COMSOL
CONFERENCE
2015 GRENOBLE

AMPHOS 21
SCIENTIFIC AND STRATEGIC ENVIRONMENTAL CONSULTING

Non-isothermal flow of CO_2 in injection wells: evaluation of different injection modes

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1994-2014
20 YEARS
FLOWING

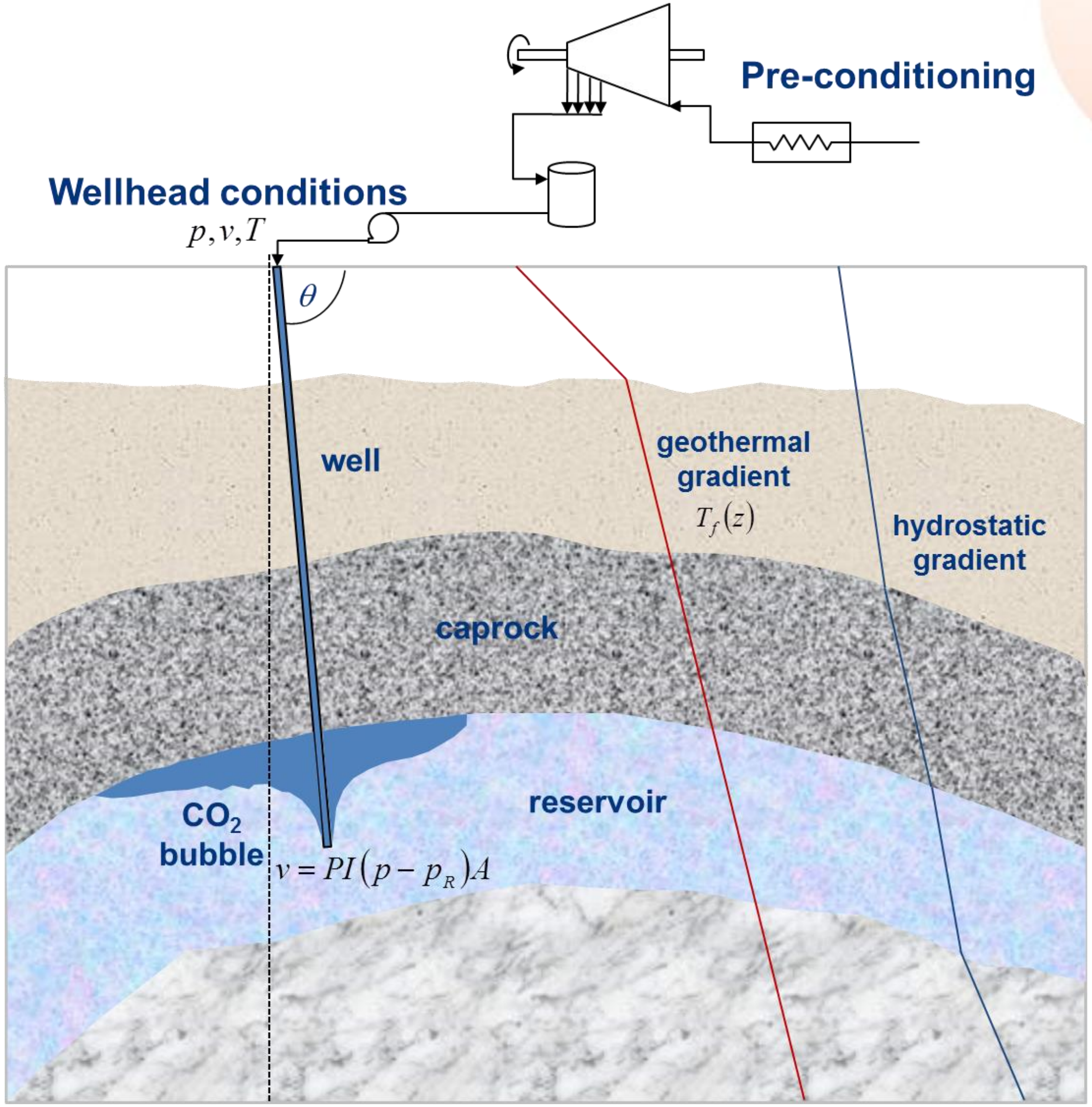
Outline

- ☐ Problem
- ☐ Objectives
- ☐ Modeling Approach
    - Governing equations
    - Implementation in Comsol
- ☐ Results
    - Different CO_2 injection conditions at surface
    - Fluctuating CO_2 injection rate
    - Pressure-controlled injection
- ☐ Conclusions

Problem

Context: CO_2 geological storage

Injection conditions of CO_2 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 CO_2 geological storage.



Objective

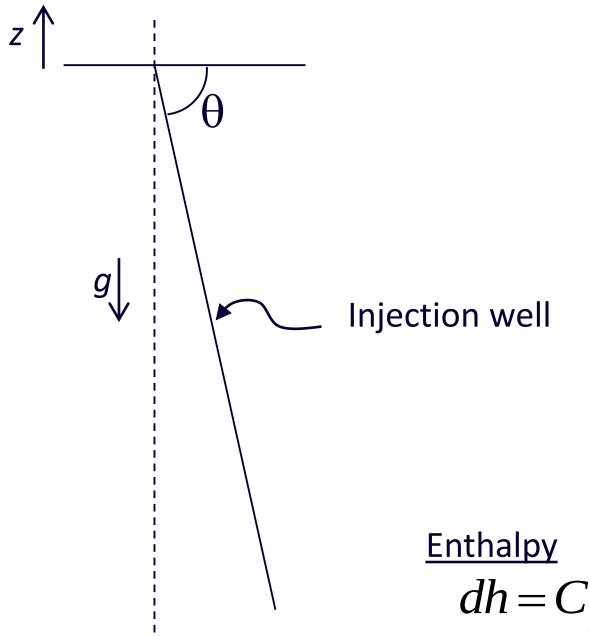
The objectives of this work are

- 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.

