China Australia Geological Storage of CO_2
中澳二氧化碳地质封存

The Studies on Environmental Impact and Risk Management of CO_2 Storage

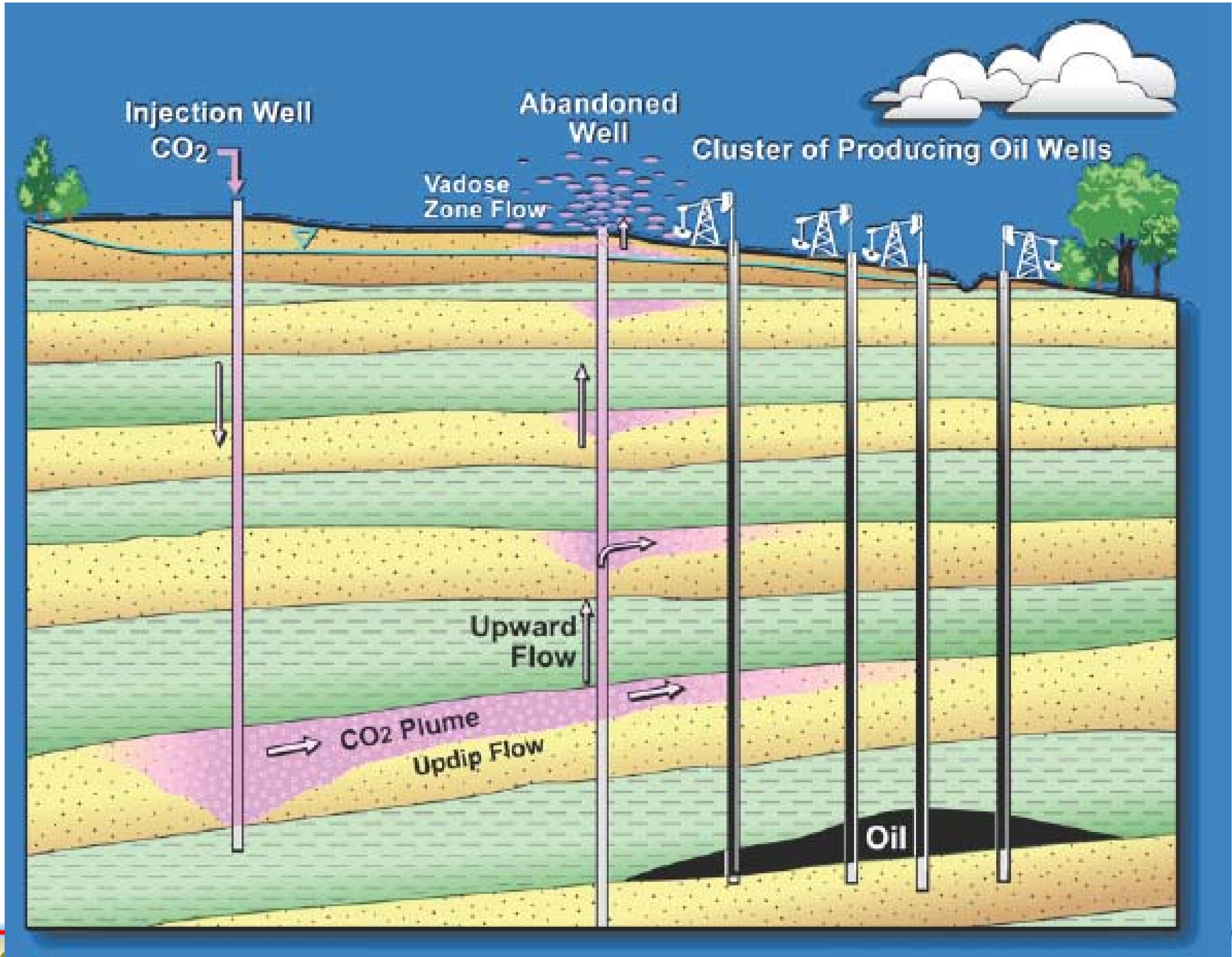
Dr. Ruina Xu

Department of Thermal Engineering, Tsinghua University

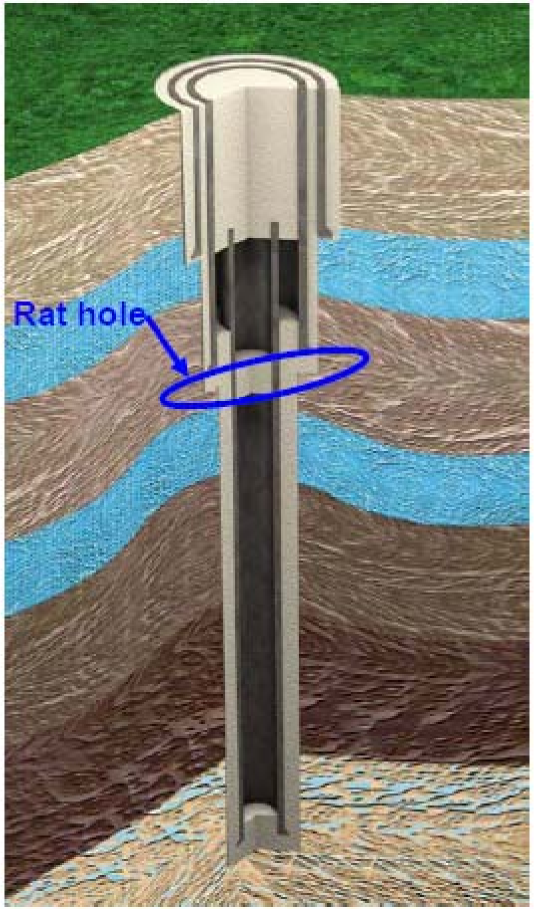
Main works

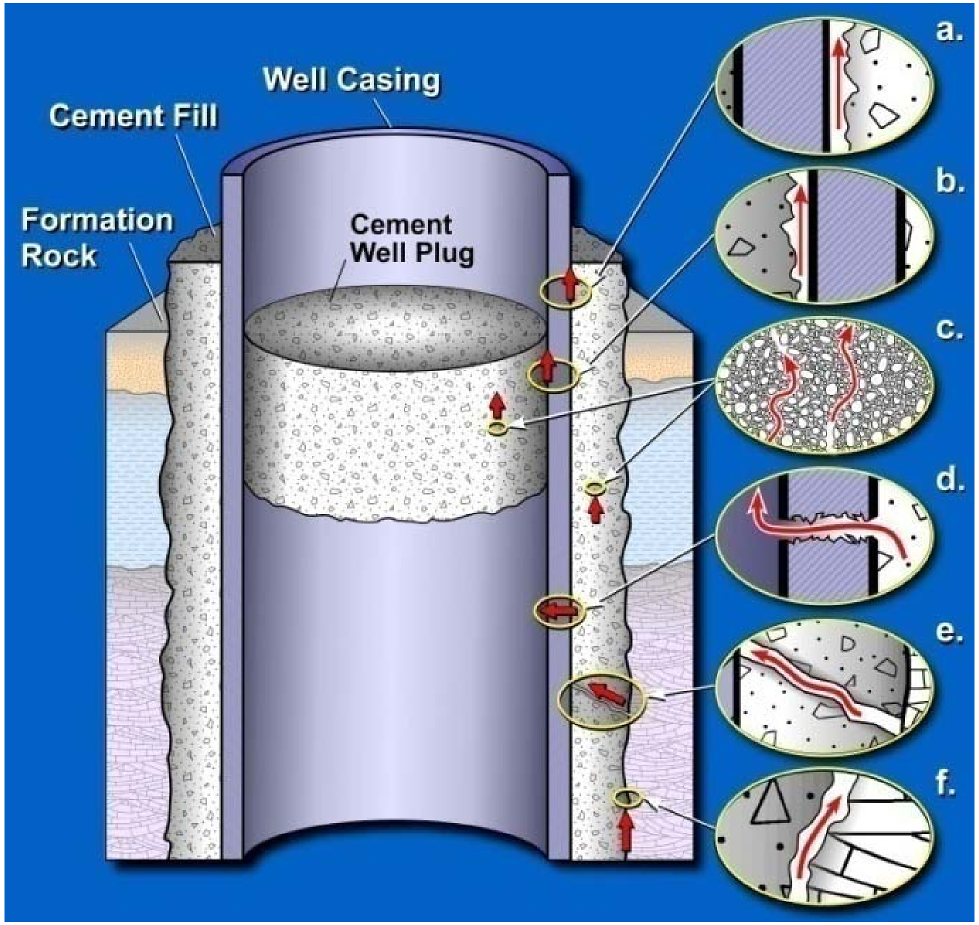
- **Case Study: Numerical Simulation on Leakage of Injected CO2 into Overlying Formations through a Leaky Well**针对封存场地中已有废弃井的情况，通过数值模拟方法，研究了废弃井对CO2地质封存泄露的影响。
  - Develop the simulation method 提出并发展了新的数值模拟方法；
  - Quantities analysis on leakage ratio, Maximum leakage ratio time, leakage rate various with time, etc. 定量分析了泄漏量随时间的变化，初步分析了相关因素对泄漏的影响；
  - Provide technical and data support to risk assessment 为CO2封存风险研究提供了技术和数据支持。

