The Influence of Capillary Entry-Pressure Representation on the Rate of CO_2 Solubility Trapping

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Introduction

CO_2 solubility trapping is an important CO_2 trapping mechanism in long-term CO_2 sequestration (CCS) in deep aquifers. An accurate representation of the capillary pressure is crucial in modeling CO_2 solubility trapping.

Usually, a P_c curve is either S-shaped (e.g., van Genuchten model) or convex (e.g., Brooks-Corey model), Their entry-pressure representations are different.

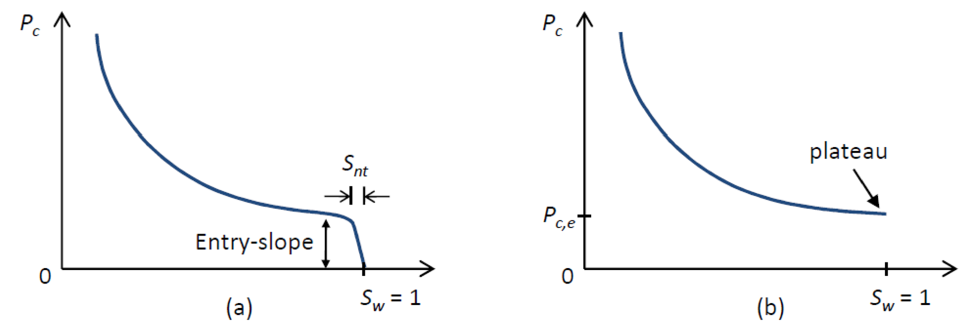


Figure 1: Capillary entry-pressure representations: (a) van-Genuchten-type (VG-type) representation; (b) Brooks-Corey-type (BC-type) representation.

Here, we show that the entry-pressure representation can greatly affect the rate of CO_2 solubility trapping, even when the S_{nt} is very small.

Why is this important?

(1) The impact on simulation result can be huge.
(2) Most CCS simulations employ one of the two P_c models.
(3) The VG model is almost exclusively used in the simulations performed by TOUGH2.

Simulation Model

2D vertical cross-section (x and z directions) of the benchmark model of Dahle et al. (2009)[1]

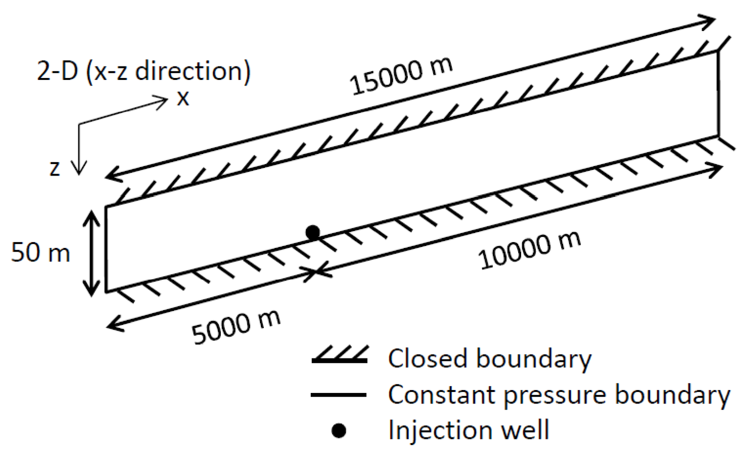


Figure 2: Sketch of the aquifer model.

Table 1: Properties of the aquifer model.

Name	Value
Grid number	$N_x = 150$, $N_y = 1$, $N_z = 40$
Gridblock size	$d_x = d_y = 100$ m, $d_z = 1.25$ m
Permeability	$k_x = k_y = k_z = 100$ md
Porosity	$\phi = 0.15$
Dip	1 %
Depth at the well	3025 m
Temperature	84.4 ℃
Salinity	0

$$k_{rw} = (S_w^*)^4,\quad k_{rn} = 0.4[1-(\hat{S}_w)^2](1-\hat{S}_w)^2, \tag{1a}$$
$$S_w^* = (S_w - S_{wi})/(1-S_{wi}),\quad S_{wi} = 0.2, \tag{1b}$$
$$\hat{S}_w = (S_w - S_{wi})/(1-S_{wi}-S_{nc}),\quad S_{nc} = 0. \tag{1c}$$
$$P_c = P_{c,e}(S_w^*)^{-0.5},\quad P_{c,e} = 0.2 \text{ bar}. \tag{2}$$

Simulation Results – Base Case

Injection rate: 9000 metric ton / year; Injection time: 20 years.
Simulator: Stanford General Purpose Research Simulator (GPRS) Fully Implicit Method.
Base case: Modify Eqn (2) into VG-type, S_{nt} = 0.005.