Governing equations

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

$$\frac{\partial h}{\partial t}+v\frac{\partial h}{\partial z}-\frac{1}{\rho}\frac{\partial p}{\partial t}+v\frac{\partial v}{\partial t}+v^{2}\frac{\partial v}{\partial z}=-vg\sin\theta-\frac{\pi d q(z,t)}{\rho A}$$

Enthalpy

$$dh=C_p\left(dT-\eta dP\right)$$

Joule-Thompson coefficient

$$\eta=T\left(\left(\partial\hat{V}/\partial T\right)_p-\hat{V}\right)$$

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

$$\boxed{\mathbf{e_a}\frac{\partial^2\mathbf{u}}{\partial t^2}+\mathbf{d_a}\frac{\partial\mathbf{u}}{\partial t}-\nabla\cdot\left(\mathbf{c}\nabla\mathbf{u}+\boldsymbol{\alpha}\mathbf{u}-\boldsymbol{\gamma}\right)+\boldsymbol{\beta}\cdot\nabla\mathbf{u}+\mathbf{a}\mathbf{u}=\mathbf{f}}$$

$$\mathbf{u}=\left(p,v,T\right)^T$$

$$\mathbf{d_a}=\begin{pmatrix}\partial\rho/\partial p & 0 & 0\\ 0 & 1 & 0\\ -\left(1/\rho+\eta\right) & v & C_p\end{pmatrix}$$

$$\boldsymbol{\beta}=\begin{pmatrix}v\,\partial\rho/\partial p & \rho & 0\\ 1/\rho & v & 0\\ -v\eta & v^2 & vC_p\end{pmatrix}$$

$$\boldsymbol{\gamma}=\mathbf{0}$$

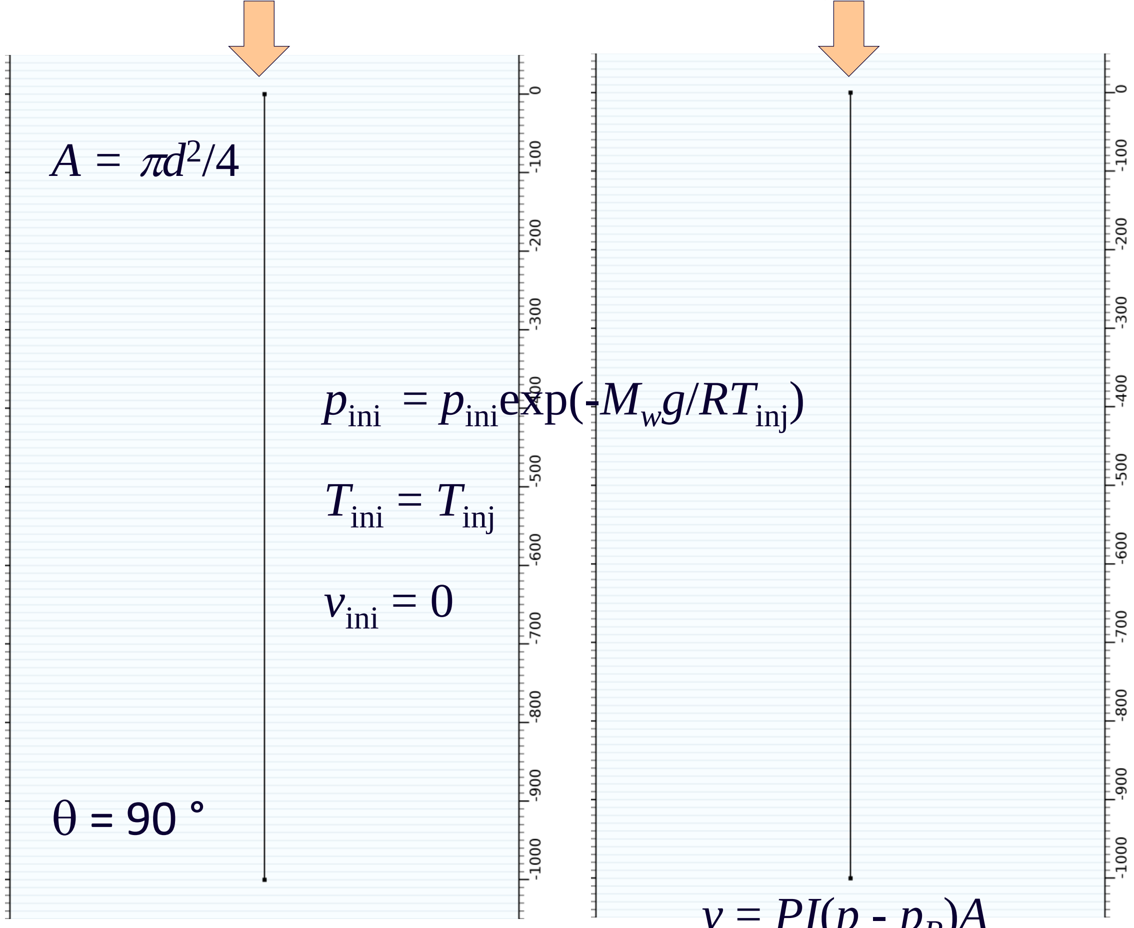
$$\mathbf{a}=\begin{pmatrix}0 & 0 & 0\\ 0 & -f_\mu v/2d & 0\\ 0 & -g\sin\theta & 4U_\infty/\rho d\end{pmatrix}$$