1.1 Leakage through a Leaky Well



China Australia Geological Storage of CO_2
中澳二氧化碳地质封存


Rat hole


Well Casing
Cement Fill
Formation Rock
Cement Well Plug
a.
b.
c.
d.
e.
f.

Problem 1: CO_2 leakage risk

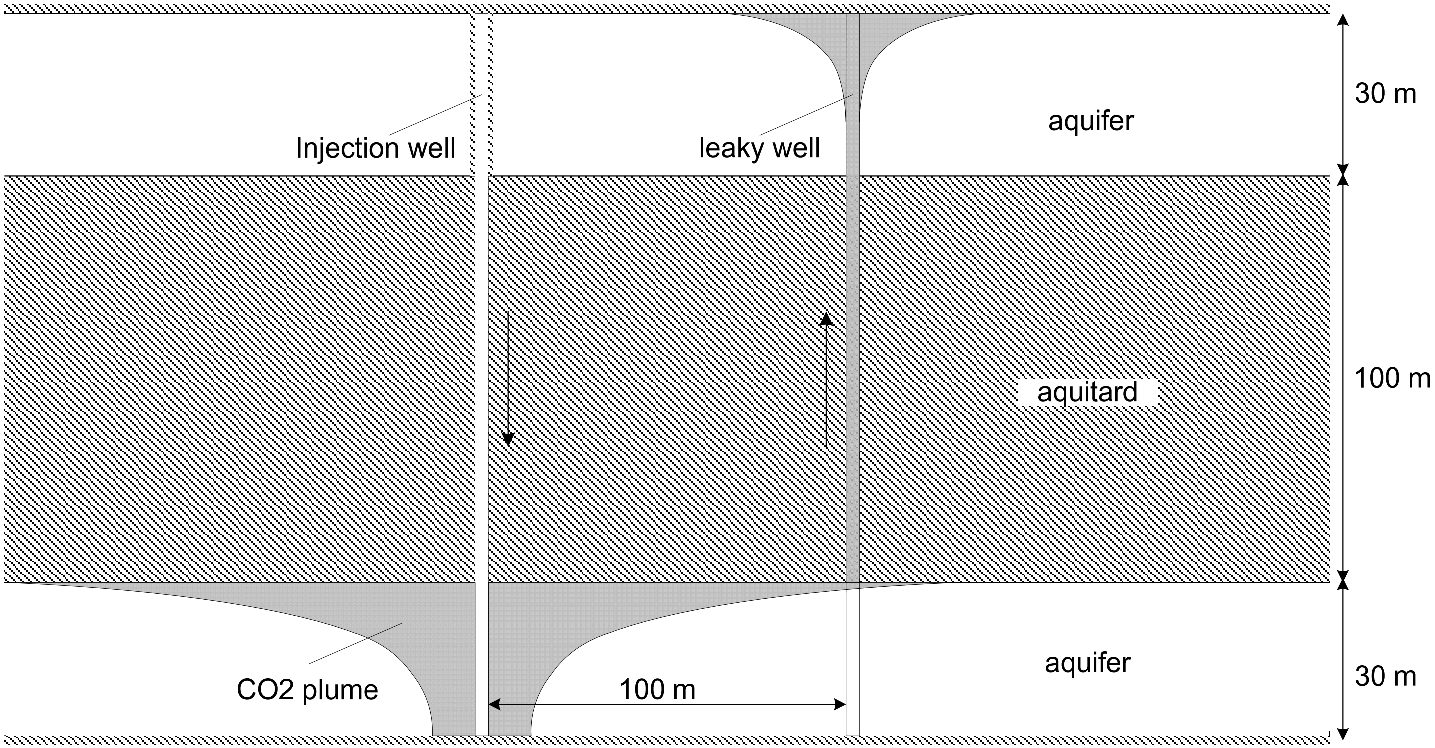


Figure Leakage scenario

CO_2 is injected into the deeper aquifer, spreads within the deeper aquifer and upon reaching the leaky well, rises up to the shallower aquifer.

Problem 1: Governing equations

Simulated by commercial software FLUENT 6.3 code,

Multi-phase model: Eulerian Model .

Continuity equation:

$$\frac{\partial(\varphi S_i \rho_i)}{\partial t} + \nabla \cdot (\varphi S_i \rho_i \overline{v_i}) = 0, \qquad (i = w, g)$$

where φ is the porosity; S_i is the saturation of phase i; ρ_i is the density of phase i; v_i is the velocity vector of phase i .

Momentum equation:

$$\frac{\partial(\varphi S_i \rho_i \overline{v_i})}{\partial t} + \nabla \cdot (\varphi S_i \rho_i \overline{v_i v_i}) = -\varphi S_i \nabla P + \nabla \cdot \left[\varphi S_i \mu_i \left(\nabla \overline{v_i} + \overline{v_i}^{\mathrm{T}} - \frac{2}{3} \nabla \cdot \overline{v_i} \mathrm{I} \right) \right] + \varphi S_i \rho_i \overline{g} - S_i \frac{\mu_i}{k_{r,i} K} \overline{v_i}$$

