Dynamic simulation of CO_2 injection wells taking the near-well reservoir into account

Svend Tollak Munkejord, Morten Hammer, Åsmund Ervik, Halvor Lund, Hans L. Skarsvåg, Lars Hov Odsæter

SINTEF Energy Research, Trondheim, Norway

http://www.elegancy.no/

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Outline of presentation

- Motivation
- Models
  - Well flow model
  - Near-well reservoir flow model
  - Thermodynamics
  - Coupling
- Results

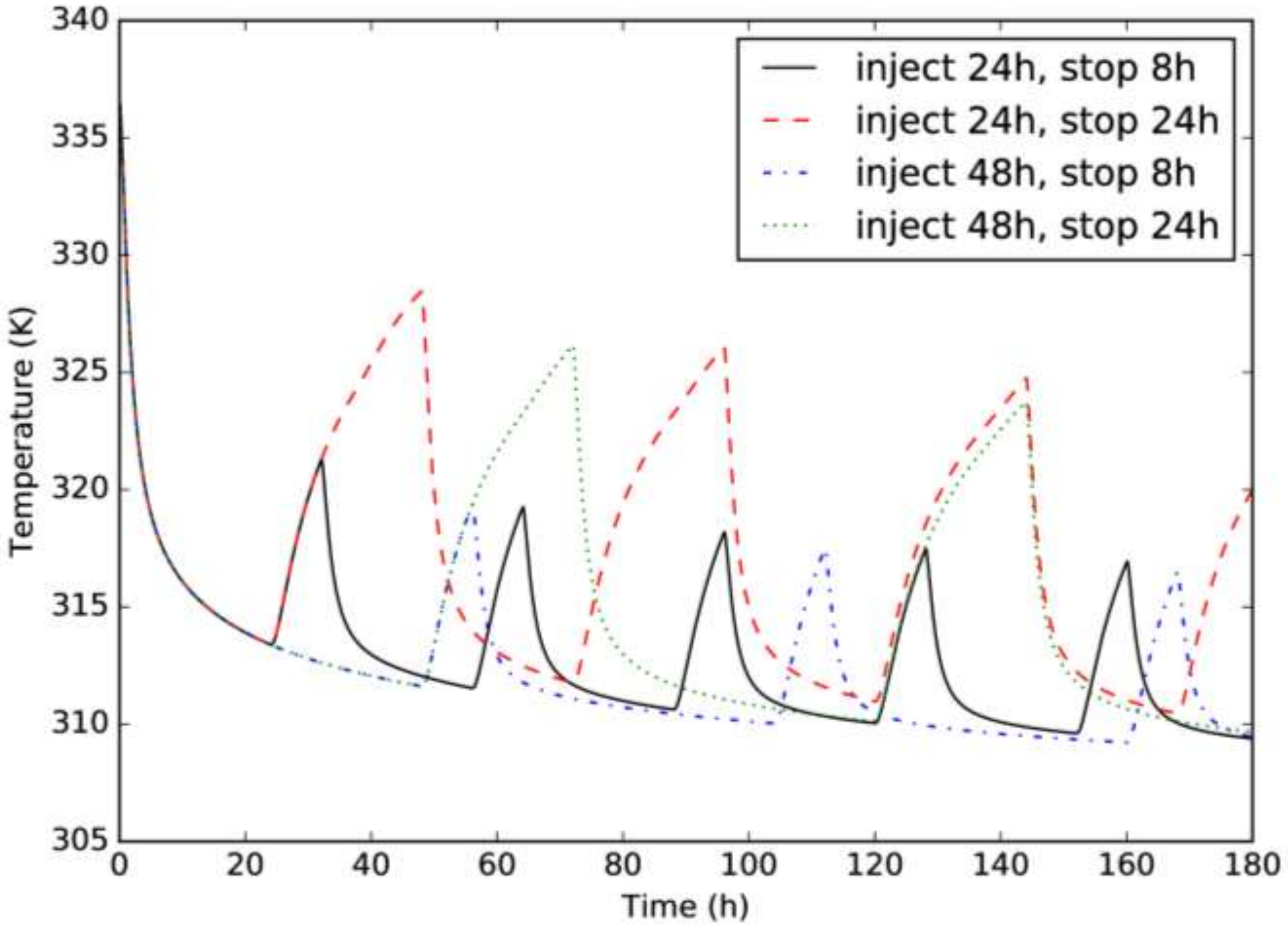
Motivation

- Injection of CO_2 is different from production of oil and natural gas, and this has implications on operation and design of wells
- Relevant scenarios
  - Intermittent injection (e.g. from ships)
  - Shut-in and start-up
  - Blow-out
  - Possible back-flow of brine into well
  - Thermal cycling and implications of well integrity
- Multiple phases may occur in the well (gas, CO_2-rich liquid, water-rich liquid, solid)
- The well dynamics are influenced by the reservoir dynamics
- We would like to couple a well model with a near-well reservoir model

CO_2 well integrity – thermal cycling

- Intermittent injection of CO_2 gives thermal cycling in the well materials.
- In some cases this may lead to debonding and affect well integrity.
- Worst case: High mass flow, low temperature and long injection and stop intervals