$$\mathbf{f}=\begin{pmatrix}0\\ -g\sin\theta\\ 4U_\infty T_f\left(z\right)/\rho d\end{pmatrix}$$

$$\mathbf{e_a}=\mathbf{c}=\boldsymbol{\alpha}=\mathbf{0}$$

- ☐ 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.

Initial-BC, mesh, constitutive relationships and solver



Flowrate-controlled injection

p_{inj}, T_{inj}, $v_{inj} = Q_{inj}/\rho_{inj}A$

$A = \pi d^2/4$

θ = 90 °

Pressure-controlled injection

p_{inj}, T_{inj}

$$p_{ini} = p_{ini}\exp(-M_w g/RT_{inj})$$

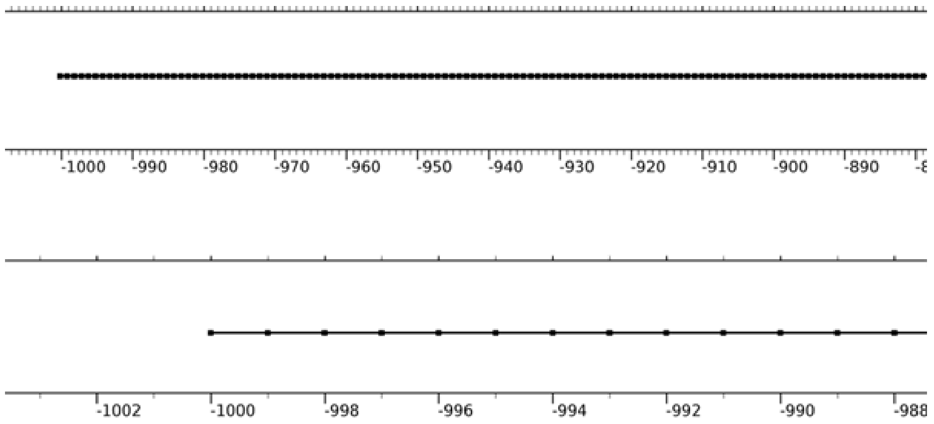
$$T_{ini} = T_{inj}$$

$$v_{ini} = 0$$

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

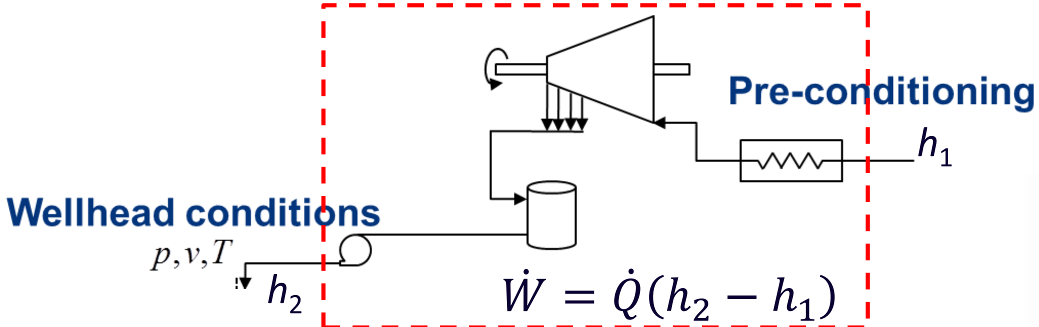
- **Constitutive relationships** were implemented as local equations by using Comsol variables:
  - Density: Redlich-Kwong EOS (1949)
  - Viscosity: Altunin & Sakhabetdinov (1972)
  - Friction factor: laminar and turbulent flow (Zigrang and Sylvester, 1985)

- **Mesh**: 1000 elements, Δz = 1 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

