Non-isothermal flow of CO$_2$ in injection wells: evaluation of different injection modes

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**Problem**

*Context: CO₂ geological storage*

Injection conditions of CO₂ at the wellhead may play a major role on the flow behavior through the wellbore. The density and the injection rate reached at the bottomhole are key factors affecting the performance and efficiency of CO₂ geological storage.
The objectives of this work are

- To implement in Comsol Multiphysics a one-dimensional (1D) model for non-isothermal single-phase flow of CO$_2$ through injection wells.

- To apply that model to evaluate different injection modes and hypothetical CO$_2$ injection scenarios.
Flow of CO$_2$, or any fluid, and its mixtures in non-isothermal wells is modeled according to the approach of Lu and Connell (2014), in which the flow equations are based on the averaged-flow model. For single-phase 1D flow:

**Mass**
\[
\frac{\partial \rho}{\partial t} + \rho \frac{\partial v}{\partial z} + v \frac{\partial \rho}{\partial z} = 0
\]

**Momentum**
\[
\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial z} + \frac{1}{\rho} \frac{\partial p}{\partial z} = -f \mu \frac{v^2}{2d} + g \sin \theta
\]

**Energy**
\[
\frac{\partial h}{\partial t} + v \frac{\partial h}{\partial z} - \frac{1}{\rho} \frac{\partial p}{\partial t} + v \frac{\partial v}{\partial t} + v^2 \frac{\partial v}{\partial z} = -v g \sin \theta - \frac{\pi d q(z,t)}{\rho A}
\]

**Enthalpy**
\[
\frac{dh}{dt} = C_p (dT - \eta dP)
\]

**Joule-Thompson coefficient**
\[
\eta = T \left( (\partial \hat{V} / \partial T)_p - \hat{V} \right)
\]

**Heat exchange with the surroundings**
\[
q(z) = -\pi d U_\infty \left( T - T_f(z) \right)
\]
Implementation in Comsol Multiphysics

The model equations were implemented in Comsol through the coefficient’s form of the PDE module with multiple dependent variables

\[
e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} - \nabla \cdot (c \nabla u + \alpha u - \gamma) + \beta \cdot \nabla u + au = f
\]

\[
u = (p, v, T)^T
\]

\[
d_a = \begin{pmatrix}
\frac{\partial \rho}{\partial p} & 0 & 0 \\
0 & 1 & 0 \\
-(1/\rho + \eta) & v & C_p
\end{pmatrix}, \quad
\beta = \begin{pmatrix}
v \frac{\partial \rho}{\partial p} & \rho & 0 \\
1/\rho & v & 0 \\
-v \eta & v^2 & v C_p
\end{pmatrix}
\]

\[
a = \begin{pmatrix}
0 & 0 & 0 \\
0 & -f \mu v/2d & 0 \\
0 & -g \sin \theta & 4U_\infty / \rho d
\end{pmatrix}, \quad
f = \begin{pmatrix}
0 \\
-g \sin \theta \\
4U_\infty T_f (z)/ \rho d
\end{pmatrix}
\]

\[
e_a = c = a = 0
\]

- All constitutive relationships were implemented as local equations by using Comsol variables.
- Uniform mesh of 1000 elements.
- Stationary and time-dependent studies to solve the problem in steady state and transient.
- Fully coupled Newton-Raphson iteration scheme.
Flowrate-controlled injection

\[ P_{inj}, T_{inj}, v_{inj} = \frac{Q_{inj}}{\rho_{inj} A} \]

Pressure-controlled injection

\[ P_{inj}, T_{inj} \]

\[ A = \pi d^2 / 4 \]

\[ p_{ini} = p_{ini} \exp\left(-\frac{M_w g}{R T_{ini}}\right) \]

\[ T_{ini} = T_{inj} \]

\[ v_{ini} = 0 \]

\[ \theta = 90 \, ^\circ \]

\[ v = PI(p - p_R)A \]

- **Constitutive relationships** were implemented as local equations by using Comsol variables:
  - Density: Redlich-Kwong EOS (1949)
  - Viscosity: Altunin & Sakhabedinov (1972)
  - Friction factor: laminar and turbulent flow (Zigrang and Sylvester, 1985)

- **Mesh**: 1000 elements, \( \Delta z = 1 \, \text{m} \)

- **Stationary and time-dependent studies** were defined to solve the problem in steady state and transient. In both cases the system of equations was solved with a fully coupled Newton-Raphson iteration scheme
Injection – Storage conditions

