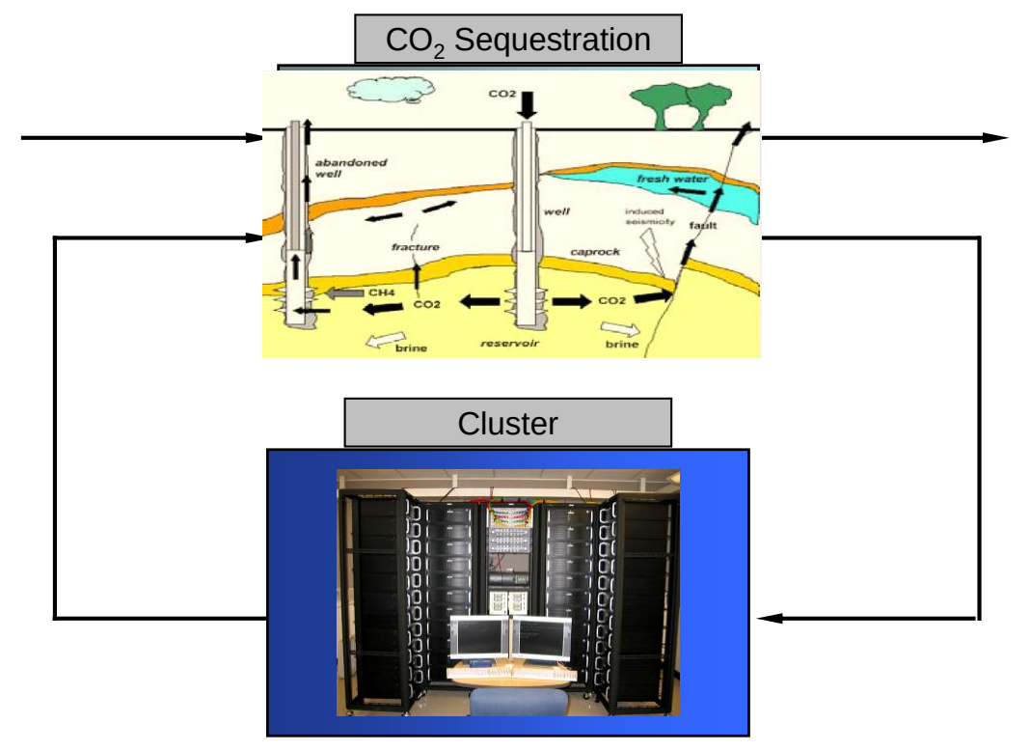

SPE 142146

On Interplay of Capillary, Gravity, and Viscous Forces on Brine/CO_2 Relative Permeability in a Compositional and Parallel Simulation Framework

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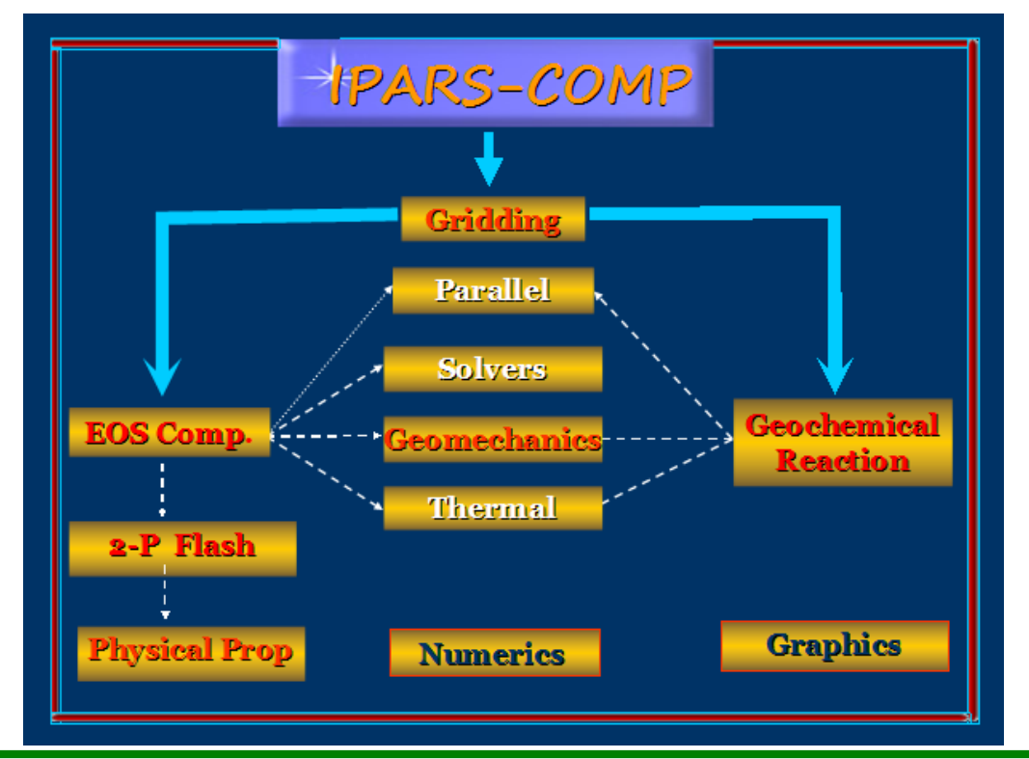
Abstract and Motivation