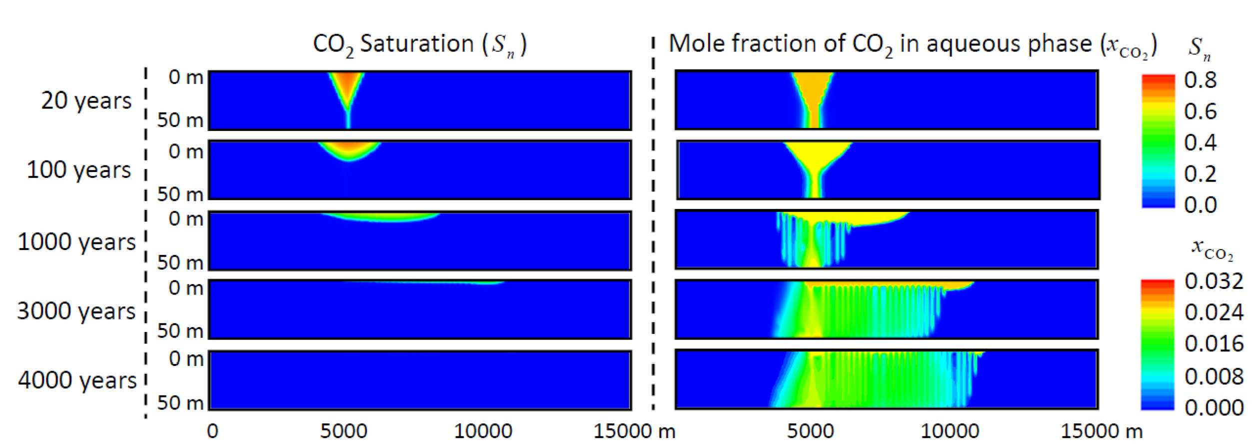


Figure 3: Base case simulation results. Hysteresis is not modeled for simplicity.

Entry-Pressure Representations

Keeping all other parameters unchanged, simulations are performed using different representations of the capillary entry pressure.

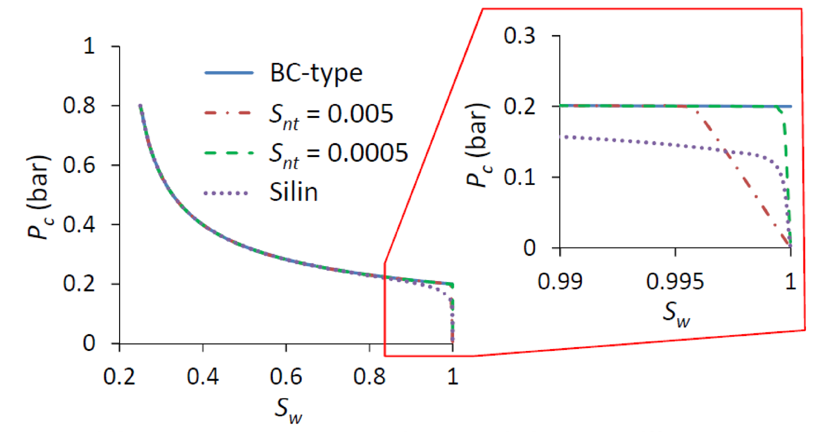


Figure 4: Different representations of the capillary entry pressure.

All four curves in Figure 4 are similar, except for the small difference near S_w = 1. However, these apparently small differences in the P_c curves lead to very large differences in the long-term predictions.

