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The effect of WACO2 ratio on CO2 geo-sequestration efficiency in homogeneous reservoirs

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Abstract

Various factors such as reservoir temperature, wettability, caprock properties, vertical to horizontal permeability ratio, salinity, reservoir heterogeneity, injection well configuration affect the CO2 geo-sequestration efficiency. Furthermore, it was previously investigated that CO2 storage efficiency can be improved by using water alternating CO2 (WACO2) technology. However, the effect of the WACO2 ratio (the ratio of the total amount of injected CO2 to the total amount of injected water) on CO2 storage efficiency has not been addressed adequately. Thus, in this paper, a 3D homogeneous reservoir simulation model has been developed to study the impact of the WACO2 ratio on CO2 mobility and CO2 trapping capacity using five different WACO2 ratios (i.e. 3, 2, 1, 1/2, and 1/3). For all WACO2 ratios tested, 9000 kton (kt) of CO2 were injected during 3 CO2 injection cycles (2 years each) and at an injection rate of 1500 kt per year. Each CO2 injection cycle was followed by a 2 years water injection cycle with injection rates of 500 kt/year, 750 kt/year, 1500 kt/year, 3000 kt/year, and 4500 kt/year for the 3, 2, 1, 1/2, and 1/3 WACO2 ratios, respectively. Then, this 12 years WACO2 injection period was followed by a 100 years post-injection period. Our results clearly indicate, after 100 years post-injection period, that the WACO2 ratio has an important effect on the CO2 migration distance, CO2 mobility and CO2 trapping capacity. The results demonstrate that lower WACO2 ratio leads to reduce the vertical CO2 plume migration and CO2 mobility. Furthermore, low WACO2 ratio enhances the capacities of capillary and solubility trapping mechanisms. Thus, we conclude that WACO2 has a significant impact on the geo-sequestration efficiency and less WACO2 ratios are preferable.

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1. Introduction

CO₂ capture and geological sequestration is considered an important technology to reduce CO₂ emission to the atmosphere by capturing the CO₂ from various sources and injecting it into deep geological reservoirs including unminable coal seams, hydrocarbon reservoirs, and saline aquifers [1]. However, due to the density difference between the injected CO₂ and formation water, CO₂ migrates upwards with a possible leaking back to the atmosphere [2]. This CO₂ leakage risk can be prevented by different trapping mechanisms including structural trapping [3], capillary trapping [4], dissolution trapping [5], and mineral trapping [6].

The storage efficiency of these geological trapping mechanisms is affected by different physical and geological parameter including CO₂ wettability [7-10], wettability heterogeneity [11], caprock characteristics [3], permeability anisotropy [12], permeability and porosity distribution [7], aquifer water salinity [13, 14]. Furthermore, CO₂ geo-sequestration efficiency can be enhanced by optimizing the CO₂ injection well configuration [15] and the CO₂ injection scenarios (e.g. WACO₂, intermittent injection, or continuous injection) [16-18]. Even though water alternating CO₂ (WACO₂) technology has been clearly addressed as an important method to improve the CO₂ geo-sequestration efficiency, the impact of the WACO₂ ratio on CO₂ geo-sequestration efficiency has not been investigated.

Thus, here, we investigated the impact of the WACO₂ ratio of the CO₂ plume migration distance, CO₂ mobility, capillary trapping capacity, and dissolution trapping capacity by building a 3D homogeneous reservoir simulation model and testing five different WACO₂ ratios: 3, 2, 1, 1/2, and 1/3.

2. Methodology

To study the influence of the WACO₂ ratio on CO₂ geo-sequestration efficiency, we have built a 3 dimensional homogeneous reservoir simulation model using TOUGH2-ECO2M [19, 20]. The model dimensions are 2000 × 2000 × 1500 m with regular and fine scale grids of 50 × 50 × 30 in X, Y, Z directions, respectively (Figure 1). The model was homogeneous in terms of porosity (22%) and permeability with a horizontal permeability of 1000 mD and vertical permeability anisotropy (Kv/kh) of 10%. The aquifer model was initially completely saturated with water with an initial water saturation (Sw) of 100% and a formation water salinity of 15 wt% NaCl. The reservoir temperature was 343 K (isothermal) and the initial reservoir pressure at the bottom depth of the reservoir (2500 m) was 25 MPa. In addition, constant pressure boundary conditions have been applied to the model outer boundaries.