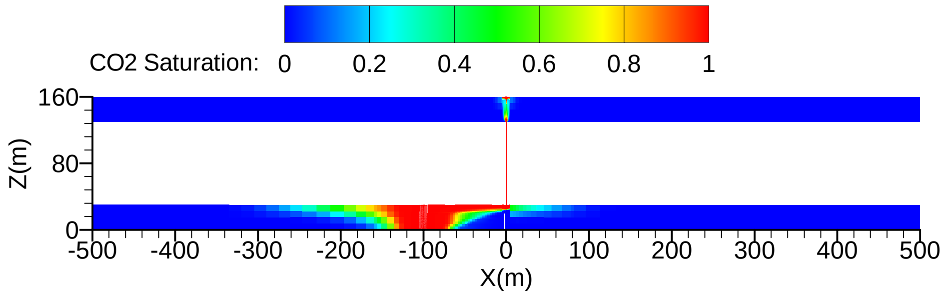
Where P is pressure, I is the unit tensor, μ_i is the viscosity of phase, g is the gravity vector, $k_{r,i}$ is relative permeability, and K is the absolute permeability tensor.

Problem 1: model parameters

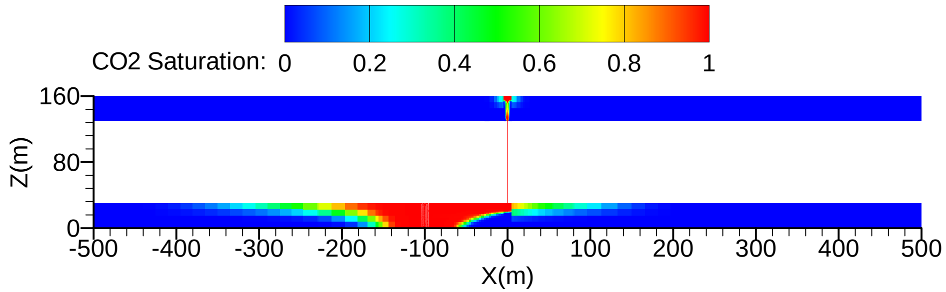
Parameter	Value
Dimensions of the model domain	1000 m ×1000m × 160m
Aquifer depth	2840 - 3000 m
Aquifer thickness	30 m
Aquitard thickness	100 m
Porosity	0.15
Radius of leaky and injection wells	0.15 m
Distance between wells	100 m
Aquifer permeability	2×10^{-14} m^2
Leaky well permeability	1×10^{-12} m^2
Relative permeability	linear
Initial brine saturation	100%
Initial pressure distribution	Hydrostatic, gradient of 10251.145 Pa/m
CO_2 density	$(k_{r,i} = S_i)$ 479 kg/m^3
Brine density	1045 kg/m^3
CO_2 viscosity	3.950 $\times10^{-5}$ Pas
Brine viscosity	2.535 $\times10^{-4}$ Pas
CO_2 injection rate	8.87 kg/s
Simulation time	1000 days