P. Aursand et al., *Int. J. Greenh. Gas Con.* **62** (2017)



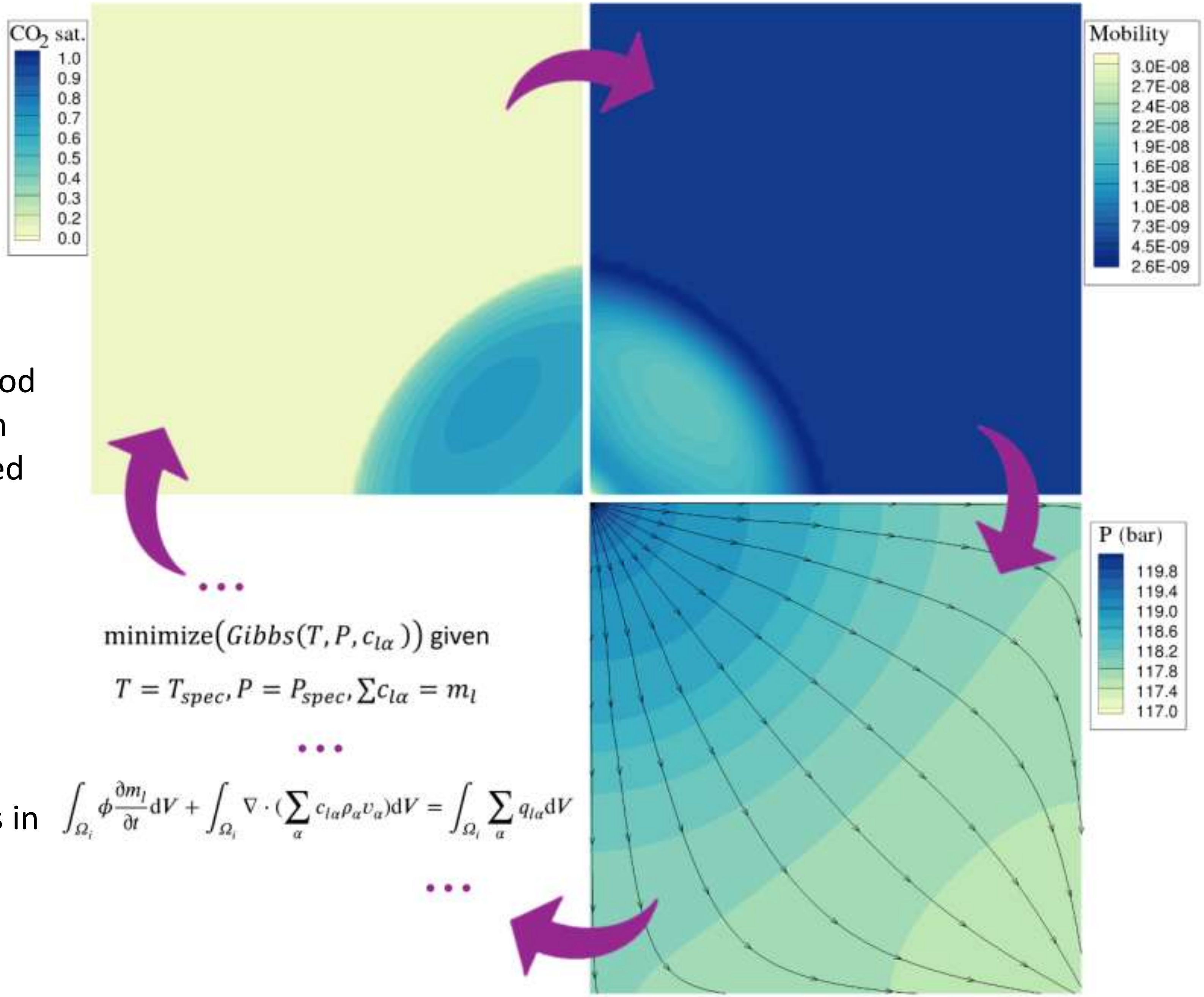
Temperature near bottomhole

Well model

- Model formulation (drift-flux model)
  - Conservation of mass for each component
  - Momentum balance for the one/two/three phase mixture
  - Total-energy balance for the mixture
  - The phasic velocities are found from an algebraic slip relation
  - Equilibrium in pressure, temperature and chemical potential between the phases
- Flexible choice of equation of state
- Numerical method
  - Fully implicit Jacobian-free Newton-Krylov method
  - Solution using the PETSc library with a Newton-Raphson method as fallback

