MODELLING OF CO$_2$ DISPERSION LEAKED FROM SEAFOOR OFF JAPANESE COAST

Yuki KANO
Institute for Geo-Resources and Environment, National Institute of Advanced Industrial Science and Technology (AIST)

Toru SATO
Dept of Ocean Technology, Policy, and Environment, University of Tokyo
**Leak-Source Band**

**Width**: 25 m

**Length**: mid 3000m of 8000m (fault)

**Flow-rate of CO\(_2\)**: \(4 \times 10^{-5}\) kg/s/m\(^2\)

RITE CO\(_2\) sequestration project
2003 annual report

**Biological Impact**: \(\Delta pCO_2\)

**width**: 25m

**length**: 3000m

---

**Backgrounds: Risk of CO\(_2\) leakage in Geological Storage**
Objects

Build numerical model and present its simulations on the behaviour of leaked CO$_2$ originally stored under the seabed and $\Delta p$CO$_2$ in seawater caused by it.

1. Conduct parameter studies to see the impacts of conditions of CO$_2$ leakage and those of seawater.
2. Conduct a more realistic simulation with topography and tidal current.
Two-phase Flow Simulation by Full-3D model

Parameter studies with simple domain and uniform flow

See the impacts of conditions of CO₂ leakage and those of seawater
Two-phase flow simulation by Full-3D model: Method

Continuous phase (Seawater): Eulerian A

Dispersed phase (CO₂ bubble or droplet): Lagrangian B

TCO₂: A-D equation C

A: \[
\frac{\partial}{\partial t} (\alpha_B \rho_B u_B) + \nabla \cdot (\alpha_B \rho_B u_B) + \frac{\partial}{\partial t} (\alpha_A \rho_A u_A) + \nabla \cdot (\alpha_A \rho_A u_A)
\]

\[= -\nabla P + \nabla \cdot \left[ \alpha_B \rho_B \left( v_B + v_r \right) d_B \right] + \alpha_B \rho_B g \]

B: \[
\frac{D}{Dt} (\alpha_A \rho_A u_A) + \frac{D}{Dt} (\beta \alpha_B \rho_B u_B) - \frac{D}{Dt} (\beta \alpha_B \rho_B u_B) = \alpha_A \left[ -\nabla P + \rho_A g - \frac{3}{8r} C_D \frac{3}{4r} \rho_B \left| u_r \right| u_r - f_L \right] \]

C: \[
\frac{\nabla}{\nabla} (\alpha_B C) + u_B \frac{\nabla}{\nabla} (\alpha_B C) = \nabla \left[ \alpha_B \left( D + \frac{v_r}{Sc} \right) \nabla C \right] + \pi d^2 k (C_I - C) \]

Each model of \( C_D, k \)

sphere
ellipsoid
spherical-cap

CD, k

method

sphere
ellipsoid
spherical-cap

Two-phase flow simulation by Full-3D model: Method

Continuous phase (Seawater): Eulerian A

Dispersed phase (CO₂ bubble or droplet): Lagrangian B

TCO₂: A-D equation C

A: \[
\frac{\partial}{\partial t} (\alpha_B \rho_B u_B) + \nabla \cdot (\alpha_B \rho_B u_B) + \frac{\partial}{\partial t} (\alpha_A \rho_A u_A) + \nabla \cdot (\alpha_A \rho_A u_A)
\]

\[= -\nabla P + \nabla \cdot \left[ \alpha_B \rho_B \left( v_B + v_r \right) d_B \right] + \alpha_B \rho_B g \]

B: \[
\frac{D}{Dt} (\alpha_A \rho_A u_A) + \frac{D}{Dt} (\beta \alpha_B \rho_B u_B) - \frac{D}{Dt} (\beta \alpha_B \rho_B u_B) = \alpha_A \left[ -\nabla P + \rho_A g - \frac{3}{8r} C_D \frac{3}{4r} \rho_B \left| u_r \right| u_r - f_L \right] \]

C: \[
\frac{\nabla}{\nabla} (\alpha_B C) + u_B \frac{\nabla}{\nabla} (\alpha_B C) = \nabla \left[ \alpha_B \left( D + \frac{v_r}{Sc} \right) \nabla C \right] + \pi d^2 k (C_I - C) \]
Two-phase flow simulation by Full-3D model: Computational domain

Domain & Grids
Domain: 1650 m x 50 m x 200 or 500 m
Grid: 132 x 25 x 100 or 250
Minimum grid spacing: 2 m x 2 m x 2m

Boundary conditions
T,S,C,P:
X,Z-directions: inflow-fixed
outflow-zero gradient

Y-direction: Periodical
Velocity: Free-slip conditions
## Two-phase flow simulation by Full-3D model: Case studies