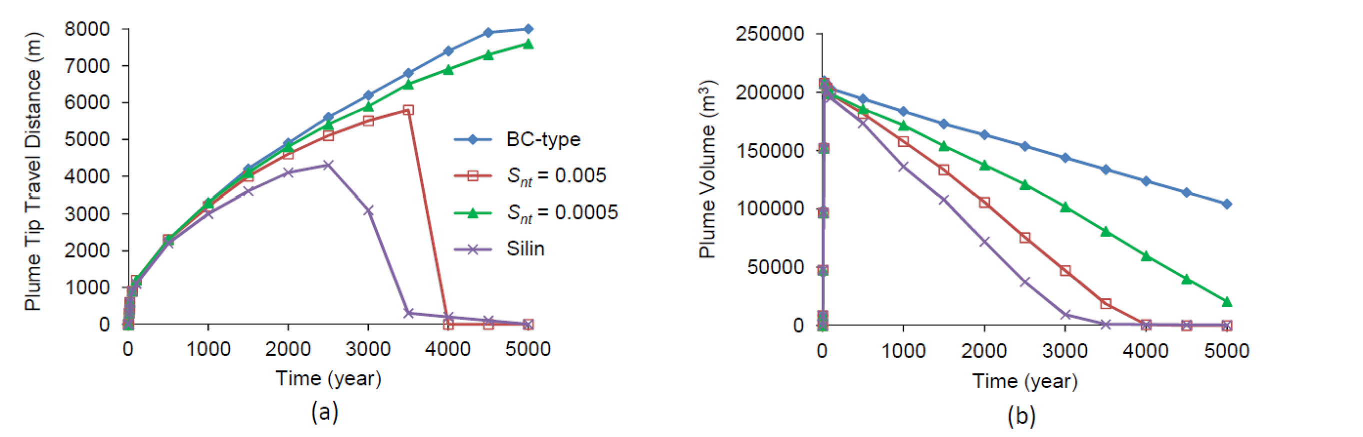


Figure 5: The sensitivity of simulation results to different entry-pressure representations.

Note that when dissolution is not modeled, the entry-pressure representation almost has no impact on simulation results.

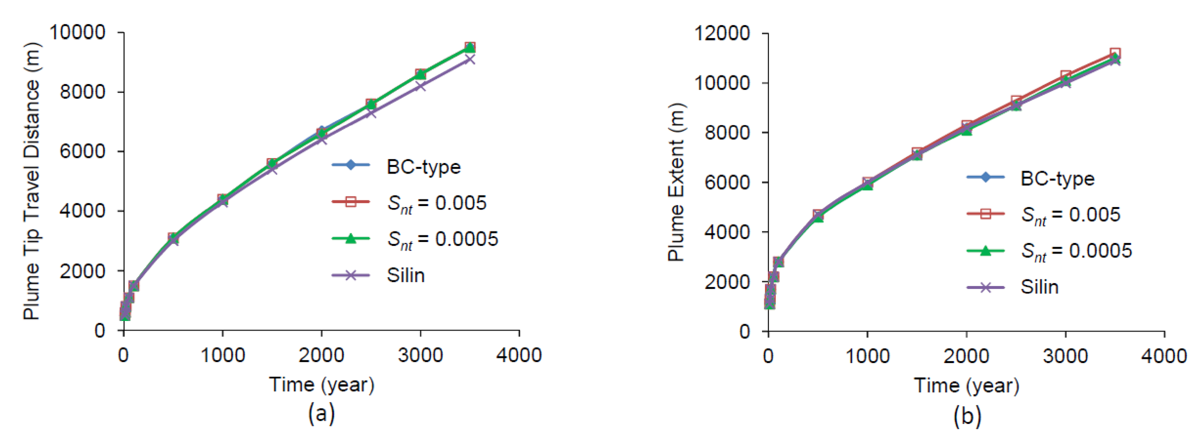
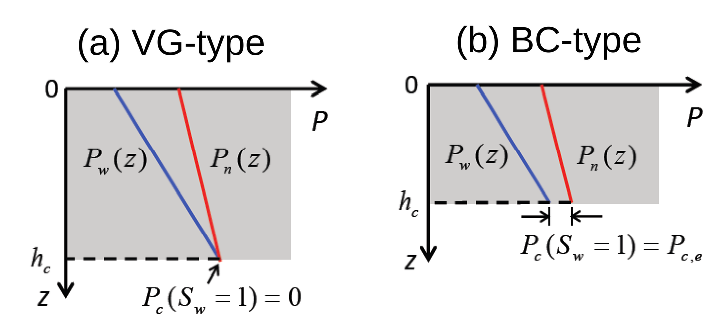


Figure 6: Simulation results when dissolution is not modeled.