- Recent experimental data reveals the impact of pressure, temperature, and salinity on interfacial tension (IFT) between CO_2 and brine. The dependence of CO_2-brine relative permeability and capillary pressure on IFT is evident in published lab results.
- Improved understanding of the mechanisms that control the migration and trapping of CO_2 in subsurface is crucial to design future storage projects that warrant long term and safe containment. Prediction of CO_2 injectivity and CO_2 migration is impossible without considering the variation of interfacial tension and its effect on petrophysical properties of CO_2 and water.
- A general relative permeability model that combines effects of pressure gradient, buoyancy, and IFT has been developed and implemented in an Equation of State (EOS) compositional and parallel simulator.
- The significance of IFT variations on CO_2 migration and trapping is assessed.

IPARS Simulator

- Integrated Parallel Accurate Reservoir Simulator (IPARS) Were used the to study the injection and migration of CO_2 in saline aquifers.
- IPARS is an advanced computer framework that serves as a test-bed for multiphase compositional flow models, multi-physics models, advanced discretizations, efficient solvers, and upscaling techniques among others.
- The simulator is capable of modeling domains with millions of grids using multiple processors with an impressive parallel scalability.
- The CO_2 module of IPARSv-3
  - ➢ compositional Peng-Robinson cubic EOS
  - ➢ geochemical reactions
  - ➢ non-isothermal



Model Description

1. Model effect of Salinity on Water/CO_2 Dissolution and Density

1a. CO_2 dissolution in water is corrected for the effect of salinity (S) via Binary Interaction Coefficient (BIC)

$$\mathrm{BIP}_{H2O-CO2} = -0.093625 + (4.861\times10^{-4}\times(T-113)) + (2.29\times10^{-7}\times S)$$

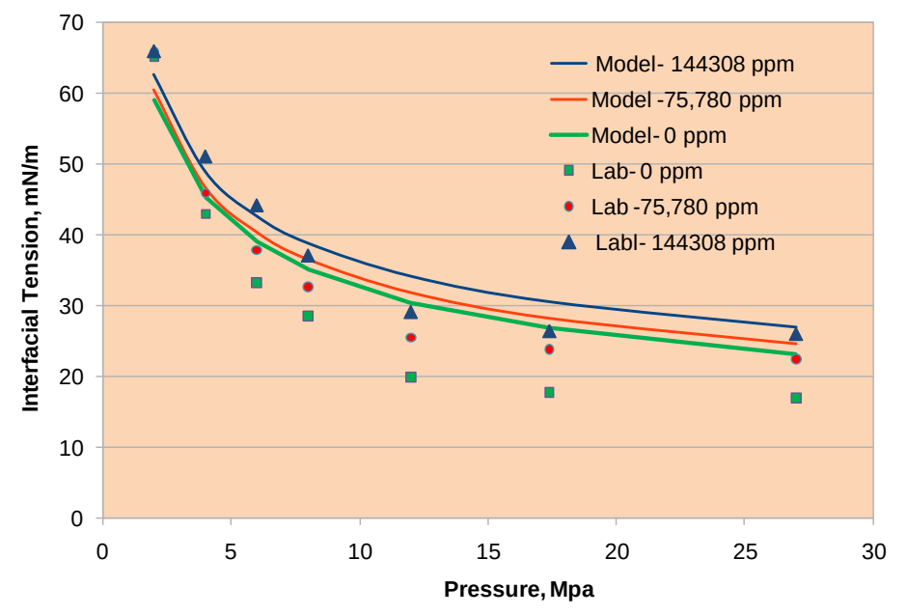
1b. Volume Shift Parameter (VSP) is tuned for accurate water density as a function of salinity and temperature