- Lateral boundary conditions: kept constant identical to the initial conditions;
- Boundaries at the top and bottom of the two aquifers no-flow boundaries;
- All processes are isothermal;
- none of the boundary changes over time.

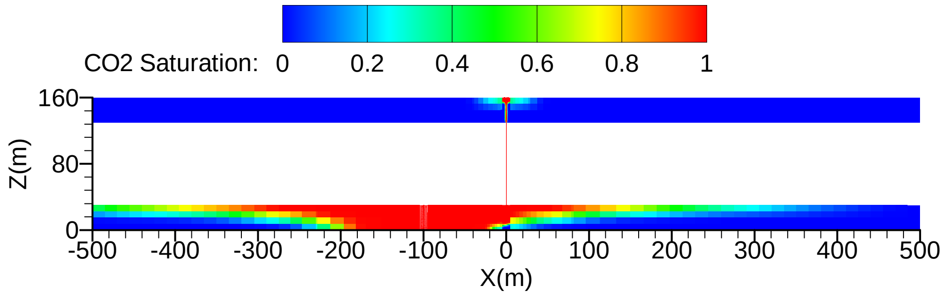
Problem 1: Results (1)



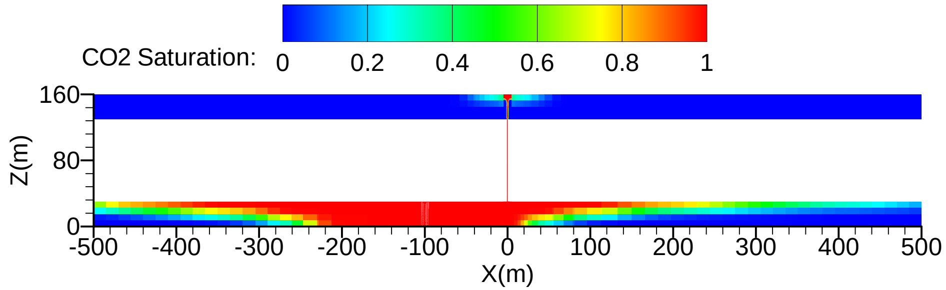
a) after 60 days of CO_2 injection



b) after 115 days of CO_2 injection



c) after 520 days of CO_2 injection



d) after 1000 days of CO_2 injection

Figure Distribution CO_2 saturation on the vertical middle slice

Injected CO_2 spreads in the radial direction from the injection location, comes in contact with the leaky well and rises to the shallower aquifer.

cags China Australia Geological Storage of CO_2 中澳二氧化碳地质封存

Problem 1: Results (2)