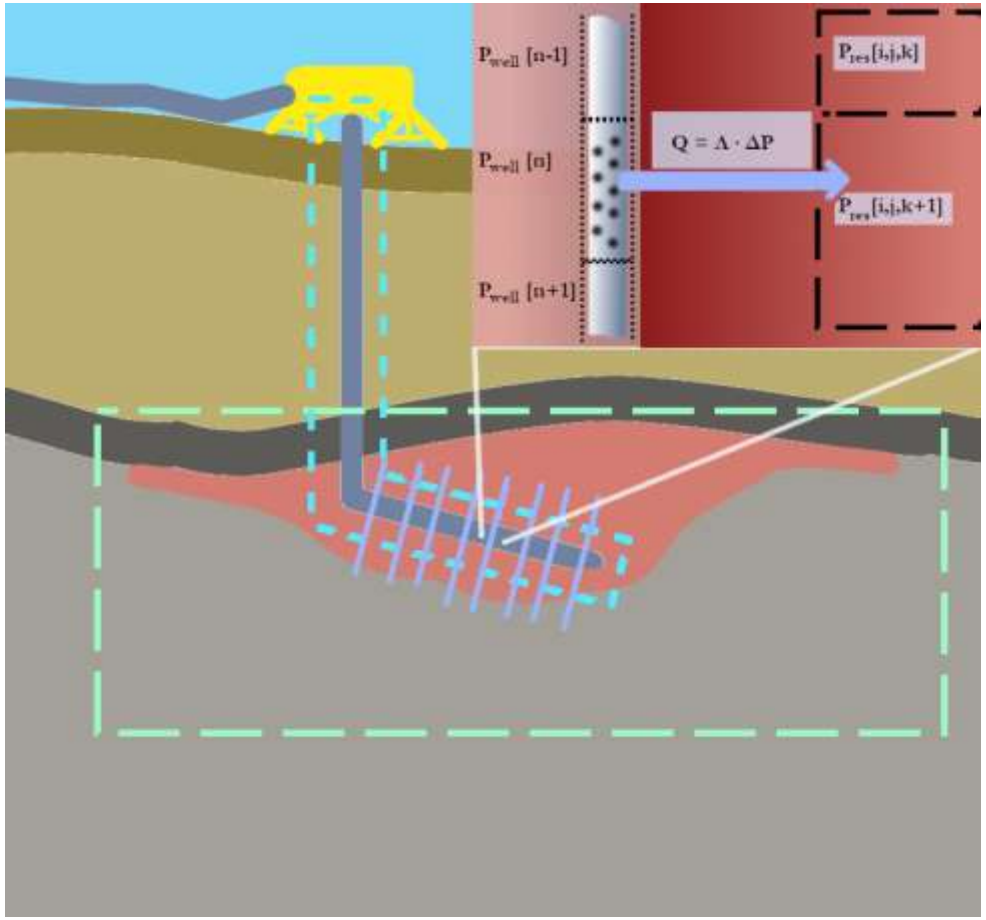
Reservoir model

- Purpose-built reservoir simulation code using a variant of the IMPES method
- Pressure is computed from mobility, which is computed from saturations
- Mass is then transported according to the phase velocities (Darcy's law)
- Thermodynamic flash calculation updates saturations, densities, dissolution of components in phases etc.
- Example: 10 m x 10 m domain, 0.78 kg/sec. injection, after 650 sec.



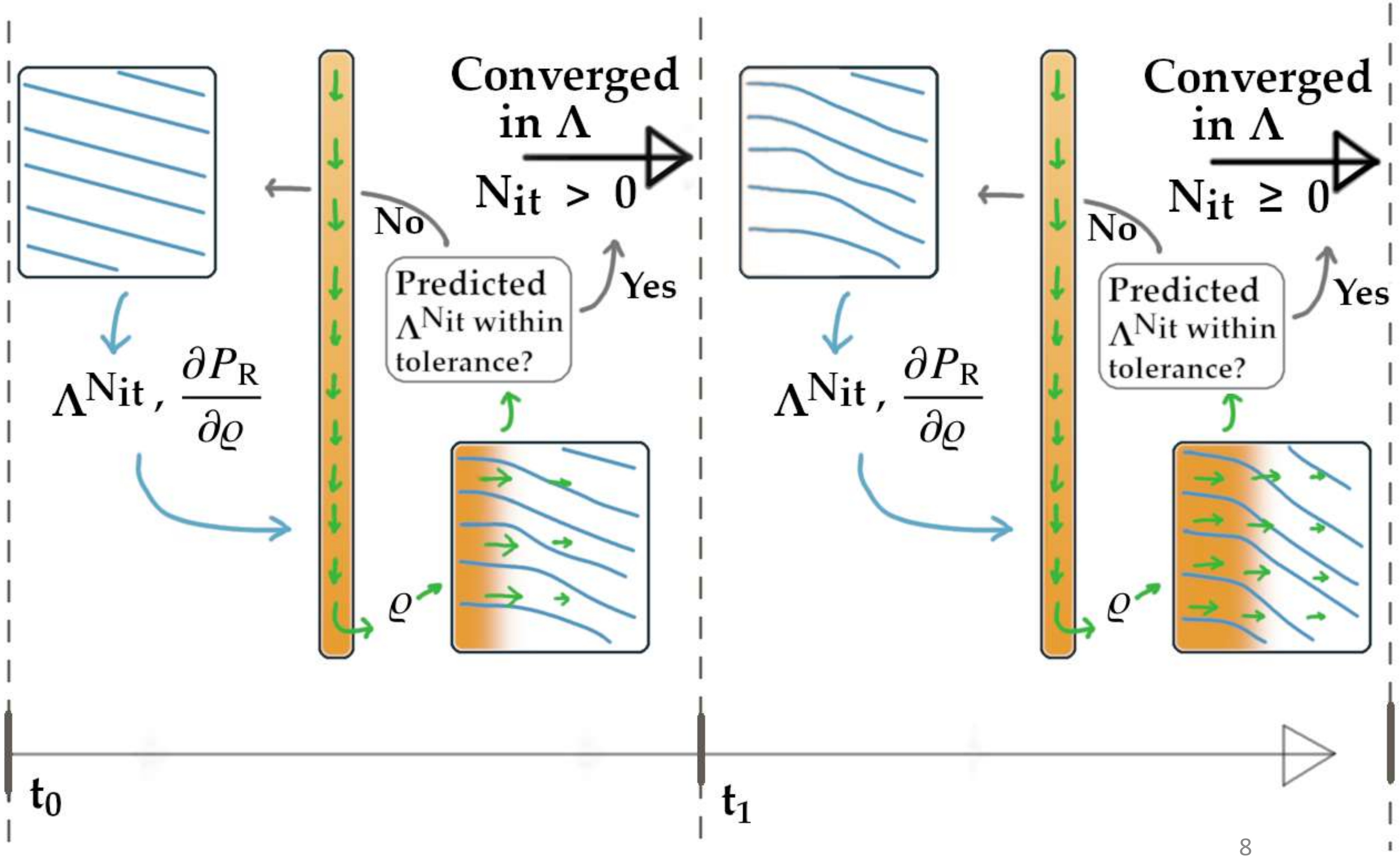
Coupling of well and reservoir model

- Well model is 1D (averaged over cross-section)
  - Well can be straight vertical or more complicated
- Reservoir model is 2D/3D
  - Focused on near-well region, assumed homogeneous rock with flow at boundaries
- Coupling is done at one or several locations
  - Partitioned coupling
  - Mass flow out of well proportional to pressure difference between well and reservoir
  - Using relative permeabilities etc. from the reservoir model to compute the well index Λ
  - Mass flow out of well becomes source term in the reservoir model

