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The effect of WACO$_2$ ratio on CO$_2$ 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 CO$_2$ geo-sequestration efficiency. Furthermore, it was previously investigated that CO$_2$ storage efficiency can be improved by using water alternating CO$_2$ (WACO$_2$) technology. However, the effect of the WACO$_2$ ratio (the ratio of the total amount of injected CO$_2$ to the total amount of injected water) on CO$_2$ 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 WACO$_2$ ratio on CO$_2$ mobility and CO$_2$ trapping capacity using five different WACO$_2$ ratios (i.e. 3, 2, 1, 1/2, and 1/3). For all WACO$_2$ ratios tested, 9000 kton (kt) of CO$_2$ were injected during 3 CO$_2$ injection cycles (2 years each) and at an injection rate of 1500 kt per year. Each CO$_2$ 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 WACO$_2$ ratios, respectively. Then, this 12 years WACO$_2$ injection period was followed by a 100 years post-injection period. Our results clearly indicate, after 100 years post-injection period, that the WACO$_2$ ratio has an important effect on the CO$_2$ migration distance, CO$_2$ mobility and CO$_2$ trapping capacity. The results demonstrate that lower WACO$_2$ ratio leads to reduce the vertical CO$_2$ plume migration and CO$_2$ mobility. Furthermore, low WACO$_2$ ratio enhances the capacities of capillary and solubility trapping mechanisms. Thus, we conclude that WACO$_2$ has a significant impact on the geo-sequestration efficiency and less WACO$_2$ 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 temperature [11], formation 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 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]:

\[ P_r = P_i \left( \left( S_r^* \right)^{\lambda} - 1 \right)^{1-\lambda} \]  
\[ k_{rg} = \left( 1 - S_r \right)^2 \left( 1 - S_w^2 \right) \quad \text{if } S_{gr} > 0 \]  
\[ k_{rg} = 1 - k_{rw} \quad \text{if } S_{gr} = 0 \]  
\[ k_{rw} = 1 \quad \text{if } S_w > S_{ws} \]
\[ k_{rw} = \sqrt{S^* \left\{1 - (1 - [S^*]^{1/\lambda})^2 \right\}} \quad \text{if} \quad S_w < S_{WS} \]  

\[ S^* = \frac{(S_w - S_{WR})}{(S_{WS} - S_{WR})}, \quad \tilde{S} = \frac{(S_w - S_{WR})}{(1 - S_{WR} - S_{GR})} \]  

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.

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 CO\(_2\) and water for the different WACO\(_2\) ratios.

<table>
<thead>
<tr>
<th>WACO(_2) ratio ((\text{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 rate (kt/year)</th>
<th>Total injected water (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
<td>1500</td>
<td>9000</td>
<td>4500</td>
<td>27000</td>
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<tr>
<td>1/2</td>
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<td>9000</td>
<td>3000</td>
<td>18000</td>
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<tr>
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<td>9000</td>
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<td>9000</td>
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<tr>
<td>3</td>
<td>1500</td>
<td>9000</td>
<td>500</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. 3. 2D views of the CO\(_2\) plume through the center of the storage reservoir for the different WACO\(_2\) ratio.

3.2. Effect of WACO\(_2\) ratio on trapping capacity

The solubility and capillary trapping capacities (Figure 4), and CO\(_2\) mobility (free supercritical CO\(_2\)) (Figure 5) have been calculated as function of different WACO\(_2\) ratios at the end of the storage period (100 years). The results
\[ k_{kr} = k_{rw} \] where:

- \( k_{kr} \) = gas relative permeability,
- \( k_{rw} \) = water relative permeability,
- \( S_{gr} \) = residual gas saturation,
- \( S_w \) = water saturation,
- \( S_{gw} \) = maximum water saturation,
- \( S_{rw} \) = residual water saturation,
- \( P_{cc} \) = capillary pressure,
- \( P_{ci} \) = capillary pressure scaling factor, and
- \( \lambda \) = pore size distribution index.

### Table 1. Amount of injected CO2 and water for the different WACO2 ratios.

<table>
<thead>
<tr>
<th>WACO2 ratio (CO2 mass/ water mass)</th>
<th>CO2 injection rate (kt/year)</th>
<th>Total injected CO2 (kt)</th>
<th>water injection rate (kt/year)</th>
<th>total injected water (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3</td>
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<td>4500</td>
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<tr>
<td>3</td>
<td>1500</td>
<td>9000</td>
<td>500</td>
<td>3000</td>
</tr>
</tbody>
</table>

### 3. Results and discussion

#### 3.1. Effect of WACO2 ratio on CO2 migration

For all WACO2 ratios, after the end of CO2 and water injection cycles (12 years), the injection well was shutdown to simulate the CO2 storage period (100 years). Figure 3 presents 2D views of the CO2 plume through the center of the reservoir for the different WACO2 ratios, at the end of the CO2 storage period. By comparing the CO2 plume migration distance for the different WACO2 ratios (i.e. 3, 2, 1, 1/2, and 1/3), it is clear that the WACO2 ratio affects the vertical CO2 plume migration. The results show that increasing the WACO2 ratio leads to increase the vertical CO2 plume migration. For example, the shallowest depth reached by CO2 plume was 1200 m for the 1/3 WACO2 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).

![Image of CO2 plume for different WACO2 ratios.](image)

Fig. 3. 2D views of the CO2 plume through the center of the storage reservoir for the different WACO2 ratio.

#### 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 WACO2 ratio has a significant effect on CO2 geo-sequestration and that lower WACO2 ratio indicated that reducing WACO2 leads to a significant increasing in the solubility trapping capacity (e.g. the results demonstrate that the CO2 mobility is affected by the ratio of WACO2 and that higher WACO2 ratio leads to 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. Therefore, we conclude that WACO2 ratio has a significant effect on CO2 geo-sequestration and that lower WACO2 ratio enhances the dissolution and capillary trapping capacities.

![Fig. 4. The capacity of solubility trapping (left side) and capillary trapping (right side) for the different WACO2 ratio after 100 years storage time.](image)

![Fig. 5. The amount of free supercritical CO2 (mobile CO2) for the different WACO2 ratio after 100 years storage time.](image)

4. Conclusions

The capacity of CO2 trapping mechanisms and underground CO2 movement are influenced by various factors (e.g. CO2 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