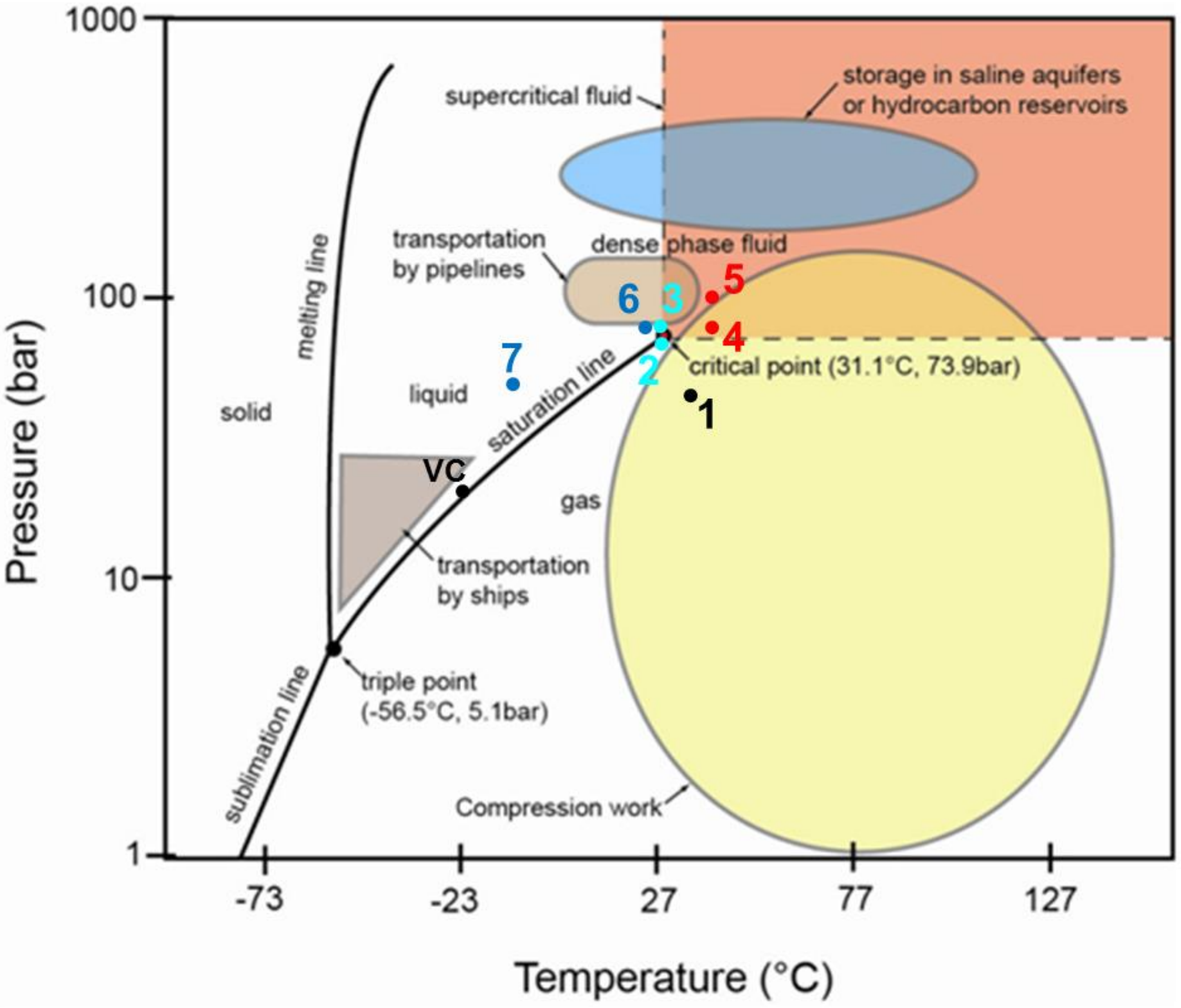


$$\dot{W} = \dot{Q}(h_2 - h_1)$$

compression work

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

	Injection conditions	p_{inj}, MPa	T_{inj}, °C	Compression work, kW
1	Gas	4.5	35	305.7
2	Gas near CP	7.0	31	245.4
3	Liquid near CP	8.0	31	125.8
4	Supercritical	8.0	40	241.3
5	Supercritical	10.0	40	146.6
6	Liquid	8.0	25	103.11
7	Liquid	5.0	-10	19.66

