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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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Keywords: $WACO_2$; Geo-sequestration; CO_2 storage; Trapping Capacity; Reservoir simulation

1. Introduction

CO_2 capture and geological sequestration is considered an important technology to reduce CO_2 emission to the atmosphere by capturing the CO_2 form 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 CO_2 and formation water, CO_2 migrates upwards with a possible leaking back to the atmosphere [2]. This CO_2 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 CO_2 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, CO_2 geo-sequestration efficiency can be enhanced by optimizing the CO_2 injection well configuration [15] and the CO_2 injection scenarios (e.g. $WACO_2$, intermittent injection, or continuous injection) [16-18]. Even though water alternating CO_2 ($WACO_2$) technology has been clearly addressed as an important method to improve the CO_2 geo-sequestration efficiency, the impact of the $WACO_2$ ratio on CO_2 geo-sequestration efficiency has not been investigated.

Thus, here, we investigated the impact of the $WACO_2$ ratio of the CO_2 plume migration distance, CO_2 mobility, capillary trapping capacity, and dissolution trapping capacity by building a 3D homogeneous reservoir simulation model and testing five different $WACO_2$ ratios: 3, 2, 1, 1/2, and 1/3.

2. Methodology

To study the influence of the $WACO_2$ ratio on CO_2 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 $WACO_2$ ratios tested, 9000 kt of CO_2 were injected at a depth of 2275 m 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 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 $WACO_2$ ratios, respectively. Then, this 12 years $WACO_2$ (6 years for CO_2 injection and 6 years for water injection) injection period was followed by a 100 years post-injection period.

Furthermore, for all tested $WACO_2$ 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 $WACO_2$ 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]:

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

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

$$k_{rg} = 1 - k_{rw} \quad \text{if} \quad S_{gr} = 0 \quad (3)$$

$$k_{rw} = 1 \qquad \text{if} \quad S_w \geq S_{ws} \quad (4)$$

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

$$S^* = (S_w - S_{wr})/(S_{ws} - S_{wr}), \;\; \hat{S} = (S_w - S_{wr})/(1 - S_{wr} - S_{gr}) \tag{6}$$

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_i = capillary pressure scaling factor, and λ = pore size distribution index.

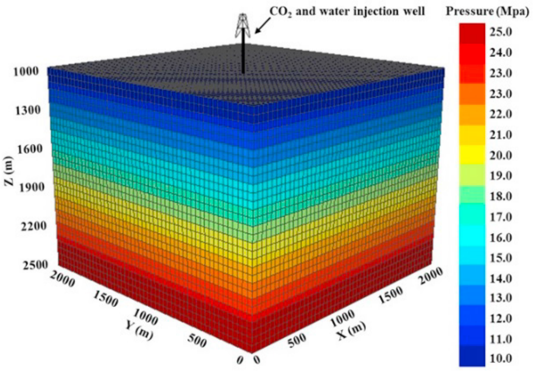

Fig.1 3D view of the developed reservoir model showing the model dimensions, reservoir pressure distribution and injection well location.

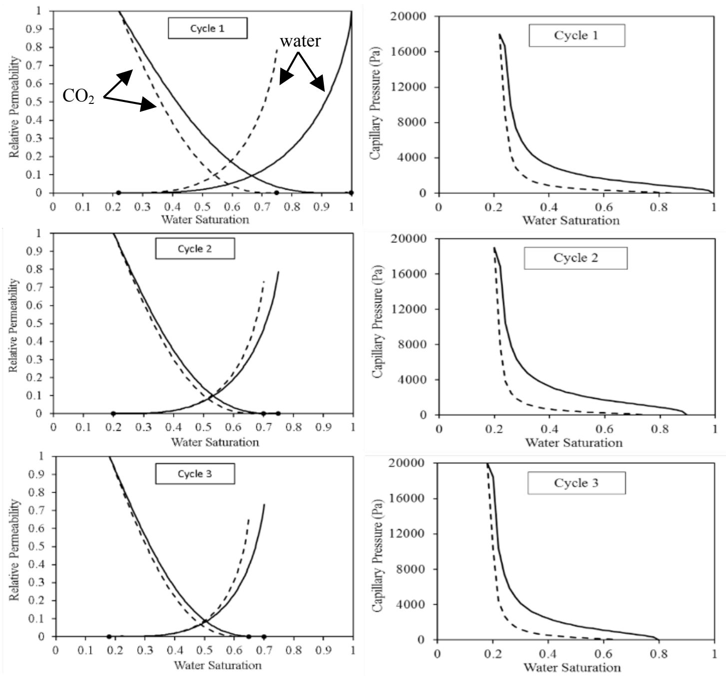

Fig.2 Relative permeability (left side) and capillary pressure (right side) curves for the three CO_2 and water injection cycles. Solid lines represent the CO_2 injection process and dashed lines represent the water injection process.

Table 1. Amount of injected CO_2 and water for the different $WACO_2$ ratios.

$WACO_2$ ratio (CO_2 mass/ water mass)	CO_2 injection rate (kt/year)	Total injected CO_2 (kt)	water injection rate (kt/year)	total injected water (kt)
1/3	1500	9000	4500	27000
1/2	1500	9000	3000	18000
1	1500	9000	1500	9000
2	1500	9000	750	4500
3	1500	9000	500	3000

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 yeas). 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).

