection wells	Injection type	Residual CO_2 saturation
Base case	Case 1	1	Constant pressure	0.25
	Case 2	1	Constant pressure	0.15
	Case 3	1	Constant pressure	0.05
	Case 4	5	Constant pressure	0.25
	Case 5	1	Constant rate (1.5kg/s)	0.25

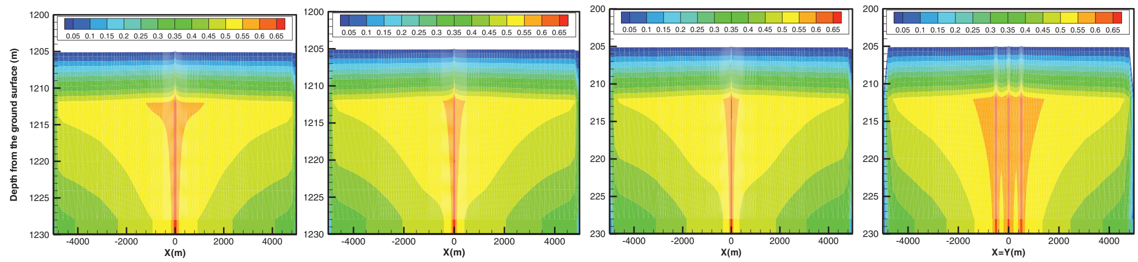
3. Simulation results and discussion

For open systems, fluid can cross the lateral boundaries of geologic formations. The pressure buildup caused by CO2 injection is usually not a limiting factor except for maximum bottom-hole pressure at the injection well, since pore water may then flow into neighboring formations and some of the pressure increase will be avoided [9-10]. In such an "open" system, the storage capacity of a reservoir may be defined as the total mass of CO2 stored in the system when the CO2 injection rate is equal to the rate it leaving the lateral boundaries (boundary leakage), or the system is at steady state. The Fig.2 (a) shows CO2 plume reaches the model boundary in several hundred years. Once it reaches the boundary, the total rate of CO2 crossing the lateral boundaries increases gradually, and finally system reaches steady-state. As shown in the Fig.2 (a), the smaller of residual CO2 saturation, the larger the CO2 injection rate can be reached. By comparing the case 1 and case 4, we can conclude that increasing the number of injection wells can greatly enhance the CO2 injection rate. If the maximum pressure buildup does not exceed allowable maximum pressure buildup, the constant pressure injection case may achieve a higher CO2 storage capacity, see Fig.2 (b) and Fig.4 (a). As shown in Fig.3, it is clear that CO2 does not fully occupy the system when the steady state is reached, and the larger the residual saturation of carbon dioxide, the higher efficient in using the aquifer storage space. We can find CO2 occupies much more storage space in open system. This may indicate that open lateral boundaries will help in enhancing the system's storage capacity.



(a) (b)

Fig.2 (a)Total CO_2 injection rate and the rate leaving model domain through lateral boundaries vs time since CO_2 injection started; (b)The maximum pressure buildup of the open system vs time

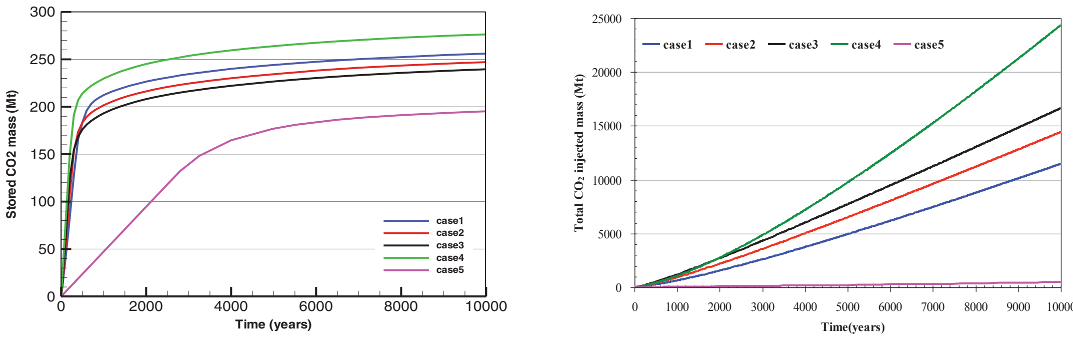


(a) (b) (c) (d)