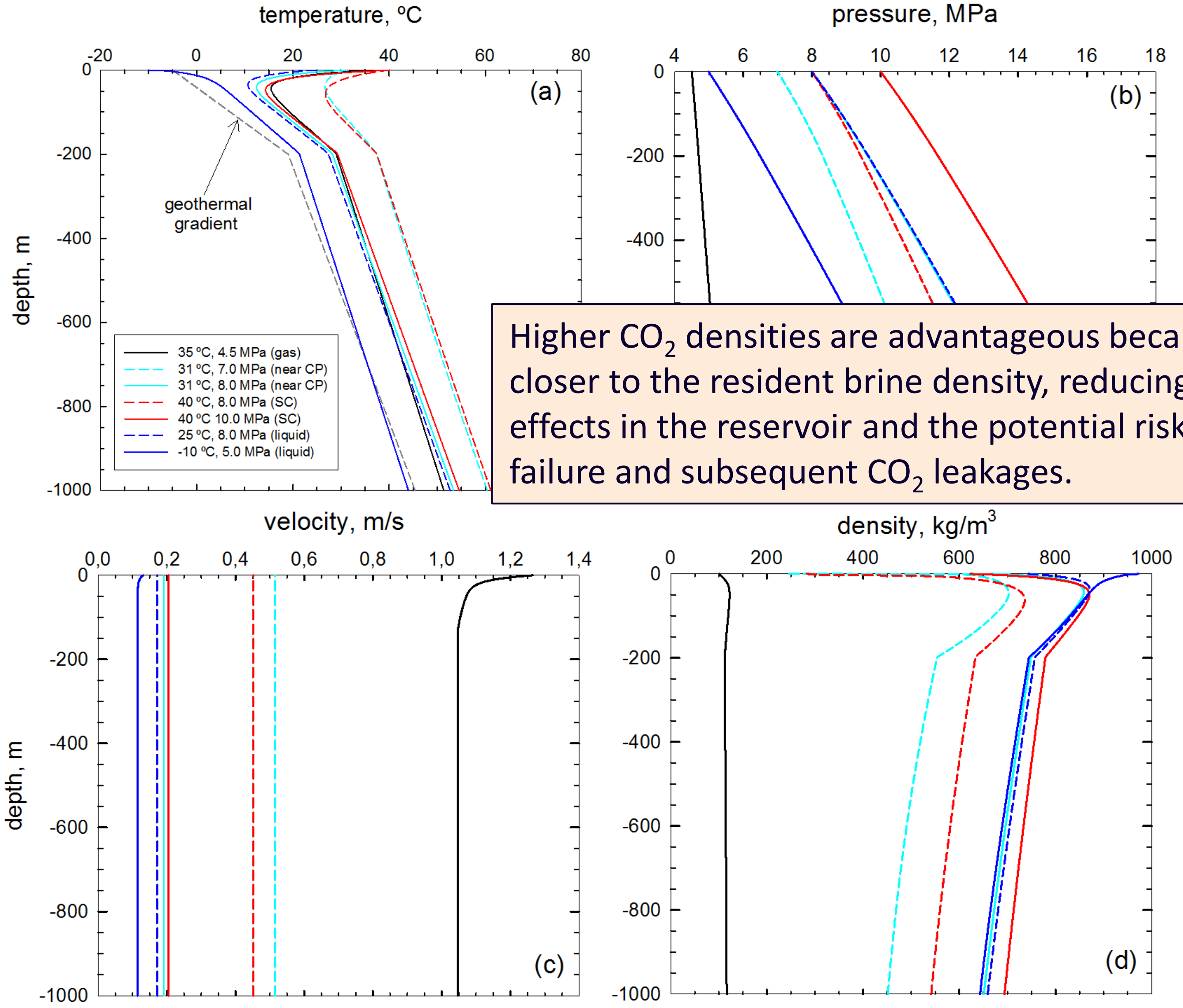


Steady state solution

Injecting gaseous CO_2 causes very low densities through the wellbore.

CO_2 injection in gaseous near the CP and SC (8 MPa) conditions increase density but at the bottom this is still lower than 600 kg/m^3.

By contrast, injecting liquid near the CP and SC (10 MPa) conditions lead to higher bottomhole densities, comparable to those reached by injecting liquid CO_2.



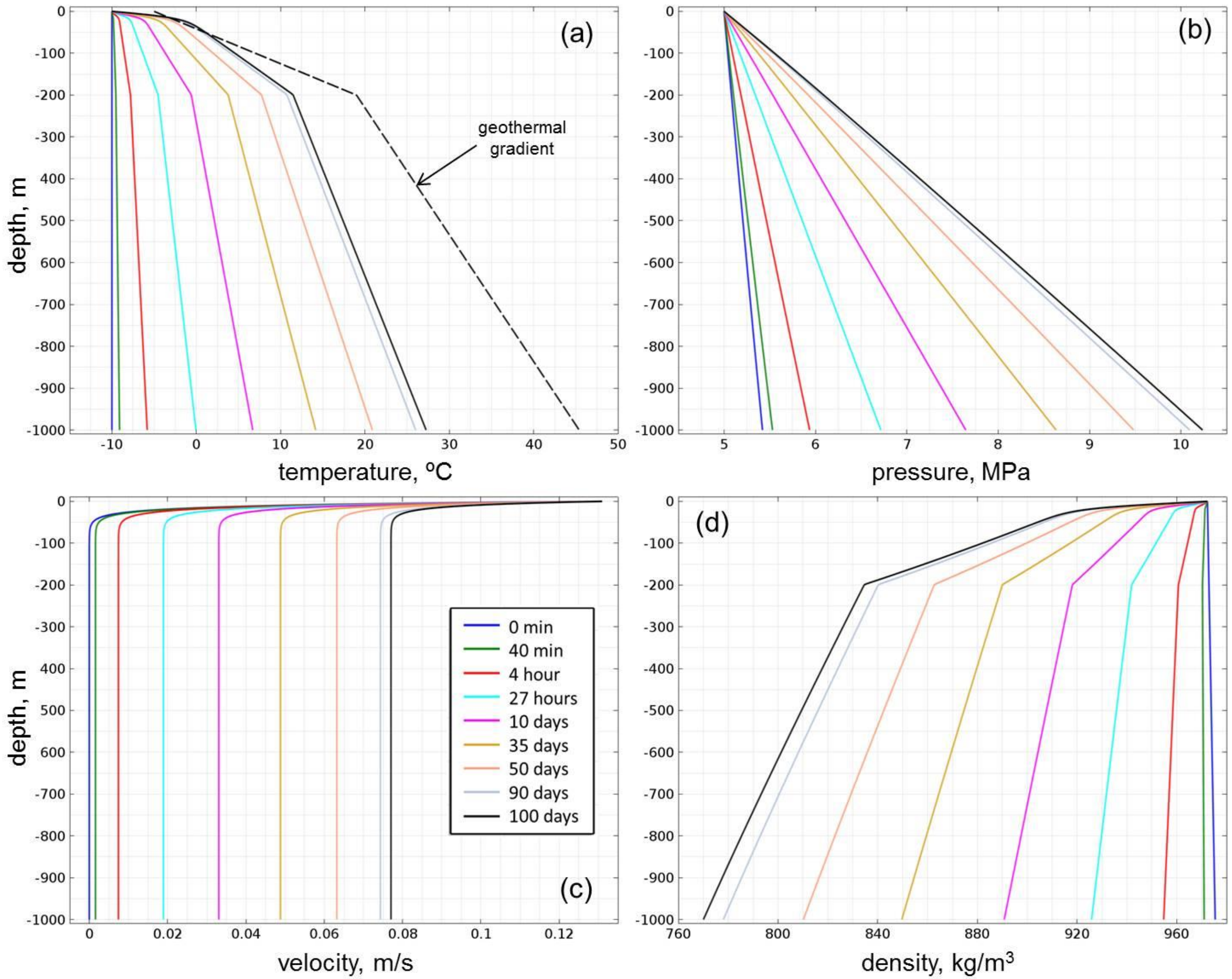
Higher CO_2 densities are advantageous because are closer to the resident brine density, reducing buoyancy effects in the reservoir and the potential risks of caprock failure and subsequent CO_2 leakages.