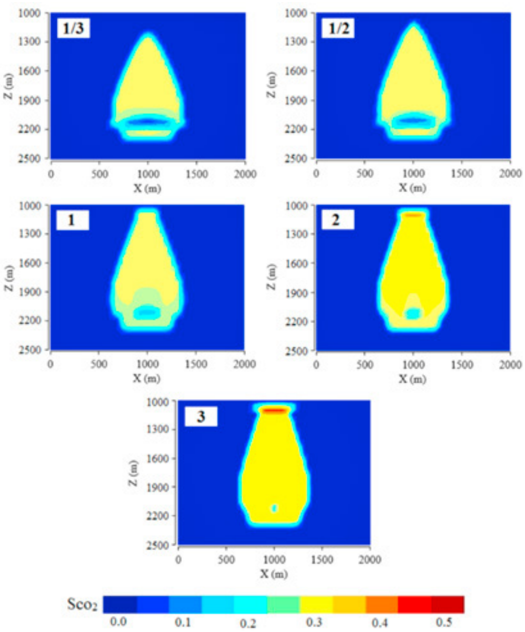

Fig. 3. 2D views of the CO_2 plume through the center of the storage reservoir for the different $WACO_2$ ratio.

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

clearly show that the CO_2 trapping capacity and CO_2 mobility are highly affected by the $WACO_2$. The results indicated that reducing $WACO_2$ leads to a significant increasing in the solubility trapping capacity (e.g. the 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 increase the amount of free supercritical CO_2 (e.g. the amount of free supercritical CO_2 (mobile CO_2) was increased from 250 kt to 2185 kt by increasing the $WACO_2$ ratio from 1/3 to 3, at the end of post-injection process; Figure 5).
Thus, we conclude that $WACO_2$ ratio has a significant effect on CO_2 geo-sequestration and that lower $WACO_2$ ratio improves the geo-sequestration efficiency by reducing the volume of free supercritical CO_2 and enhancing the dissolution and capillary trapping capacities.

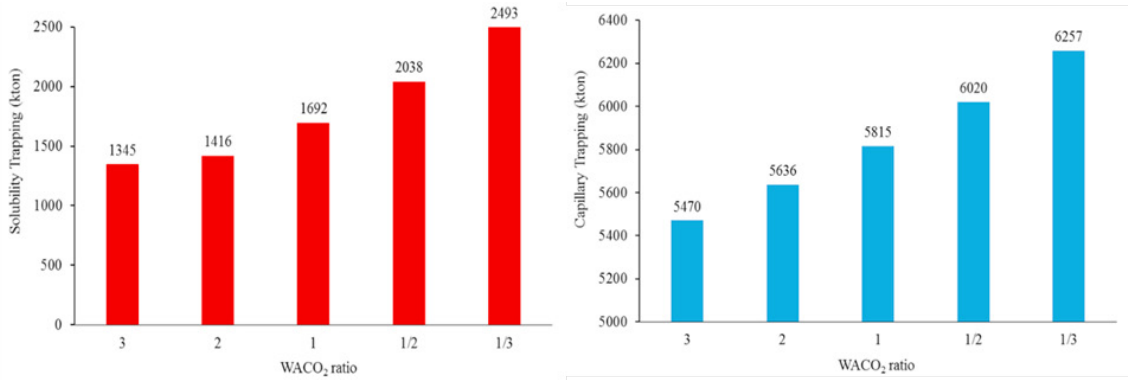

Fig. 4. The capacity of solubility trapping (left side) and capillary trapping (right side) for the different $WACO_2$ ratio after 100 years storage time.

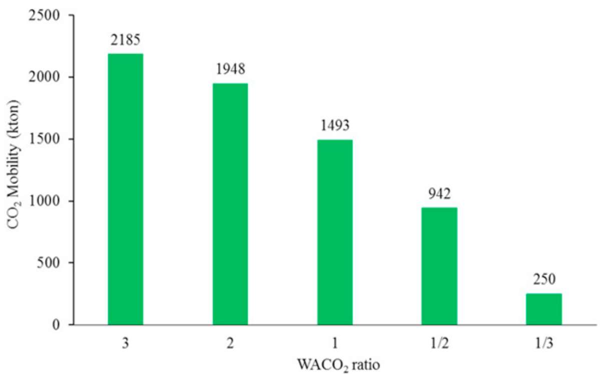

Fig. 5. The amount of free supercritical CO_2 (mobile CO_2) for the different $WACO_2$ ratio after 100 years storage time.

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 $WACO_2$ injection can improve the CO_2 trapping capacity and reduce the risk of CO_2 leakage [16-18]. However, the influence of the $WACO_2$ ratio on CO_2 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 $WACO_2$ ratios (ranging from 3 to 1/3).

Our simulation results clearly show that $WACO_2$ ratio has a noticeable effect on CO_2 trapping capacity and CO_2 movement. Our results demonstrate that decreasing $WACO_2$ ratio decreases the vertical CO_2 migration. In addition, the results show that reducing $WACO_2$ ratio can improve the solubility and dissolution trapping capacities.
Thus, we conclude that $WACO_2$ has a significant impact on the CO_2 geo-sequestration efficiency and less $WACO_2$ ratios are preferable.

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