Numerical investigation of multi-layer CO$_2$ injection in deep saline aquifers with improperly abandoned wells

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Abstract

Single-layer and multi-layer CO$_2$ injection scenarios in idealized three-aquifer-two-aquitard systems have been numerically investigated. The investigation also assesses the impact of an improperly abandoned leaky well in the vicinity of the injection zone for both injection strategies. It is found that the maximum pressure buildups in multi-layer CO$_2$ injection cases are significantly less than that predicted in the corresponding single-layer CO$_2$ injection cases. Additionally, focused CO$_2$ leakage rates in multi-layer injection cases are found to be highly dependent on the thickness of the separating aquitard, which influences the mutual interference of the active-injection aquifers.

1. Introduction

Amongst all storage options available for geological CO$_2$ storage, deep saline aquifers were estimated to offer the largest storage potential. However, leaky wells and faults are believed to present a general concern over CO$_2$ leakage; in particular, improperly abandoned wells in the vicinity of the CO$_2$ injection wells present a particular concern over the security of the CO$_2$ sequestration process [1]. At present, there are many different injection strategies which have been either proposed or implemented in potential CO$_2$ sequestration sites. Recently, a brief investigation on the effect of multi-layer CO$_2$ injection in the Ordos Basin (China) has been carried out by Lui et al. [2] using a simplified three-dimensional (3D) symmetric model that imposes no-flux boundary condition at the centreline. The current work is motivated by the recent work of Lui et al. [2], with the aim of briefly comparing multi-layer CO$_2$ injections with single-layer injections. The effect of CO$_2$ leakage through an improperly abandoned well in the vicinity of the injection zone has also been investigated for both injection scenarios.

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2. Model setup and computational parameters

The multi-phase multi-component flow and transport of brine and CO₂ in idealized three-aquifer-two-aquitard sub-surface geo-storage systems, located approximately 1500 m below ground surface, was investigated using fully three-dimensional (3D) geometrical models of dimension 20 km x 20 km x 290 m as shown in Figure 1. The values chosen to represent the permeability, porosity and pore compressibility of the modelled aquifers, aquitards and the abandoned well can be found listed in Table 1.

![Figure 1](image-url) (a) Schematic of geomodel A; and (b) geomodel B used to represent three-aquifer-two-aquitard systems (NOT TO SCALE).

| Properties          | Values for aquifers | Values for aquitards | Leaky well field |
|---------------------|---------------------|----------------------|------------------|
| Permeability, $k$ (m$^2$) | $5.0 \times 10^{-14}$ | $1.0 \times 10^{-18}$ | $1.0 \times 10^{-11}$ |
| Pore compressibility, $\beta_p$ (Pa$^{-1}$) | $4.5 \times 10^{-10}$ | $9.0 \times 10^{-10}$ | $4.5 \times 10^{-10}$ |
| Porosity, $\phi$ | 0.30                | 0.10                 | 0.30             |

A total annual injection rate of 100,000 tonnes of CO₂ was specified, corresponding to the initial directives of the Ordos Basin pilot project. As for the initial conditions, hydrostatic pressure profile was assumed with respect to 150 bar at the top of aquifer 3, which roughly corresponds to pressure at a depth of 1,500 m. A geothermal gradient of 30 °C/km, varying from 60 °C at the top of aquifer 3 to 68.7 °C at the bottom of the storage formation, was also described. Moreover, the system was assumed to have an initial uniform salt mass fraction of 0.01. At the lateral walls, the fluid was allowed to escape the model domain by imposing a constant Dirichlet boundary condition, thus overpressuring of the system was avoided. Because the system was assumed to be bounded by the impermeable rocks on the uppermost and lowermost surface, no-flux Neumann boundary condition was imposed on the upper and lower surface. A total of four simulations were performed as summarised in Table 2.
3. Computational results

The numerical results show that the maximum pressure buildups in response to multi-layer CO₂ injection are significantly below that of the corresponding single-layer CO₂ injection cases with the same overall CO₂ injection rate. The results also show that mutual interference between active-injection aquifers in multi-layer injection scenarios may still lead to larger pressure buildups in certain strata, especially when the separating aquitard is shallow. From Figure 2, it can be noticed that for case 2, where injection takes places in the middle aquifer, downward migration of CO₂ via the abandoned well (from aquifer 2 to aquifer 1) may also occur. Although this downward migration assures the security of the injected CO₂, it is only estimated to be about 0.02% during the active-injection phase following the initial onset period, but it is insignificant once injection stops. Additionally, it is also revealed that for multi-layer injection scenarios, focused CO₂ leakage into overlying strata are likely to be suppressed due to mutual interference of the adjacent active-injection aquifers.

