Abstract for master thesis (March 2008) (submitted January 31st 2008)

Numerical Study on the Rise of pCO_2 in Seawater by the Leakage of CO_2 Purposefully Stored under the Seabed

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1 Backgrounds and Objects

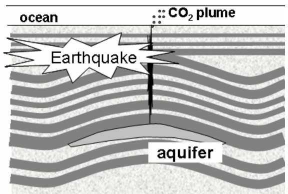
Geological storage of CO_2 under the seabed is one of the methods to mitigate the global warming. This method is considered to reduce CO_2 in the atmosphere and to attenuate the acidification in the surface water. However, this method has a risk of CO_2 leakage, which may cause impacts on the organism in the ocean near the leakage site. Therefore, it is important to know the behaviour of leaked CO_2 and its biological impact.

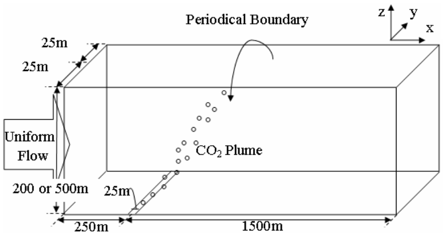
In this study, numerical simulations were conducted to investigate the behaviour of leaked CO_2 in the forms of bubbles and droplets, which is originally stored in the aquifer under the seabed, in a very extreme case, such as a large fault accidentally connects the CO_2 reservoir and the seabed by big earthquakes or other large diastrophisms (Fig.1). First, simulations were conducted in a simple rectangular domain in uniform flows (Fig.2) to see the impact of conditions of CO_2 leakage. In addition, a more realistic case simulation was also conducted with topography and tidal current around a Japanese coast (Fig.3).

2 Methods

A numerical model necessary for this purpose is similar to those developed to predict the behaviour of droplets of CO_2, which is purposefully injected in water column of the deep ocean, such as Sato and Sato [1]. Their method adopted an Eulerian-Lagrangian two-phase model; i.e. it used a finite difference method for the continuous seawater phase, and the movement of the dispersed phase was analysed by solving the motion equation of an individual bubble or droplet. Because the method of Sato and Sato [1] was developed to simulate the movement and dissolution of CO_2 droplets only, it is necessary to change the drag and mass transfer coefficients when dealing with bubbles in more shallow water. When a bubble rises in water, the water depth, or in other words, hydrostatic pressure, controls its shape; a sphere, an ellipsoid, or a spherical cap. The method was modified to adopt those shape change effect.

To simulate the broad area along a coastal line, MEC Full-3D Model [2] was adopted, which solves the hydrostatic-approximated NS-equation in a mesoscale domain, and the Full-3D NS-equation in a small domain. The Full-3D model domain was nested in a vertical cell-column of the mesoscale domain. The two-phase flow model mentioned above was incorporated in the Full-3D model. The target space in this study was limited to the ocean above the seabed, and did not include subsea underground. Leakage rate was based on the simulations of the CO_2 flow in geological formations found by the RITE [3].





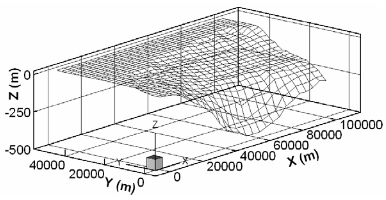


Fig.1 Image of CO_2 leakage. Fig.2 Schematic view of case studies. Fig.3 Calculation topography for the realistic simulation.

3 Two-phase simulation by Full-3D model

Table 1 shows the conditions of the case studies simulated with the computational domain as shown in Fig.2. These case studies were conducted to see the effects of leakage depth, size of bubbles/droplets, current velocity, and the background profiles of temperature, salinity, and TCO_2, on the rises of TCO_2 (ΔTCO_2) and pCO_2 (ΔpCO_2) from the background values. Leak-source band was perpendicular to the uniform flow, and was set to be infinity long by periodical boundary condition. Figs. 4 and 5 show the contour maps of volume fraction of undissolved CO_2 and ΔTCO_2, respectively, in Case 1 after 10 hours. CO_2 dissolves within the vertical distance of 100 m, and because of the infinity long leak-source band, ΔTCO_2 is almost equal in the downstream direction. Figs. 6 and 7 show the vertical profile of calculated ΔTCO_2 and ΔpCO_2, respectively, in each case at x=750 m. The figures show that the current velocity and the temperature profile have reasonable influences on the change of TCO_2 in the water, while the salinity profile is hardly meaningful. The size of bubbles/droplets is very important, because its effects on ΔTCO_2 are not monotonous. In particular, the background TCO_2 makes a large difference in ΔpCO_2, because of a nonlinear relation between pCO_2 and TCO_2. As a result, ΔpCO_2 in the all cases were smaller than the predicted non-effective concentration (PNEC), 500 ppm, proposed by Kita *et al* [4].