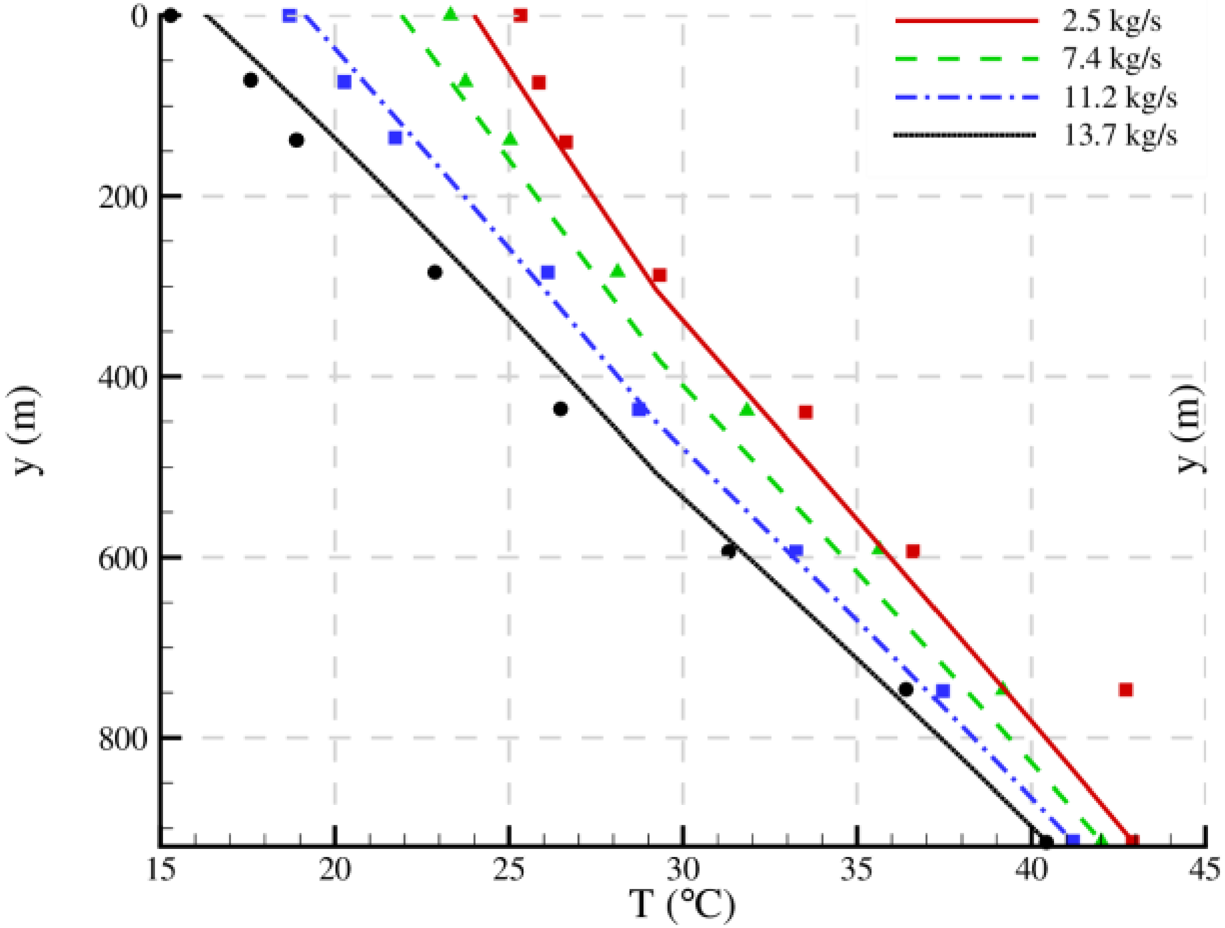


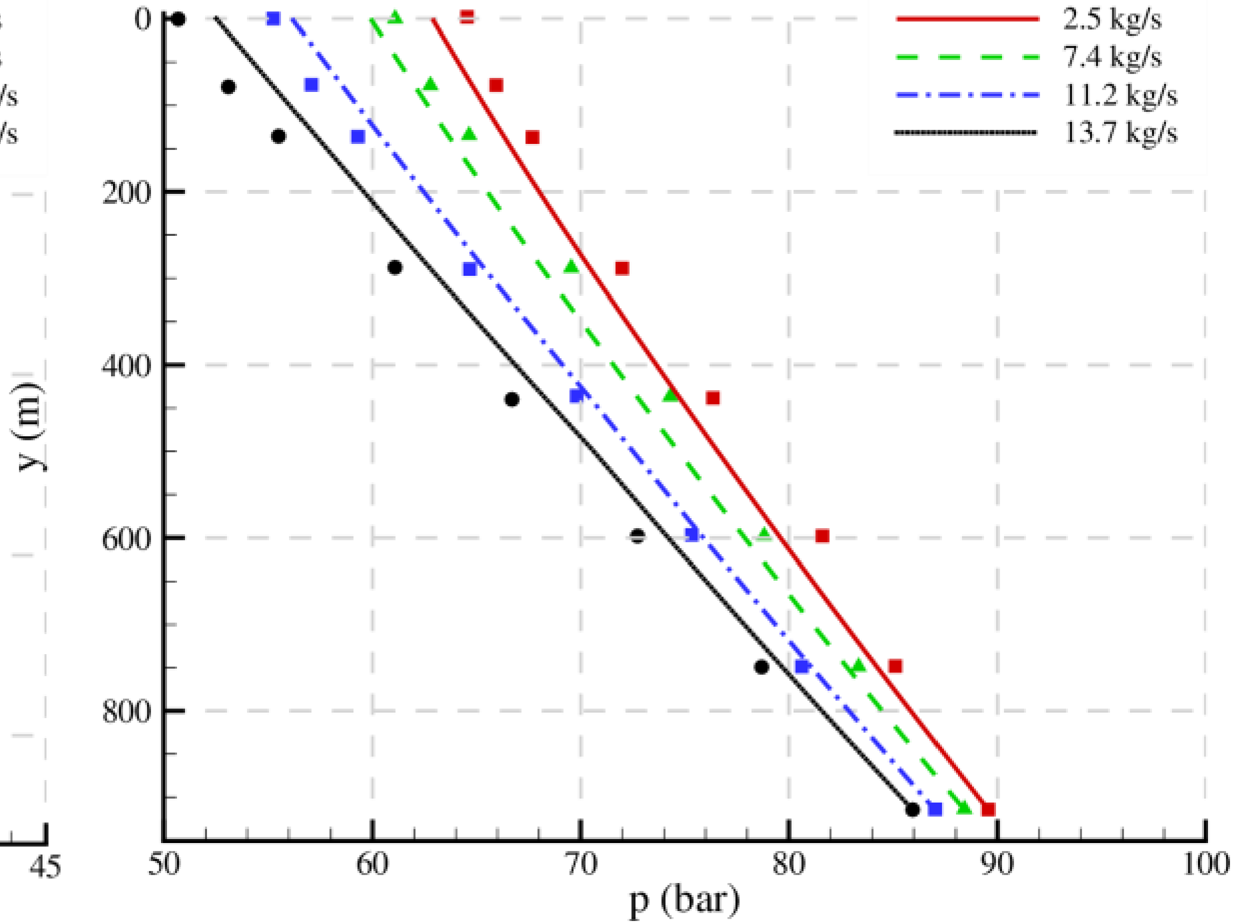
Coupling of well and reservoir model

- Well index (Λ) determines volume flow from well to reservoir
- It depends on saturation, which again depends on volume flow
- Stable coupling requires that the scheme is implicit in Λ
- Thus in situations where Λ changes quickly, we must iterate to obtain correct Λ at the end of the time step



Validation of well model





- Steady flow in a CO_2-production well
- Data from Cronshaw and Bolling (1982)

- Assumptions: Adiabatic flow and pure CO_2
- The case is sensitive to the way boundary conditions are set

Coupled case

Well conditions:

- 1500 m vertical well (ID=0.0883m)
- Initially
  - P = 150 bar at bottom hole
  - Pure CO_2.
  - No flow.
  - Hydrostatic pressure profile in pipe