For all WACO₂ ratios tested, 9000 kt of CO₂ were injected at a depth of 2275 m during 3 CO₂ injection cycles (2 years each) and at an injection rate of 1500 kt per year. Each CO₂ injection cycle was followed by a 2 years water injection period at a depth of 2125 m with injection rates of 500 kt/year, 750 kt/year, 1500 kt/year, 3000 kt/year, and 4500 kt/year for the 3, 2, 1, 1/2, and 1/3 WACO₂ ratios, respectively. Then, this 12 years WACO₂ (6 years for CO₂ injection and 6 years for water injection) injection period was followed by a 100 years post-injection period.

Furthermore, for all tested WACO₂ ratios, the same pair of relative permeability and capillary pressure curves (intermediate-wet) has been used, for each injection cycle [7, 8]. The influence of the WACO₂ injection on the capillary pressure and relative permeability curves has been simulated based on previous experimental data (Figure 2) [21-23]. These relative permeability and capillary pressure curves have been imported into the developed model using Van Genuchten-Mualem model [24, 25]:

\[
(P_c) = P_i \left((S^*)^{-1/\lambda} - 1\right)^{1-\lambda}
\]

\[
k_{rg} = (1 - S)^{2} \left(1 - S^{2}\right) \quad \text{if} \quad S_{gr} > 0
\]

\[
k_{rg} = 1 - k_{rw} \quad \text{if} \quad S_{gr} = 0
\]

\[
k_{rw} = 1 \quad \text{if} \quad S_{w} \geq S_{ws}
\]

\[
\text{if} \quad S_{gr} > 0
\]

\[
\text{if} \quad S_{gr} = 0
\]

\[
\text{if} \quad S_{w} \geq S_{ws}
\]
\[ k_{rw} = \sqrt{S^* \left(1 - \left[1 - \left(S^*/\lambda\right)^{1/\lambda}\right]\right)^2} \quad \text{if} \quad S_w < S_{WS} \quad (5) \]

\[ S^* = \frac{(S_w - S_{wr})}{(S_{WS} - S_{wr})}, \quad \bar{S} = \frac{(S_w - S_{wr})}{(1 - S_{wr} - S_{gr})} \quad (6) \]

where: \( k_{rg} \) = gas relative permeability, \( k_{rw} \) = water relative permeability, \( S_{gr} \) = residual gas saturation, \( S_w \) = water saturation, \( S_{WS} \) = maximum water saturation, \( S_{wr} \) = residual water saturation, \( P_c \) = capillary pressure, \( P_l \) = capillary pressure scaling factor, and \( \lambda \) = pore size distribution index.

Fig. 1 3D view of the developed reservoir model showing the model dimensions, reservoir pressure distribution and injection well location.

Table 1. Amount of injected CO\(_2\) and water for the different WACO\(_2\) ratios.

<table>
<thead>
<tr>
<th>WACO(_2) ratio (CO(_2) mass/ water mass)</th>
<th>CO(_2) injection rate (kt/year)</th>
<th>Total injected CO(_2) (kt)</th>
<th>Total injected water (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>1500</td>
<td>9000</td>
<td>27000</td>
</tr>
<tr>
<td>1/2</td>
<td>1500</td>
<td>9000</td>
<td>18000</td>
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<tr>
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<td>9000</td>
<td>9000</td>
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<td>2</td>
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<td>9000</td>
<td>4500</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>9000</td>
<td>3000</td>
</tr>
</tbody>
</table>

3. Results and discussion

3.1. Effect of WACO\(_2\) ratio on CO\(_2\) migration

For all WACO\(_2\) ratios, after the end of CO\(_2\) and water injection cycles (12 years), the injection well was shutdown to simulate the CO\(_2\) storage period (100 years). Figure 3 presents 2D views of the CO\(_2\) plume through the center of the reservoir for the different WACO\(_2\) ratios, at the end of the CO\(_2\) storage period. By comparing the CO\(_2\) plume migration distance for the different WACO\(_2\) ratios (i.e. 3, 2, 1, 1/2, and 1/3), it is clear that the WACO\(_2\) ratio affects the vertical CO\(_2\) plume migration. The results show that increasing the WACO\(_2\) ratio leads to increase the vertical CO\(_2\) plume migration. For example, the shallowest depth reached by CO\(_2\) plume was 1200 m for the 1/3 WACO\(_2\) ratio at the end of the storage period (100 years), while it reached the top depth of the model (1000 m) after only 10 years storage time and then flowed horizontally beneath the top seal (Figure 3).