CO_2 injected at low pressure

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

<u>Liquid CO_2 at 5.0 MPa and -10 °C</u>

Operational equilibrium is reached only after 100 days by injecting gaseous or liquid CO_2 at low pressure

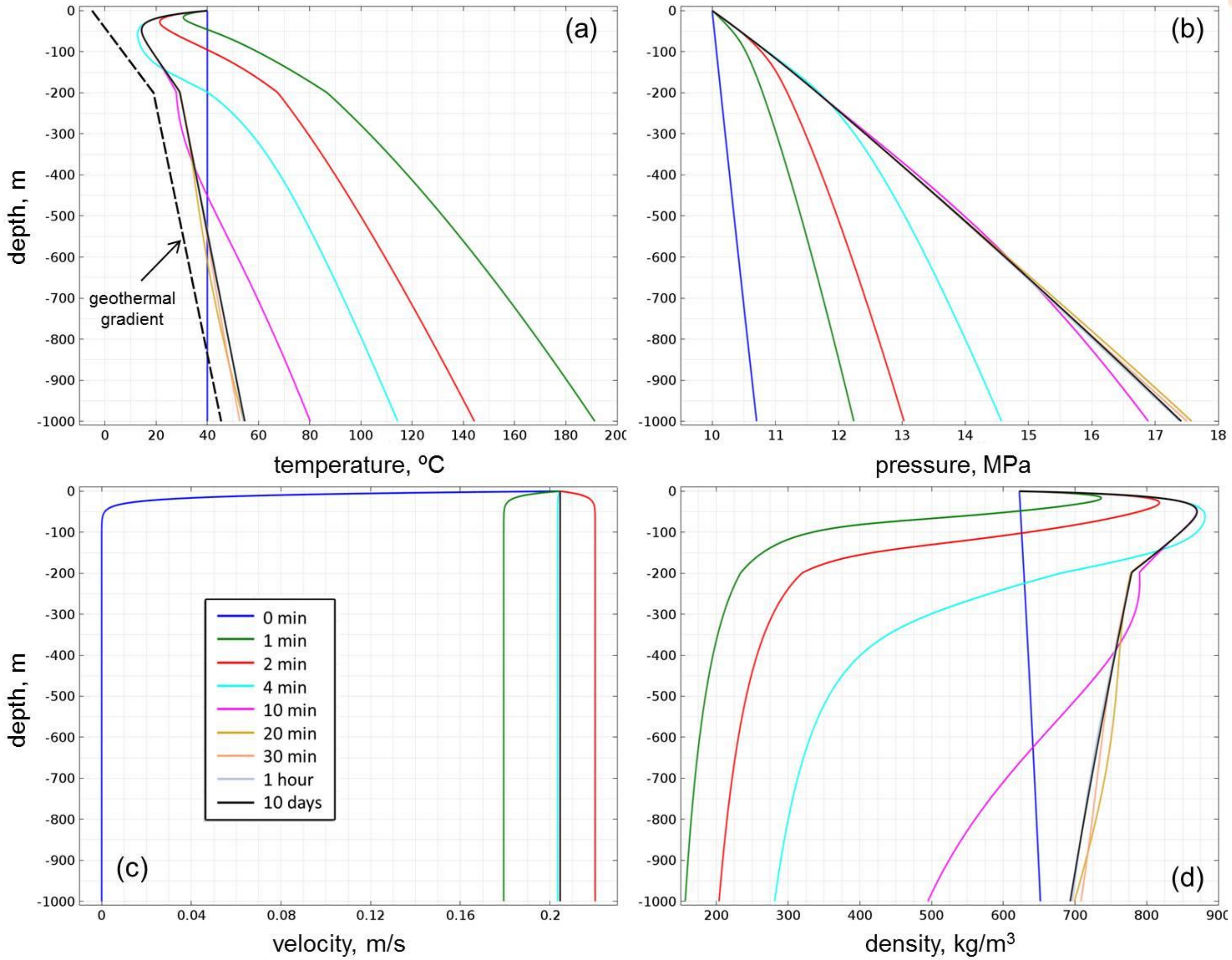


CO_2 injected at high pressure

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

<u>SC CO_2 at 10.0 MPa and 40 °C</u>

Steady state flow regime is obtained after 1 hour when injecting SC CO_2 at the wellhead