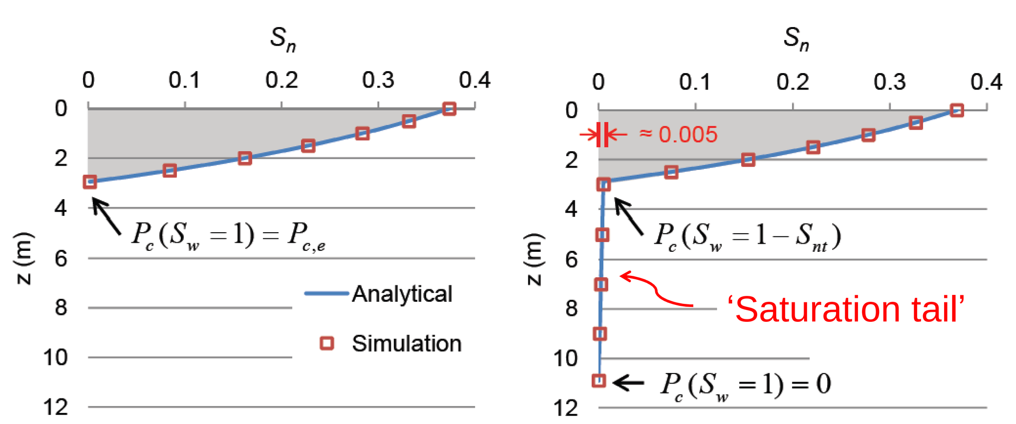
Causes of the Sensitivity

Gravity-capillary equilibrium:

$$P_w(z) = P_w|_{z=h_c} - r_w g(h_c - z), \tag{3a}$$
$$P_n(z) = P_n|_{z=h_c} - r_n g(h_c - z), \tag{3b}$$
$$P_c(z) = P_n(z) - P_w(z), \tag{3c}$$



Simulation:1D vertical column of 50 m. Each gridblock is 1 cm in size. Initially, S_n = 0.8 at the top 0.8 m, below is 0. The simulated CO_2 saturation distribution under equilibrium match analytical solutions exactly.



Name	Value
ρ_n	727 kg/m³
ρ_w	982 kg/m³
μ_n	0.070 cP
μ_w	0.342 cP

$$V = \int_0^{h_c} S_n(z)dz = 0.64$$

Figure 7: CO_2 saturation distribution under gravity-capillary-equilibrium (no dissolution).

The VG-type representation creates a 'saturation tail' under the major body of the CO_2 plume. This is not a numerical artifact – it is corroborated by analytical solutions. The 'tail' has almost no impact when dissolution is not modeled (e.g., Fig 6).

Length of the 'saturation tail': $h_c^{VG} - h_c^{BC} \approx [P_c^{BC}|_{S_w=1} - P_c^{VG}|_{S_w=1}]/[(r_w - r_n)g]$, (4)

When dissolution is modeled, the 'tail' can quickly dissolve, refill, and dissolve again. The cycle repeats, facilitating CO_2 dissolution.

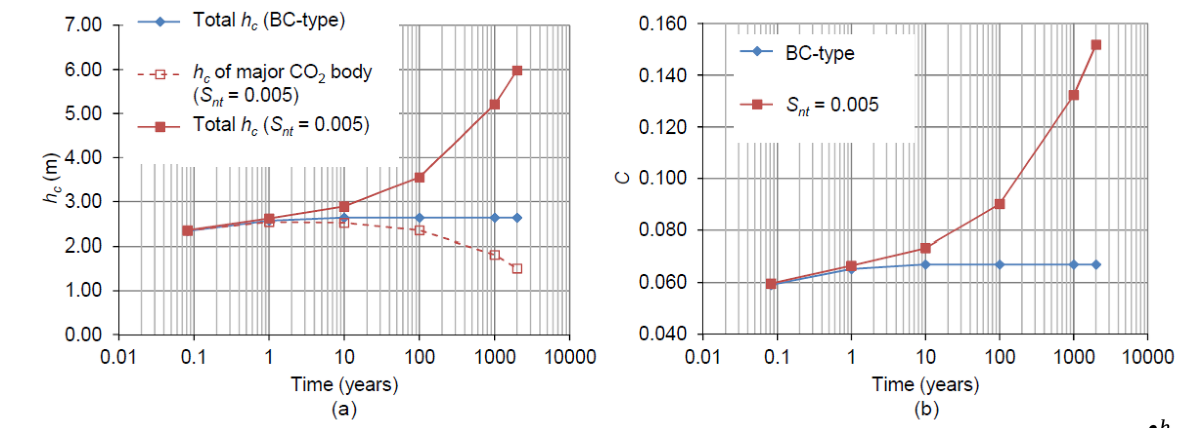


Figure 8: Development of the transition zone (dissolution is modeled). $C = \int_0^{h_c} x_{CO_2}(z)dz$