Table 1 Calculation conditions (The profile indicators suggest that S and D are shallow and deep, respectively, and L, H, and X are low, high, and extreme high, respectively.)

Case	Seabed depth (m)	Inflow velocity (m/s)	Mean initial diameter (m)	Temperature profile	Salinity profile	TCO_2 profile
1	200	0.05	0.020	T_{SL}	S_{SL}	C_{SL}
2	200	0.1	0.020	T_{SL}	S_{SL}	C_{SL}
3	200	0.05	0.040	T_{SL}	S_{SL}	C_{SL}
4	200	0.05	0.011	T_{SL}	S_{SL}	C_{SL}
5	200	0.05	0.020	T_{SH}	S_{SL}	C_{SL}
6	200	0.05	0.020	T_{SL}	S_{SH}	C_{SL}
7	200	0.05	0.020	T_{SL}	S_{SL}	C_{SH}
8	200	0.05	0.020	T_{SL}	S_{SL}	C_{SX}
9	500	0.05	0.020	T_{DL}	S_{DL}	C_{DL}
10	500	0.05	0.011	T_{DL}	S_{DL}	C_{DL}
11	500	0.05	0.0072	T_{DL}	S_{DL}	C_{DL}
12	500	0.05	0.020	T_{DH}	S_{DL}	C_{DL}
13	500	0.05	0.020	T_{DL}	S_{DH}	C_{DL}
14	500	0.05	0.020	T_{DL}	S_{DL}	C_{DH}

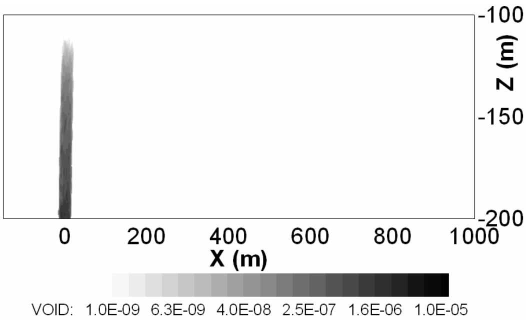


Fig. 4 Void fraction in Case 1.

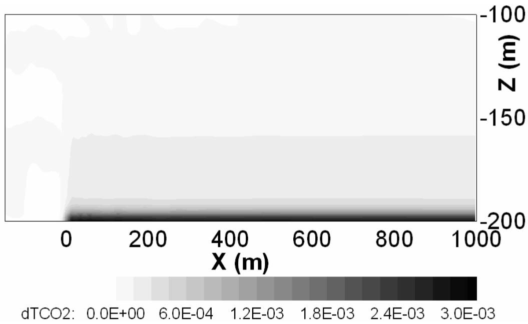
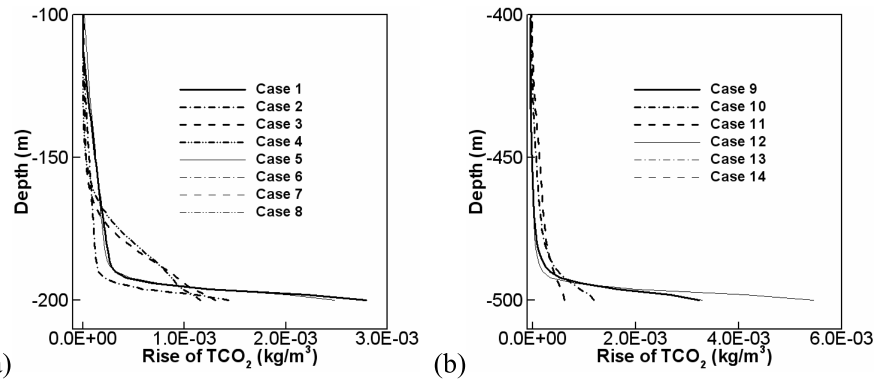
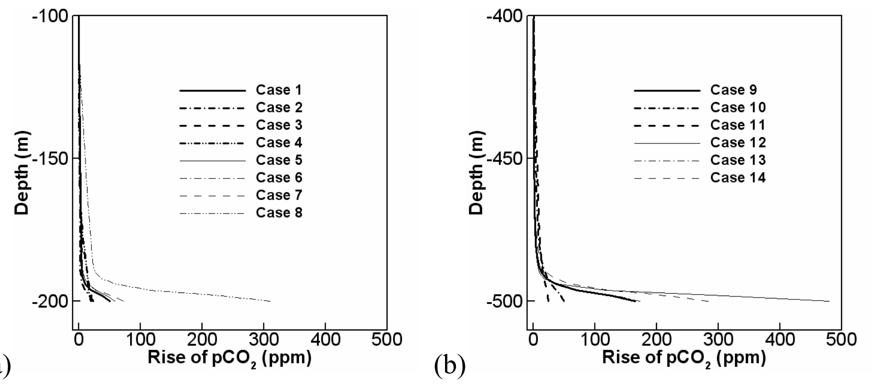


Fig. 5 ΔTCO_2 (kg/m^3) in Case 1.