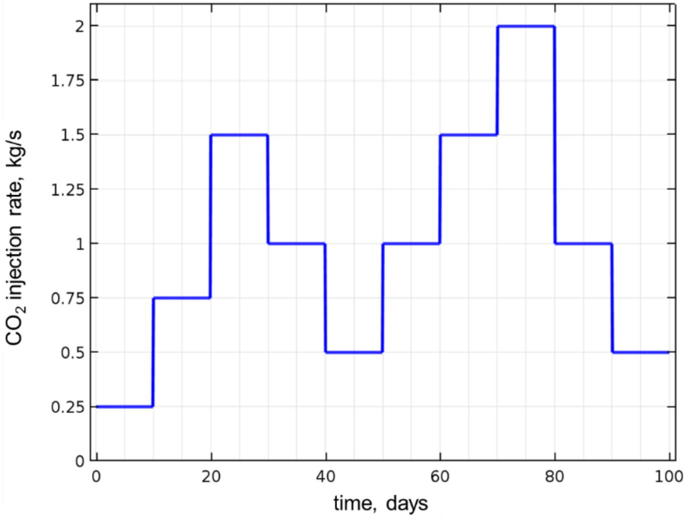


Fluctuating CO_2 injection rate

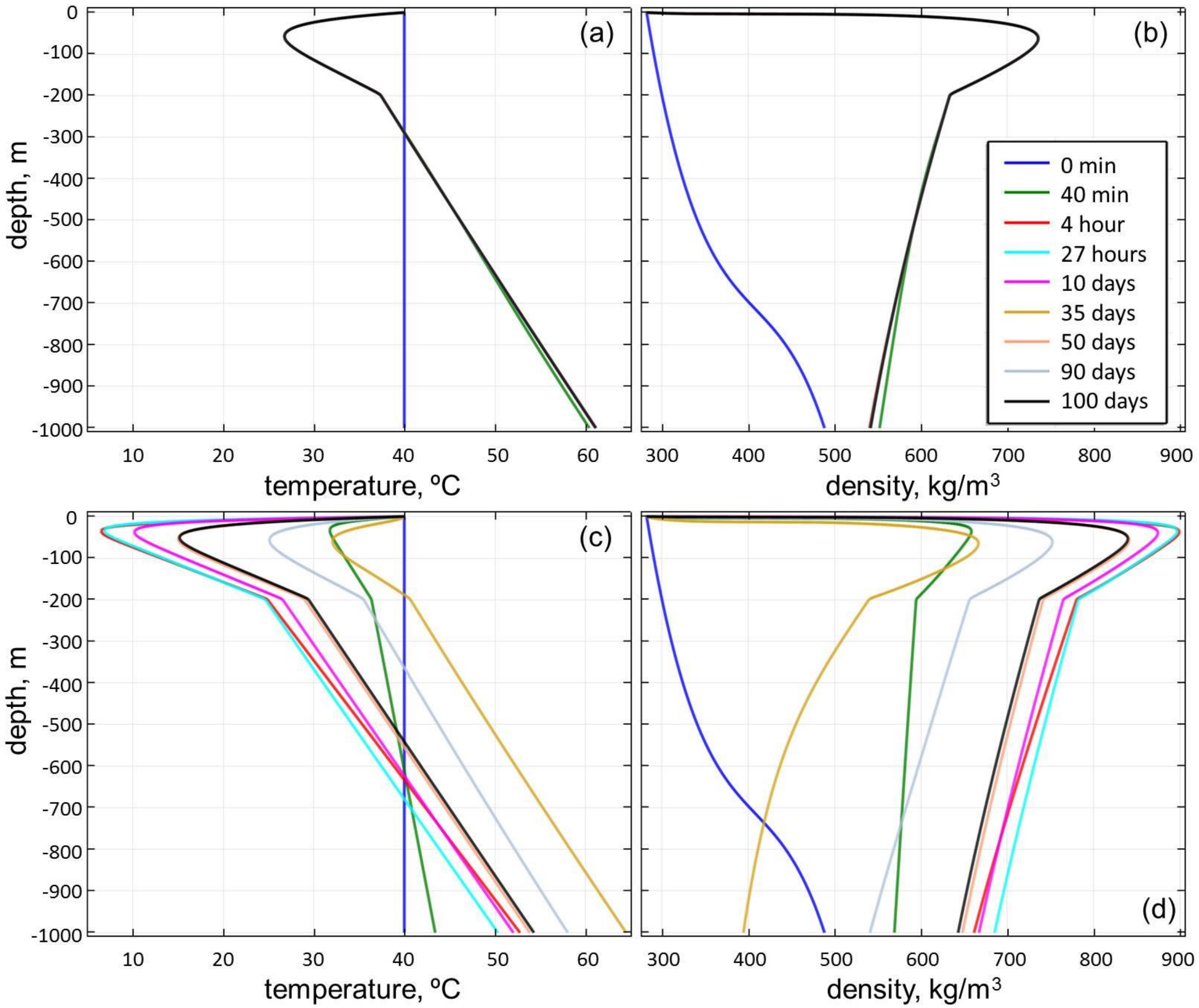
> “A fluctuating injection regime can enhance CO_2 dissolution into the resident brine of the storage aquifer” (Hidalgo and Carrera, 2009).