<table>
<thead>
<tr>
<th>Case</th>
<th>Seabed depth (m)</th>
<th>Inflow velocity (m/s)</th>
<th>Mean initial diameter (m)</th>
<th>Temperature profile</th>
<th>Salinity profile</th>
<th>TCO$_2$ profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{SL}$</td>
<td>$S_{SL}$</td>
<td>$C_{SL}$</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>0.1</td>
<td>0.020</td>
<td>$T_{SL}$</td>
<td>$S_{SL}$</td>
<td>$C_{SL}$</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>0.05</td>
<td>0.040</td>
<td>$T_{SL}$</td>
<td>$S_{SL}$</td>
<td>$C_{SL}$</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>0.05</td>
<td>0.011</td>
<td>$T_{SL}$</td>
<td>$S_{SL}$</td>
<td>$C_{SL}$</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{SH}$</td>
<td>$S_{SL}$</td>
<td>$C_{SL}$</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{SL}$</td>
<td>$S_{SH}$</td>
<td>$C_{SL}$</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{SL}$</td>
<td>$S_{SL}$</td>
<td>$C_{SH}$</td>
</tr>
<tr>
<td>8</td>
<td>200</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{SL}$</td>
<td>$S_{SL}$</td>
<td>$C_{SX}$</td>
</tr>
<tr>
<td>9</td>
<td>500</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{DL}$</td>
<td>$S_{DL}$</td>
<td>$C_{DL}$</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>0.05</td>
<td>0.011</td>
<td>$T_{DL}$</td>
<td>$S_{DL}$</td>
<td>$C_{DL}$</td>
</tr>
<tr>
<td>11</td>
<td>500</td>
<td>0.05</td>
<td>0.0072</td>
<td>$T_{DL}$</td>
<td>$S_{DL}$</td>
<td>$C_{DL}$</td>
</tr>
<tr>
<td>12</td>
<td>500</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{DH}$</td>
<td>$S_{DL}$</td>
<td>$C_{DL}$</td>
</tr>
<tr>
<td>13</td>
<td>500</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{DL}$</td>
<td>$S_{DH}$</td>
<td>$C_{DL}$</td>
</tr>
<tr>
<td>14</td>
<td>500</td>
<td>0.05</td>
<td>0.020</td>
<td>$T_{DL}$</td>
<td>$S_{DL}$</td>
<td>$C_{DH}$</td>
</tr>
</tbody>
</table>

S: 200 m case, D: 500 m case, L: Low, H: High, X: Super high
Two-phase flow simulation by Full-3D model: Initial Conditions

Equilibrium Concentration
Coexisting with Hydrate
Two-phase flow simulation by Full-3D model: Results & Discussions

+ Volume fraction of CO₂ liquid and gas

+ $\Delta$TCO₂ (kg/m³)
Two-phase flow simulation by Full-3D model: Results & Discussions

+ Vertical profile of $\Delta$TCO$_2$ --- Size Effect

$$F_T = kA_T \left( C_I - C_\square \right)$$
Two-phase flow simulation by Full-3D model: Results & Discussions

+ Vertical profile of $\Delta T\text{CO}_2$ --- Temperature Effect

**Bubble cases**

**Droplet cases**
Two-phase flow simulation by Full-3D model: Results & Discussions

+ Vertical profile of $\Delta TCO_2$

- Small size
- High T

Droplet cases

High T
Two-phase flow simulation by Full-3D model: Results & Discussions

- Vertical profile of $\Delta p\text{CO}_2$ --- Effect of Background TCO$_2$
Two-phase flow simulation by Full-3D model: Results & Discussions

+ Correlation between TCO$_2$ and $\Delta$pCO$_2$
Ocean model simulation

Mesoscale simulation incorporating
Full-3D model into small domain

See the impacts of realistic topography and tidal current around Japanese coast
Ocean model simulation: Computational conditions

Mesoscale
Model: Hydrostatic-approximated NS-equation
(MEC Ocean Model)
Domain: 132 km x 50 km x 460 m
Grid: 33 x 25 x 48
Horizontal grid spacing: 4 km x 2 km
Minimum vertical grid spacing: 2 m

Small scale
Model: Full-3D NS-equation
(Two-phase flow model)
Domain: 4 km x 2 km x 120 m
Grid: 160 x 80 x 25
Horizontal grid spacing: 25 m x 25 m
Minimum vertical grid spacing: 2 m

Boundary conditions
T,S,C: inflow-fixed & outflow-zero gradient
Wave height: No-reflection
Ocean model simulation: Computational conditions

**Input Data**
- \( T, S \): Annual average (JODC)
- Surface condition: Annual average (JMA)
- Tide: M2, K1, O1, S2
- Bubble size: 2 cm diameter
- Calculation period: 45 days
- Calculation time step: 1 second

**Leak-Source Band**
- Width: 25 m
- Length: 3000 m
- Flow-rate of \( CO_2 \): \( 4 \times 10^{-5} \) kg/s/m²
Ocean model simulation: Results

+ Distribution of \( \Delta p\text{CO}_2 \) in the mesoscale domain

\( \Delta p\text{CO}_2 \) in the mesoscale domain does not exceed 200 ppm.

- \( \text{CO}_2 \)-rich water diffuses and flows by tidal current

\( X = 60000 \text{ m} \)

70 m depth
Ocean model simulation: Results

+ Distribution of $\Delta pCO_2$ in the small domain

- Intrusion by density flow
- Distribution change by tidal current

$\Delta pCO_2$ in the small domain sometimes exceeds 500 ppm above the leak-source band.
Ocean model simulation: Results

+ Biological impact on zooplanktons

Trajectories of zooplanktons

$\Delta pCO_2$ experienced by zooplanktons

The maximum $\Delta pCO_2$ is less than 300 ppm.
Conclusions

- Numerical model was built and its simulation results were presented on the behaviour of leaked CO$_2$ and $\Delta pCO_2$ caused by it.
- Parameter studies show the large impact of temperature, size of bubbles/droplets, and background TCO$_2$.
- $\Delta pCO_2$ sometimes exceeded 500 ppm in the case of realistic topography and tidal current.
- Impact of leaked CO$_2$ on floating marine organisms, such as zooplanktons, may not be significant in the present cases.
- More detailed and careful examination on impact on marine organisms which rarely travel, such as benthos.
- Accurate validity of the present simulation --- Natural Analogue may be useful.