- Start simulation by ramping linearly form 0 to 25kg/s in 60s at the well head
- Enthalpy specified at inlet, to give approximately 300K

Reservoir conditions:

- P = 150 bar initial and boundary condition, outflow from near-well reservoir domain (30m height x 40m radius, cylindrically symmetric)
- T = 310 K isothermal
- Permability 3.0 Darcy, porosity 0.3 for ‘Case A’
- Permability 0.3 Darcy, porosity 0.15 for ‘Case B’
- Consider three situations for each case:
  - Neglect gravity
  - Include gravity
  - Spatially varying rock permeability (log-normal distribution)

Coupled case

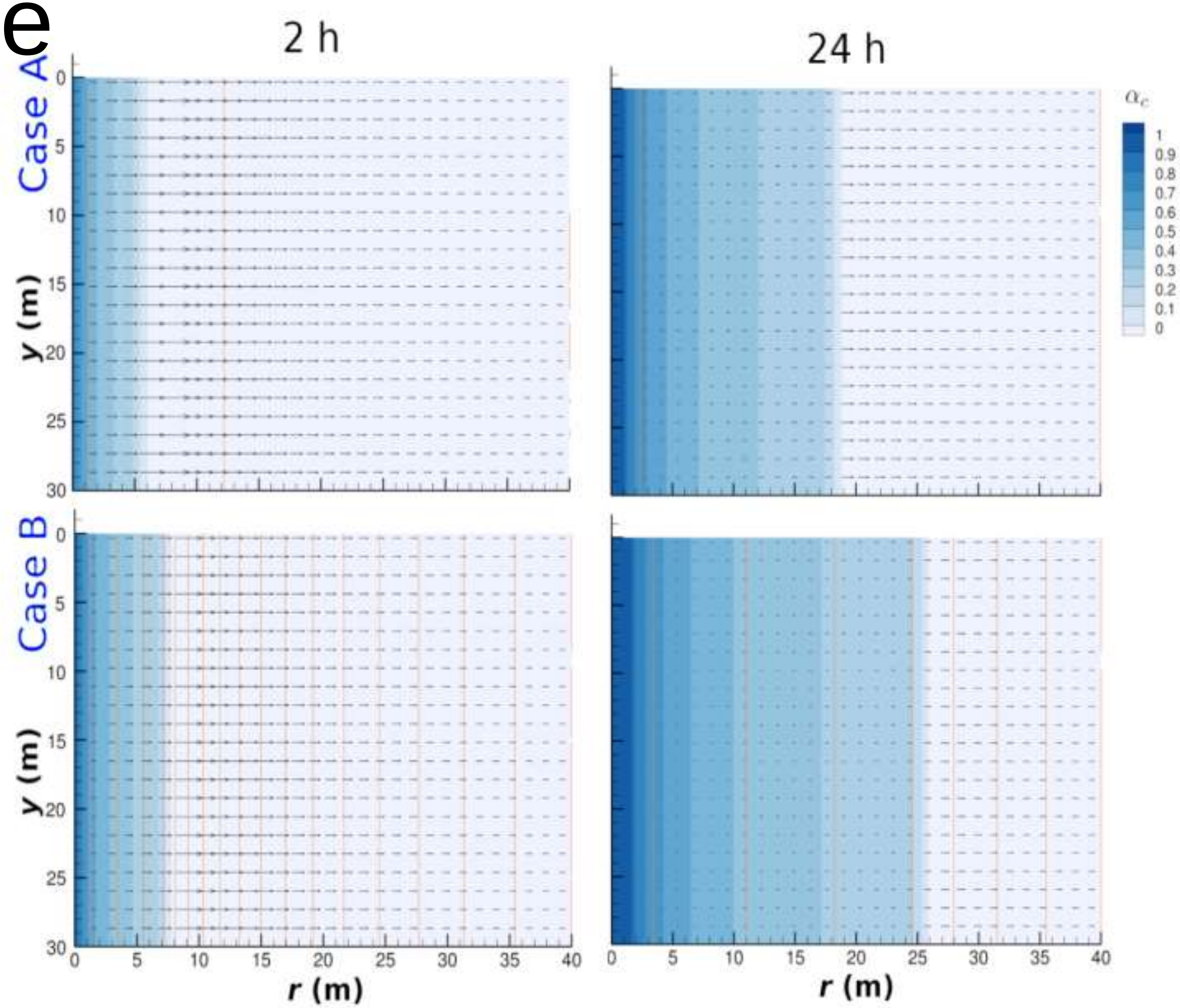
Neglecting gravity

CO_2 volume fraction in blue

Pressure contours in orange

Water flow as vectors

For Case B with lower porosity, front advances further.