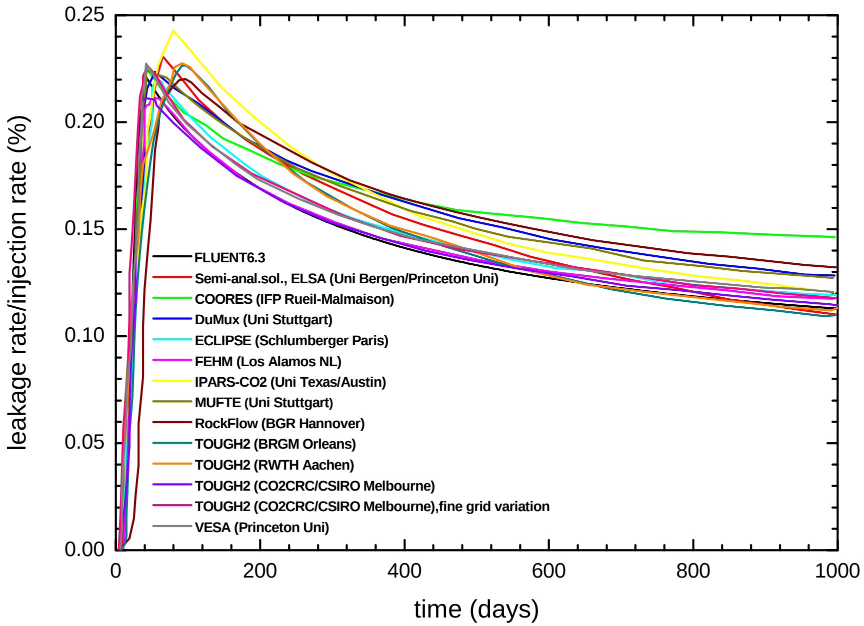


Figure Comparison of predicted CO_2 leakage ratio values over time obtained by different codes

Table Comparison of some interesting values computed by different codes

Code	Max. leakage (%)	Time at max. leakage (days)	Leakage at 1000 days (%)	Arrival time (days)
FLUENT 6.3	0.221	42	0.113	10
ELSA (Semi-analytical solution) (Uni Bergen/Princeton Uni)	0.231	63	0.109	14
COORES (IFP)	0.219	50	0.146	8
DuMux (Uni Stuttgart)	0.220	61	0.128	6
ECLIPSE (Schlumberger)	0.225	48	0.118	8
FEHM (Los Alamos NL)	0.216	53	0.119	4
IPARS-CO2 (Uni Texas/Austin)	0.243	80	0.120	10
MUFTE (Uni Stuttgart)	0.222	58	0.126	8
RockFlow (BGR)	0.220	74	0.132	19
TOUGH2/ECO2N (BRGM)	0.226	93	0.110	4
TOUGH2/ECO2N (refined grid) (CO2CRC/CSIRO)	0.212 0.225	46 45	0.115 -	10 8
TOUGH2 (RWTH Aachen)	0.227	89	0.112	9
VESA (Princeton Uni)	0.227	41	0.120	7

leakage ratio

(ratio of leakage rate to injection rate)

- Maximum CO_2 leakage ratio;
- Maximum leakage ratio time;
- Leakage ratio after 1000 days of injection;
- CO_2 arrival time at the leaky well (leakage ratio is larger than 5.0×10^{-3} %).

China Australia Geological Storage of CO_2 中澳二氧化碳地质封存

Problem 1: results(3)

Non-linear relative permeability:

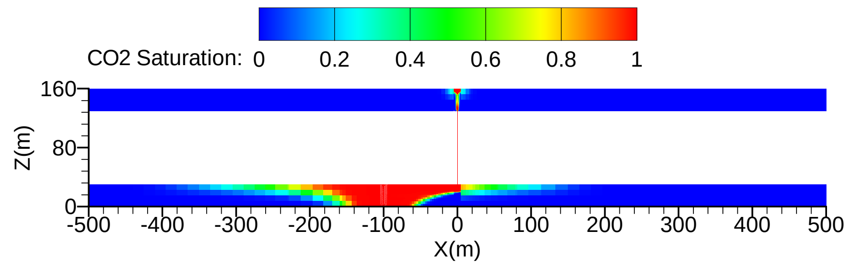
$$\begin{cases} k_{w,r} = S_e^4 \\ k_{g,r} = (1-S_e)^2 \cdot (1-S_e^2) \end{cases} \quad \& \quad S_e = \frac{S_w - S_{w,R}}{1 - S_{w,R} - S_{g,R}}$$

S_e is effective saturation;
$S_{w,R}$ is the residual brine saturation;
$S_{g,R}$ is the residual gas saturation.