(a) (b)

Fig. 6 Vertical profiles of calculated ΔTCO_2 (kg/m^3) at x = 750 m
for bubble cases (a) and for droplet cases (b).



(a) (b)

Fig. 7 Vertical profiles of calculated ΔpCO_2 (ppm) at x = 750 m
for bubble cases (c) and for droplet cases (d).

4 Mesoscale model simulation

More realistic simulation was conducted to see the impacts of topography and tidal current. Fig. 8 shows the time series of calculated TCO_2 in the Full-3D model domain. The values of TCO_2 gradually increased with time and came to be stable after 45 days. Fig. 9 shows the horizontal distribution of ΔpCO_2 in the hydrostatic model domain. CO_2-rich water gradually diffuses and flows by residual tidal current. In the hydrostatic model domain, ΔpCO_2 does not exceed the PNEC. Fig. 10 shows the vertical distribution of ΔpCO_2 in the Full-3D model domain. CO_2-rich water exceeds the PNEC at the timing of the stagnation of the tidal current. Fig. 11 shows ΔpCO_2 experienced by zooplanktons, which move as passive tracer. The figure shows that high-ΔpCO_2 period is short enough that the mortality does not reach the threshold. Therefore, it is suggested that the biological impact on moving organisms, such as zooplanktons, is not significant even in the extreme case.

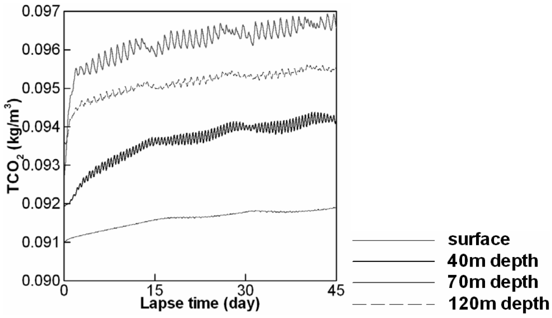


Fig.8 Time series of TCO_2.

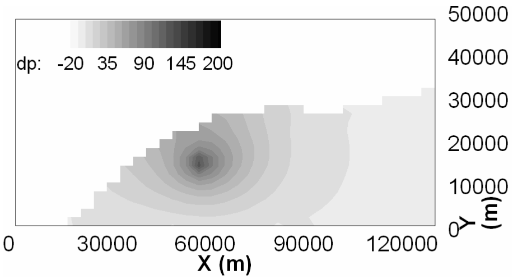


Fig.9 ΔpCO_2 (ppm) in the hydrostatic model domain.

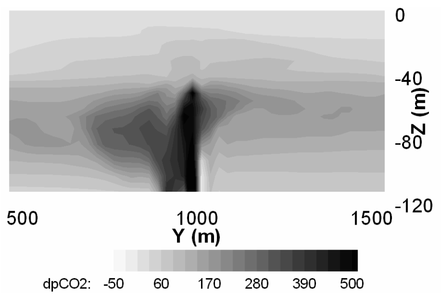


Fig.10 ΔpCO_2 (ppm) in the Full-3D model domain.

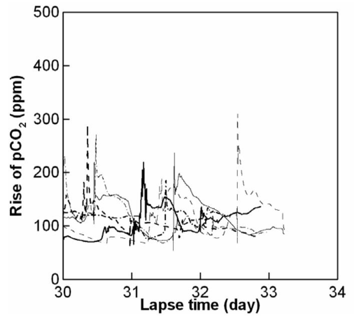


Fig.11 ΔpCO_2 experienced by zooplanktons.

4 Conclusions

In this study, a numerical simulation model was built and its simulation results were presented to show the behaviour of leaked CO_2, which is purposefully stored under the seabed. CO_2 was supposed to leak through an enormously large fault connecting directly the seabed and the reservoir.

The two-phase simulation by a Full-3D model was conducted with the simple rectangular solid water column with uniform background flows. Case studies show the large impact of temperature and background TCO_2 on ΔpCO_2, although ΔpCO_2 in the all cases were smaller than the PNEC. In a more realistic simulation with topography and tidal current near Japanese coast, even though the tidal current caused the stagnation of CO_2-rich water, the impact of ΔpCO_2 did not reach the fatal mortality for moving organisms, such as zooplanktons, in the present case. Therefore, it was suggested by the model simulations that the impact of leaked CO_2 on marine organisms is not significant, even in such an extreme case. However, for marine organisms that rarely travel, such as benthos, more detailed and careful examination is left as a future work. The accurate validation of the present simulation is another future work, because the actual experiment of CO_2 leakage from the seabed is difficult to be conducted in the present state. Natural analogue, such as the natural leakage of CO_2 observed in Kagoshima Bay, may be useful for this purpose.

References

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