Coupled cas

Including gravity

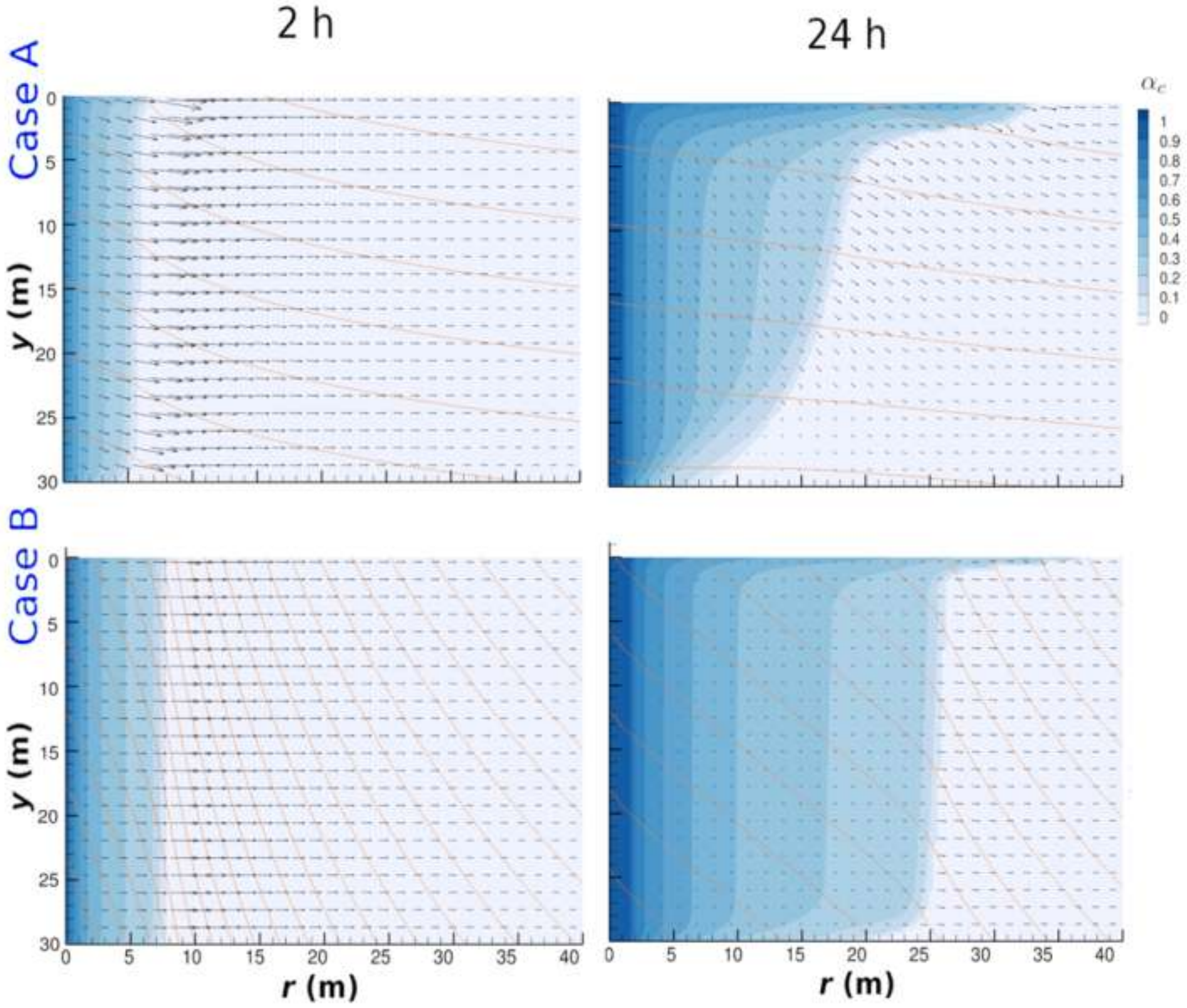
CO_2 volume fraction in blue

Pressure contours in orange

Water flow as vectors

For Case A with higher permeability, gravity has bigger effect.