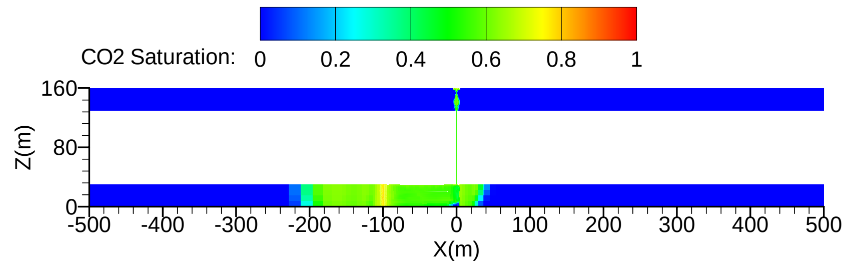
Non-linear relative permeability:

- increases overall resistance;
- enhances the influence of viscous force;
- weakens the buoyancy driven force;

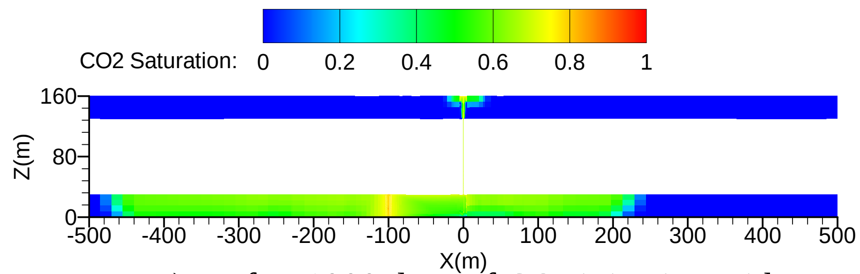
these make the CO_2 front shape more cylindrical than linear rela.perm. case.



a) after 115 days of CO_2 injection with linear relative permeability



b) after 115 days of CO_2 injection with non-linear relative permeability



c) after 1000 days of CO_2 injection with non-linear relative permeability

Figure Distribution CO_2 saturation on the vertical middle slice

Problem 1: results(4)

Non-linear relative permeability:

$$\begin{cases} k_{w,r} = S_e^4 \\ k_{g,r} = (1-S_e)^2 \cdot (1-S_e^2) \end{cases} \quad \& \quad S_e = \frac{S_w - S_{w,R}}{1 - S_{w,R} - S_{g,R}}$$

S_e is effective saturation;
$S_{w,R}$ is the residual brine saturation;
$S_{g,R}$ is the residual gas saturation.

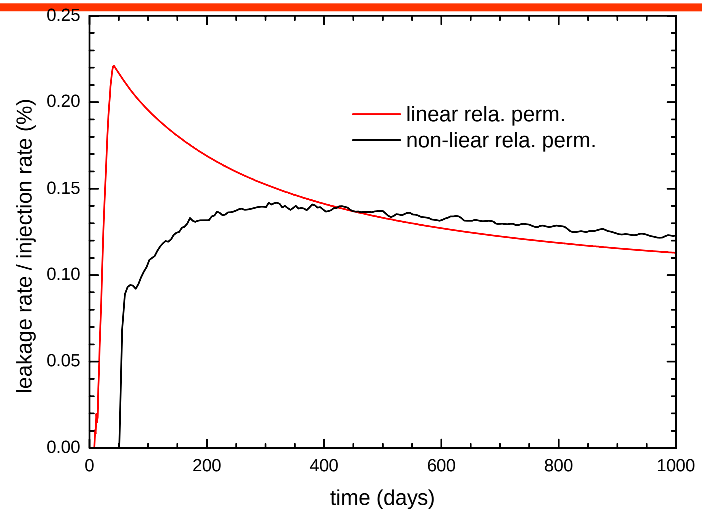


Figure Predicted CO_2 leakage ratio values over time with linear relative permeability-saturation or non-linear relative permeability-saturation

Table Computed esults with different relative permeability relations

Case	Max. leakage (%)	Time at max. leakage (days)	Leakage at 1000 days (%)	Arrival time (days)
Linear relative permeability-saturation	0.221	43	0.113	9
Non-linear relative permeability-saturation	0.142	307	0.123	52

Non-linear relative :

- decelerates CO_2 arrival time;
- lowers the maximum leakage rate;
- lowers leakage rate in the early period;
- improves leakage rate in the late period.

cags China Australia Geological Storage of CO_2 中澳二氧化碳地质封存