Characteristic time for the development of the transition zone [2]:

$$t^* = \frac{f}{k_z(\Delta r g)^2}\left(\frac{1}{l_w}+\frac{1}{l_n}\right)^*\left(\frac{dP_c}{dS_w}\right)^*, \tag{5}$$

Important factors: k_z, Δr, $l = k_r/m$, S_{nc} in Eqn (1c)

Density-driven convection is an important process in CO_2 solubility trapping [3,4]. We show that the VG-type representation facilitates the convection process.

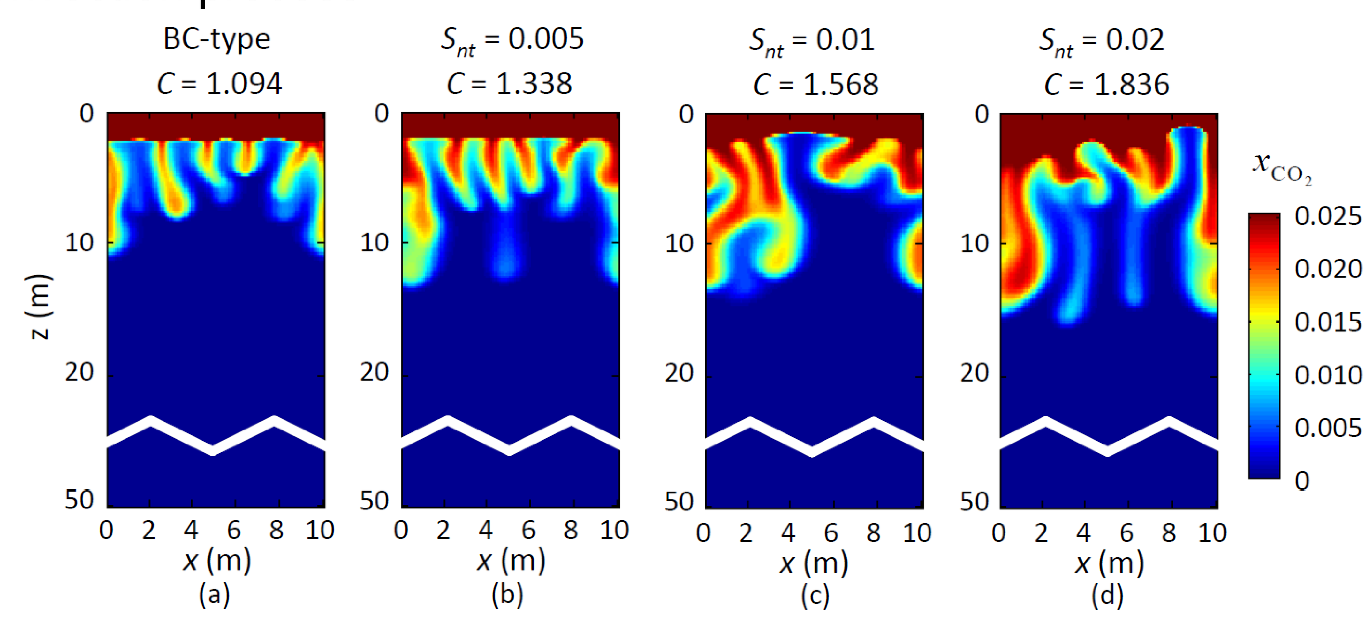


Figure 9: Influence of entry-pressure representation on density-driven convection.

Conclusions

(1) VG-type capillary entry-pressure representation can accelerate CO_2 solubility trapping significantly, compared with the BC-type.
(2) Simulation results are sensitive to the slope of the VG-type curve around the entry-pressure region.
(3) Recognizing this problem is important to long-term CCS simulation.
(4) We recommend using BC-type P_c model for its conservative estimates of CO_2 solubility trapping.

References

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Acknowledgements

The authors acknowledge Global Climate and Energy Project (GCEP) for financial support, and Dr. Gary Li, Dr. Yaqing Fan, and Ruslan Iskhakov for helpful discussions.

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