For this reason, leading CO_2 edge catches up to Case B



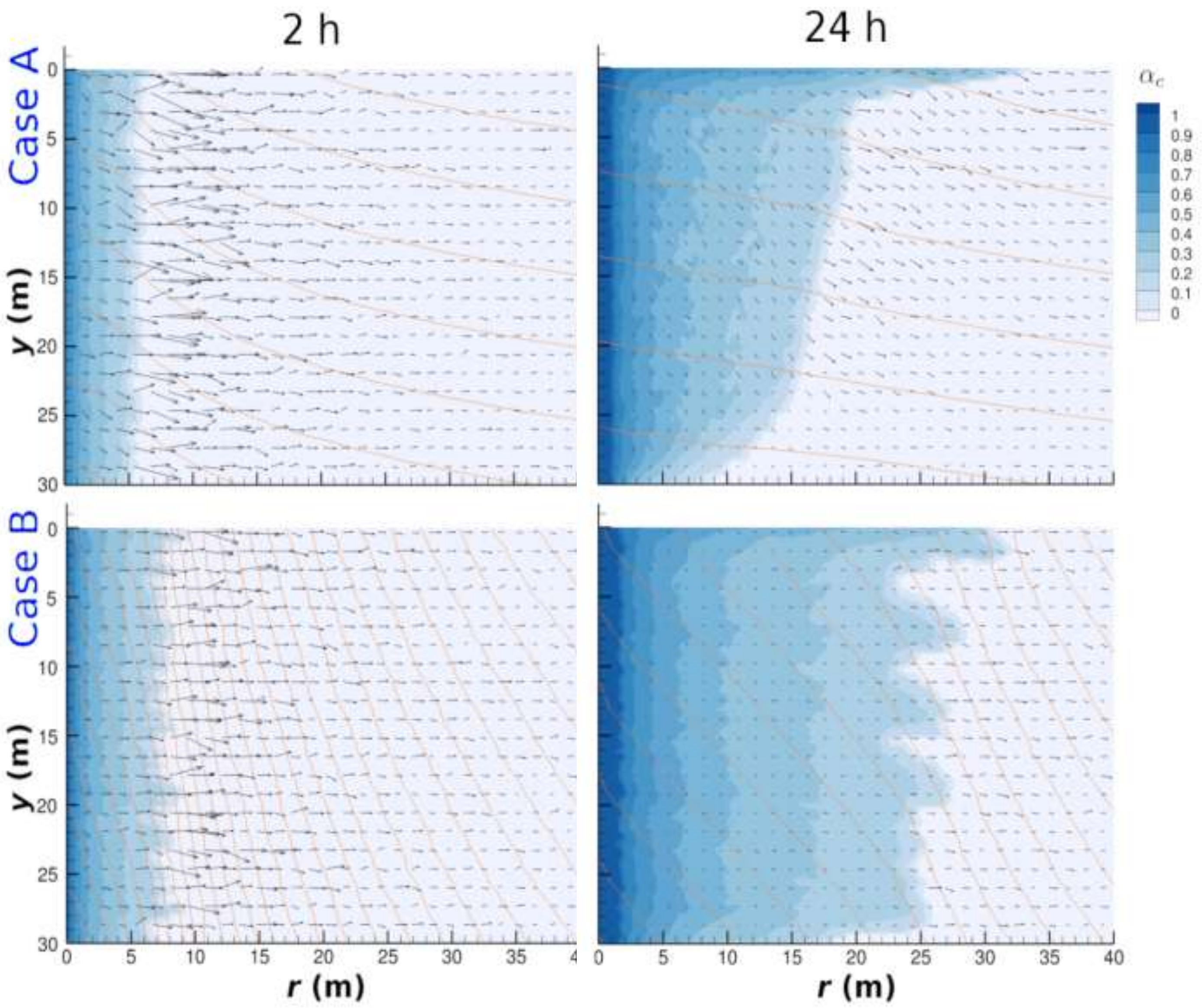
Coupled case

With varying permeability

CO_2 volume fraction in blue

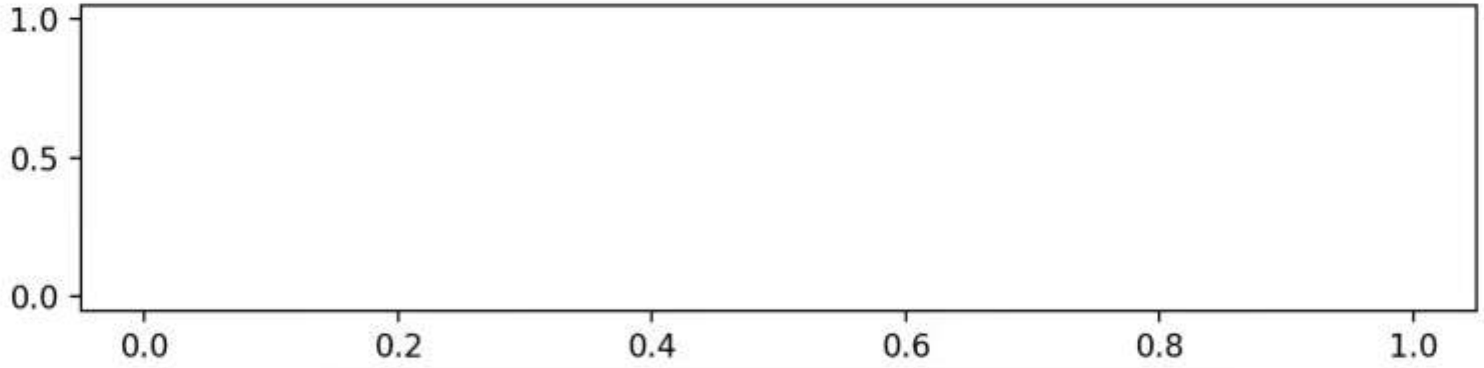
Pressure contours in orange

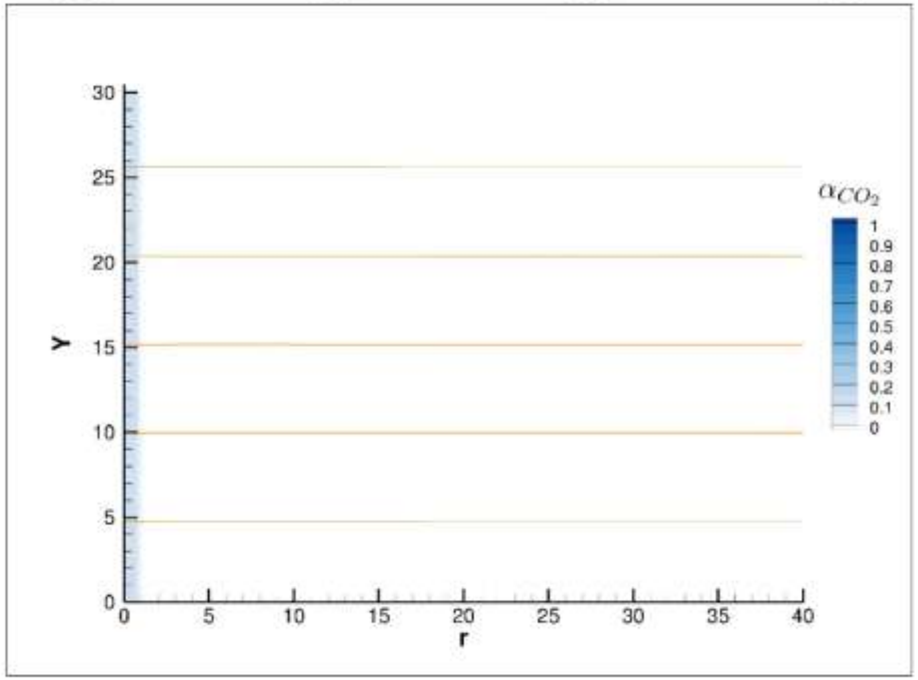
Water flow as vectors



For Case A, overall trend is unchanged. For Case B, viscous fingering is observed.