Injecting SC CO_2 at 8.0 MPa and 40 °C

Fluctuation injection regime modeled in Comsol as a piecewise function



The total mass of injected CO_2 is equal to the mass injected at a constant rate of 1.0 kg/s (8640 ton of CO_2 in 100 days)



Constant injection regime

Fluctuating injection regime

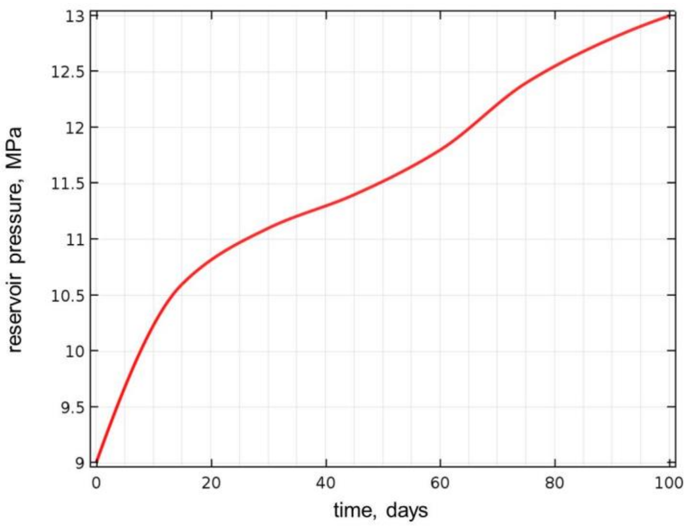
Pressure-controlled injection

Injection flowrate

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

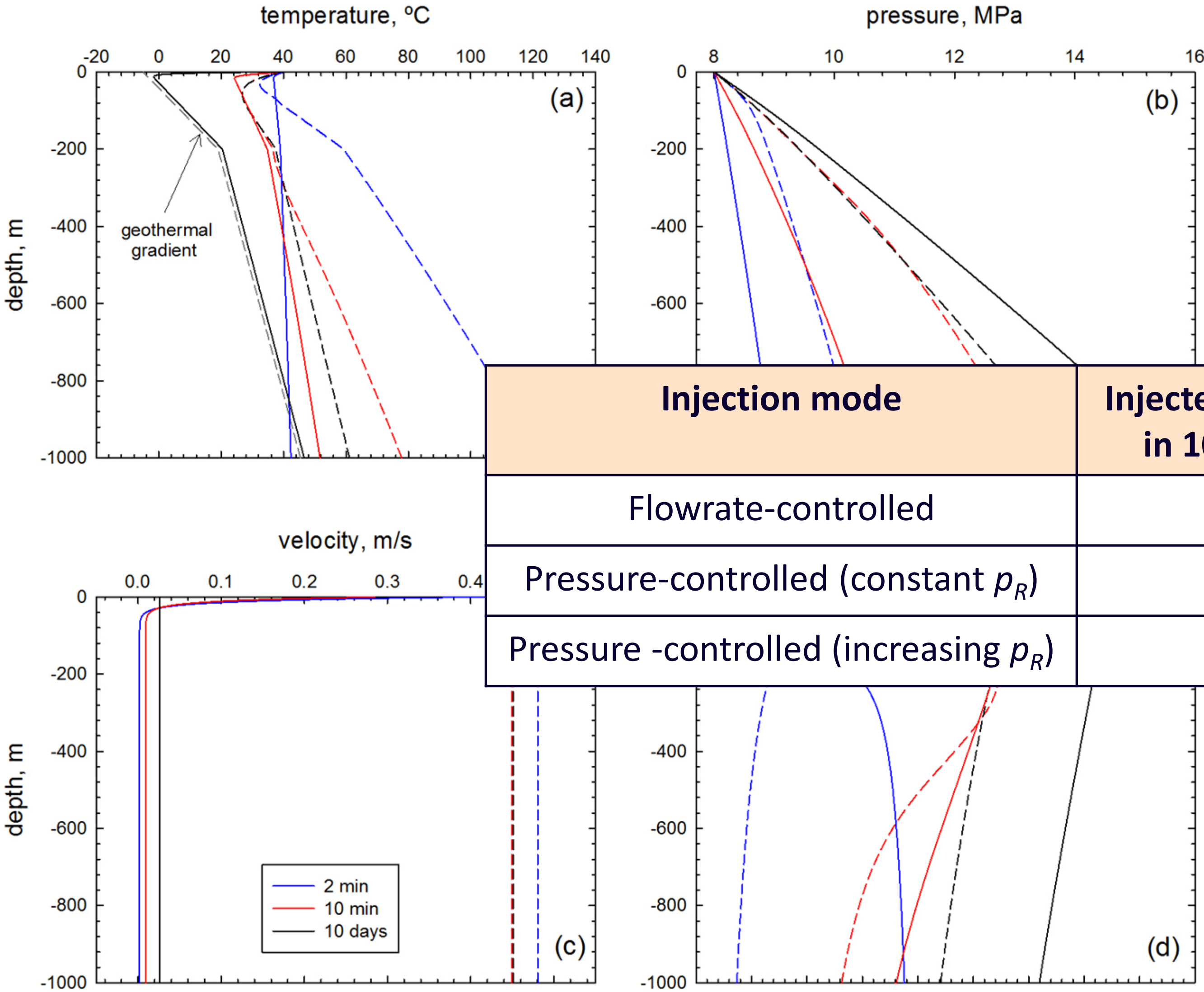
Productivity index

$$PI = 6\times10^{-7}\ \mathrm{m\ s^{-1}\ N^{-1}}$$



Reservoir pressure (p_R) increase due to CO_2 injection modeled in Comsol as a piecewise cubic interpolation function

Injecting SC CO_2 at 8.0 MPa and 40 °C. Flowrate-controlled (dashed line) versus pressure-controlled injection with variable p_R (solid line)



Injection mode	Injected mass of CO_2 in 100 days, ton
Flowrate-controlled	8640
Pressure-controlled (constant p_R)	1322
Pressure -controlled (increasing p_R)	980

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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