![Figure 2](image)

**Figure 2.** Focused CO₂ leakage rate via the abandoned well from aquifer 1 to aquifer 2 and aquifer 2 to aquifer 3 for simulation cases 1–4. The leakage rate has been expressed as a percentage of CO₂ injection rate.

| Computational case | Geometric model used | Aquifers with CO₂ injection | Annual CO₂ injection rate (tonnes/year) |
|--------------------|----------------------|-----------------------------|-----------------------------------------|
| Case 1             | Geomodel A           | Aquifer 1                   | 10⁵                                     |
| Case 2             | Geomodel A           | Aquifer 2                   | 10⁵                                     |
| Case 3             | Geomodel A           | Aquifer 1 & Aquifer 2       | 5 x 10⁴ in each of the aquifers         |
| Case 4             | Geomodel B           | Aquifer 1 & Aquifer 2       | 5 x 10⁴ in each of the aquifers         |
In large-scale carbon sequestration, CO2 dissolution in brine may play a vital role in improving the security of the injected CO2 by essential forming an intermediary process that gives way to negative buoyancy and immobilization via mineralisation. Therefore, an important parameter to characterize for different injection strategies is the fraction of the injected CO2 that dissolves in brine. The numerical results also indicate that the multi-layer injection cases led to larger dissolution rates than single-layer injection cases. It was estimated that at the end of 10 years simulation time, approximately 16% of the injected CO2 would be in aqueous form in multi-layer injection cases, whereas only 15% (approx.) would have dissolved in case 1 and 2. Although CO2 solubility generally increases with pressure [3,4] and multi-layer injection cases were associated with relatively low pressure buildups in the vicinity of the CO2 plume, cases 3 and 4 were still predicted to have the largest fraction of CO2 dissolved; it is likely that the enhanced dissolution rates in the multi-layer injection cases were due to relatively larger volume of brine available in contact with the CO2 plumes for dissolution.

4. Conclusions

A fully 3D modelling study was conducted to investigate the possible implications of deploying single- and multi-layer injection technologies in CO2 sequestration. The investigation reveals that if any two injection aquifers were separated by a shallow aquitard, focused CO2 leakage into overlying strata is likely to be suppressed due to mutual interference of the adjacent active-injection aquifers. Nonetheless, the optimum conditions for the different injection strategies depend on a variety of factors. Although it is generally not feasible for any one study to address a comprehensive parametric study, it is recommended that pursuance of further studies, namely parametric investigations involving many different factors including reservoir heterogeneities and complexities, are necessary to improve the understanding of flow behaviour with different injection strategies.

References

[1] Intergovernmental Panel on Climate Change (IPCC). Chapter 5 Underground geological storage. In: Metz B, Davidson O, de Coninck H, Loos M, Mayer L, editors. Special report on carbon dioxide capture and storage, Cambridge, UK/New York: Cambridge University Press; 2005, p.195-276.

[2] Lui H, Hou Z, Were P, Gou Y, Sun X. Simulation of CO2 plume movement in multilayered saline formations through multilayer injection technology in the Ordos Basin, China. Environ Earth Sci 2013; DOI:10.1007/s12665-013-2839-4.

[3] Pruess K. ECO2N: a TOUGH2 fluid property module for mixtures of water, NaCl, and CO2. Report no.: LBNL-57952. Berkeley (CA): Lawrence Berkeley National Laboratory Report; 2005.

[4] Carroll JJ, Slupsky JD, Mather AE. The solubility of carbon dioxide in water at low pressure. J Phys Chem Ref Data 1991;20(8):1201–9.

Biography:

Wasim A. Akber Hassan currently holds a BEng degree from Brunel University (2009) and a Ph.D. in Engineering from Lancaster University (2014) under the supervision of Professor Xi Jiang. His current research focuses on numerical simulations of geological CO2 storage.