Coupled case

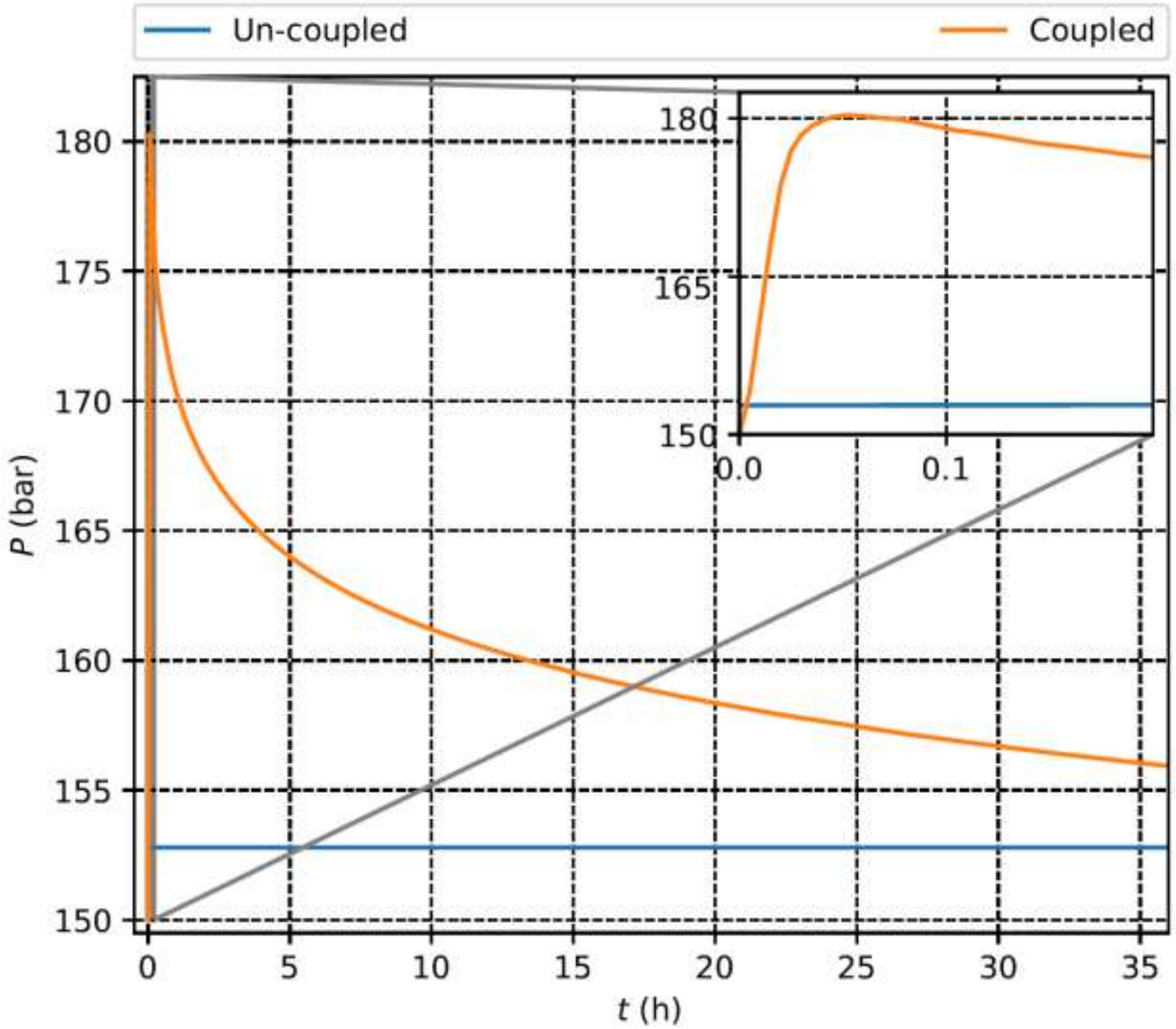




- "Case B" with gravity and varying permeability
- Top: pressure in well at the coupling point
- Bottom: CO_2 volume fraction (blue) and pressure (orange lines) in the reservoir

Coupled vs. uncoupled case B

- Uncoupled well case identical to coupled case, except the reservoir in-flow model:
  - $Q = \Lambda \frac{\rho}{\mu}\left(P_w - \left[P_R^0 + \frac{dP_R}{dQ} Q\right]\right)$
  - For illustration, the reservoir pressure is set to match $P_{far} + \ (P_{max} - P_{far})\frac{\mu_{CO_2}}{\mu_{water}}$
- Plot shows bottom hole pressure. Zoom of first 0.2h.



Conclusion

- Coupled model with three building blocks:
  - Well model
  - Near-well reservoir model
  - Thermodynamics
  - Partitioned coupling means these can be developed independently
- Full thermodynamic model is employed in the reservoir under the assumption of constant temperature
  - Future work to implement an energy transport equation in the reservoir, and possibly to take fluid compressibility into account
- Results indicate the versatility of the model
  - Results emphasize the need for a near-well model to describe the reservoir pressure response from an injection well.
  - The specific nature of the reservoir needs to be modelled, in particular for tighter formations, and the effect of buoyancy as well as heterogeneities may be important.

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Contact: Svend Tollak Munkejord, svend.t.munkejord@sintef.no