Injection conditions at the wellhead ($Q_{\text{inj}} = 1.0 \text{ kg/s}$)

<table>
<thead>
<tr>
<th>Injection conditions</th>
<th>$p_{\text{inj}}$ MPa</th>
<th>$T_{\text{inj}}$ °C</th>
<th>Compression work, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Gas</td>
<td>4.5</td>
<td>35</td>
<td>305.7</td>
</tr>
<tr>
<td>2 Gas near CP</td>
<td>7.0</td>
<td>31</td>
<td>245.4</td>
</tr>
<tr>
<td>3 Liquid near CP</td>
<td>8.0</td>
<td>31</td>
<td>125.8</td>
</tr>
<tr>
<td>4 Supercritical</td>
<td>8.0</td>
<td>40</td>
<td>241.3</td>
</tr>
<tr>
<td>5 Supercritical</td>
<td>10.0</td>
<td>40</td>
<td>146.6</td>
</tr>
<tr>
<td>6 Liquid</td>
<td>8.0</td>
<td>25</td>
<td>103.11</td>
</tr>
<tr>
<td>7 Liquid</td>
<td>5.0</td>
<td>-10</td>
<td>19.66</td>
</tr>
</tbody>
</table>
Injecting gaseous CO₂ causes very low densities through the wellbore.

CO₂ injection in gaseous near the CP and SC (8 MPa) conditions increase density but at the bottom this is still lower than 600 kg/m³.

By contrast, injecting liquid near the CP and SC (10 MPa) conditions lead to higher bottomhole densities, comparable to those reached by injecting liquid CO₂.

Higher CO₂ densities are advantageous because are closer to the resident brine density, reducing buoyancy effects in the reservoir and the potential risks of caprock failure and subsequent CO₂ leakages.
**CO₂ injected at low pressure**

Steady state flow regime is reached slowly by injecting at low pressures (< 7.2 MPa)

Liquid CO₂ at 5.0 MPa and -10 °C

Operational equilibrium is reached only after 100 days by injecting gaseous or liquid CO₂ at low pressure
**CO₂ injected at high pressure**

On the contrary, steady state is reached faster by injecting at high pressures (>7.2 MPa)

SC CO₂ at 10.0 MPa and 40 °C

Steady state flow regime is obtained after 1 hour when injecting SC CO₂ at the wellhead
Injecting SC CO₂ at 8.0 MPa and 40 °C

Fluctuation injection regime modeled in Comsol as a piecewise function

The total mass of injected CO₂ is equal to the mass injected at a constant rate of 1.0 kg/s (8640 ton of CO₂ in 100 days)

“A fluctuating injection regime can enhance CO₂ dissolution into the resident brine of the storage aquifer” (Hidalgo and Carrera, 2009).
Pressure-controlled injection

Injecting SC CO₂ at 8.0 MPa and 40 °C. Flowrate-controlled (dashed line) versus pressure-controlled injection with variable $p_R$ (solid line)

Injection flowrate

$$v = PI(p - p_R)A$$

Productivity index

$$PI = 6 \times 10^{-7} \text{ m s}^{-1} \text{ N}^{-1}$$

Reservoir pressure ($p_R$) increase due to CO₂ injection modeled in Comsol as a piecewise cubic interpolation function

<table>
<thead>
<tr>
<th>Injection mode</th>
<th>Injected mass of CO₂ in 100 days, ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowrate-controlled</td>
<td>8640</td>
</tr>
<tr>
<td>Pressure-controlled (constant $p_R$)</td>
<td>1322</td>
</tr>
<tr>
<td>Pressure-controlled (increasing $p_R$)</td>
<td>980</td>
</tr>
</tbody>
</table>
Conclusions

- Wellhead conditions of CO$_2$ below the critical point cause low fluid densities through the injection pipe. Conversely, injecting liquid CO$_2$ or CO$_2$ at high pressure helps to increase the density at the bottomhole, which has added benefits for the efficiency and security of the geological storage.

- Steady state is reached faster by injecting at higher pressures.

- Higher densities at the bottomhole can also be achieved by a fluctuating injection regime, which also has the advantage of enhancing the CO$_2$ storage efficiency.

- Pressure-controlled injection may induce high densities as well, although at a reduced injected mass of CO$_2$.

- CO$_2$ injection conditions should be tuned considering a balance between optimal storage densities and the stability of the operation.
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