Fig. 2 Relative permeability (left side) and capillary pressure (right side) curves for the three CO\(_2\) and water injection cycles. Solid lines represent the CO\(_2\) injection process and dashed lines represent the water injection process.
Table 1. Amount of injected CO₂ and water for the different WACO₂ ratios.

<table>
<thead>
<tr>
<th>WACO₂ ratio (CO₂ mass/ water mass)</th>
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<td>9000</td>
<td>4500</td>
<td>27000</td>
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<td>4500</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>9000</td>
<td>500</td>
<td>3000</td>
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</tbody>
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3.2. Effect of WACO₂ ratio on trapping capacity

The solubility and capillary trapping capacities (Figure 4), and CO₂ mobility (free supercritical CO₂) (Figure 5) have been calculated as function of different WACO₂ ratios at the end of the storage period (100 years). The results
Thus, we conclude that WACO\(_2\) ratio has a significant effect on CO\(_2\) geo-sequestration and that lower WACO\(_2\) ratio solubility trapping capacity was 1345 kt for the 3 WACO\(_2\) ratio scenario, 1416 kt for the 2 WACO\(_2\) ratio scenario, 1692 for the 1 WACO\(_2\) ratio scenario, 2038 for the 1/2 WACO\(_2\) ratio scenario, and 2493 for the 1/3 WACO\(_2\) ratio scenario, after 100 years storage time; Figure 4). Furthermore, our results show that lower WACO\(_2\) ratio enhances the capillary trapping capacity (e.g. the capillary trapping capacity was only 5470 kt in the 3 WACO\(_2\) ratio model, while it was 6257 kt in the 1/3 WACO\(_2\) ratio model, after 100 years post-injection time; Figure 4). Moreover, the results demonstrate that the CO\(_2\) mobility is affected by the ratio of WACO\(_2\) and that higher WACO\(_2\) ratio leads to improvements in the geo-sequestration efficiency by reducing the volume of free supercritical CO\(_2\) and enhancing the dissolution and capillary trapping capacities.

![Fig. 4](image)

**Fig. 4.** The capacity of solubility trapping (left side) and capillary trapping (right side) for the different WACO\(_2\) ratio after 100 years storage time.

![Fig. 5](image)

**Fig. 5.** The amount of free supercritical CO\(_2\) (mobile CO\(_2\)) for the different WACO\(_2\) ratio after 100 years storage time.

4. Conclusions

The capacity of CO\(_2\) trapping mechanisms and underground CO\(_2\) movement are influenced by various factors (e.g. CO\(_2\) wettability, wettability heterogeneity, the properties of caprock, permeability anisotropy, permeability and porosity distribution, aquifer temperature, formation water salinity, and injection well configuration [3, 7-15].
Furthermore, Previous studies clearly showed that WACO₂ injection can improve the CO₂ trapping capacity and reduce the risk of CO₂ leakage [16-18]. However, the influence of the WACO₂ ratio on CO₂ geo-sequestration efficiency is not fully understood yet. Thus, in this paper, we have developed a 3D homogeneous reservoir simulation model to test five different WACO₂ ratios (ranging from 3 to 1/3).

Our simulation results clearly show that WACO₂ ratio has a noticeable effect on CO₂ trapping capacity and CO₂ movement. Our results demonstrate that decreasing WACO₂ ratio decreases the vertical CO₂ migration. In addition, the results show that reducing WACO₂ ratio can improve the solubility and dissolution trapping capacities.

Thus, we conclude that WACO₂ has a significant impact on the CO₂ geo-sequestration efficiency and less WACO₂ ratios are preferable.

References