Fig.3 Spatial distributions of CO_2 saturation for an open system when the CO_2 injection rate is equal to the boundary leakage rate (cutoff=0.01) (a) case1: residual CO_2 saturation=0.25; (b) case2: residual CO_2 saturation=0.15; (c) case3: residual CO_2 saturation=0.05; (d)case9: residual CO_2 saturation=0.25, 5wells

Comparison of Fig.2 (a) and Fig.4 (a) indicates that the mass of CO2 storage in the entire system increases rapidly before CO2 reaches the lateral edge of the model. Once CO2 begins to leave the model domain through lateral boundaries, the amount of CO2 accumulation in the system slows down. The mass of CO2 stored in entire system gradually reaches a steady state after hundreds to thousands of years. Fig.4 (a) indicates that the residual CO2 saturation has an important impact on the CO2 storage capacity. Case 1, which has the largest residual CO2 saturation, demonstrates the maximum storage capacity. The mass of CO2 stored in an aquifer increases with the increasing of residual CO2 saturation. Comparison of case 1 and case 4 shows that increase of the number of injection wells has a significant influence on the total CO2 storage capacity. Increasing the number of injection wells will improve the aquifer's storage capacity. However, no matter how the wells are located, it is always difficult for CO2 to occupy the entire space. Case 5 shows much less storage capacity than other cases. This may indicate that higher injection rate (higher injection pressure) will help in enhancing the system's storage capacity. By comparing Fig.4 (a) and Fig.4 (b), we can find that only small portion of the injected CO2 stays in the domain, and most of it leaks through the lateral boundaries, especially at the later times.

At steady state, most CO2 is stored in the aquifer (accounting for about 98%), most of which exists in super critical gas (accounting for about 92%), and only about 8% dissolved in the aqueous phase, see Table 3. In addition, there is a small amount of CO2 stored in the cap rock, which mainly exists in dissolved aqueous phase.



(a) (b)

Fig.4 (a) The total mass of CO_2 stored in the system at different time; (b) The total injected CO_2 mass vs time

Table 3 Total storage of CO_2 (in Mt) in the model domain at steady-state

	Case 1	Case 2	Case 3	Case 4	Case 5
Cap rock (aqueous)	4.9244	4.9140	4.9064	4.9715	4.4266
Cap rock (gas)	0.1911	0.1839	0.1785	0.2090	0.1141
Total mass in cap rock	5.1154	5.0979	5.0849	5.1805	4.5407
Aquifer (aqueous)	18.8311	19.2940	19.6651	18.2981	21.5485
Aquifer (gas)	241.5676	233.7450	227.1980	257.3472	169.1808
Total mass in aquifer	260.3987	253.0390	246.8631	275.6453	190.7293
Total mass in entire system	265.5141	258.1369	251.9480	280.8258	195.2700

4. Summary and Conclusions

The conclusions are summarized as follows:

- For the open system, the storage capacity of a reservoir is defined by the total mass of CO2 in the domain when the rate of CO2 leakage through lateral boundaries equals the rate of injection. The simulation results show the mass of CO2 stored in the entire system reaches a steady state after thousands of years. When the steady state is reached, CO2 does not fully occupy the system, but we can find CO2 occupies much more storage space. So the system with open lateral boundaries can help in enhancing the CO2 storage capacity. Most of CO2 is stored in the aquifer (accounting for about 98%), and most of which exists in a gas-like phase (accounting for about 92%). The leakage of CO2 into the overlying aquitard is small, and mainly exists in a dissolved in the aqueous phase. This is due to low permeability of the sealing layer.
- The residual CO2 saturation has a significant impact on the spatial distribution of CO2 plume and mass of CO2 stored in the open system. Moreover, the number of injection wells may have an influence on the storage capacity. The constant pressure injection cases demonstrate higher storage capacity than the constant injection rate case. The mass of CO2 stored in aquifer increases as the residual CO2 saturation increase. In addition, the increase of the number of injection wells will enhance the CO2 storage capacity.
- Even though this study is based on the simplified aquifer system, the approach can apply to any complicated CO2 storage reservoir, and we can assess the CO2 storage capacity of Songliao Basin by this model. We recommended that it is better to estimate storage capacity through reservoir simulations firstly. Simulation results can give us a more reasonable injection strategy, injection time, wells layout strategy.

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