$$\mathrm{VSP}_{H2O} = 0.179 + (2.222\times10^{-4}\times(T-113)) + 4.9867\times10^{-7}\times S$$

2. Calculate CO_2-water interfacial tension (IFT)

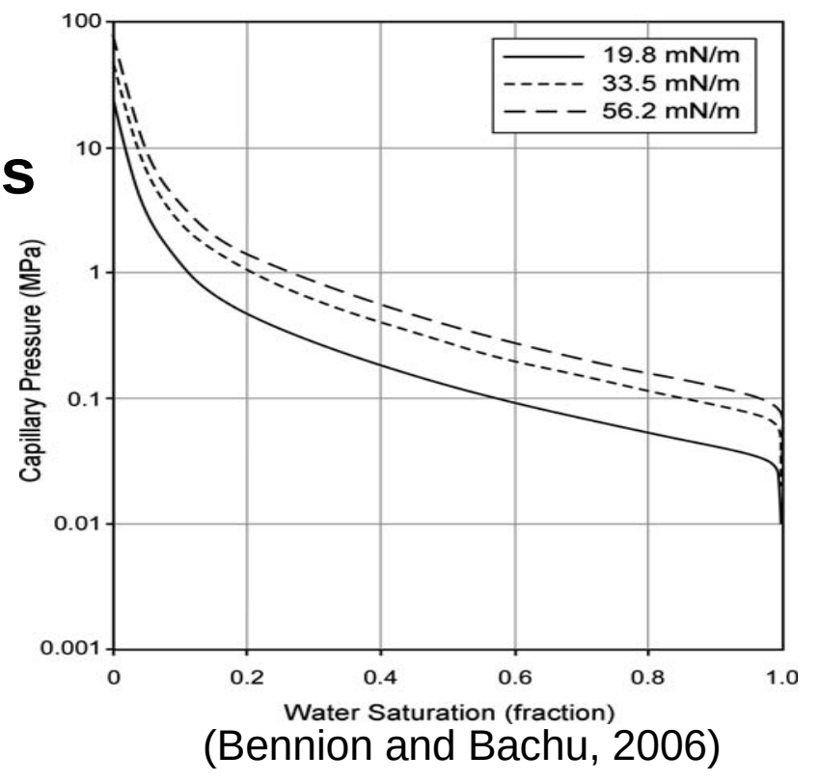
IFT is calculated as a function of pressure, temperature, and salinity using empirical correlation of Bennion and Bachu (2008)

$$\sigma = 71.6924P^{-0.432639} + 0.2100587T^{-0.900261} + 0.075859S^{1.457937}$$



3. Scale Capillary Pressure with IFT

$$P_c = P_c^{entr}\left(\frac{\phi}{k}\right)^{0.5}\frac{\sigma}{\sigma^{ref}}\bar{S}_w^{\,epc}$$



(Bennion and Bachu, 2006)

4. Calculate Capillary, Bond, and Trapping Numbers

Capillary Number (Nc)

$$N_{cl} = \frac{\left|\vec{k}\cdot\vec{\nabla}\Phi_l\right|}{\sigma_{ll'}}$$

Bond Number (NB)

$$N_B = \frac{kg(\rho_{l'}-\rho_l)}{\sigma_{ll'}}$$

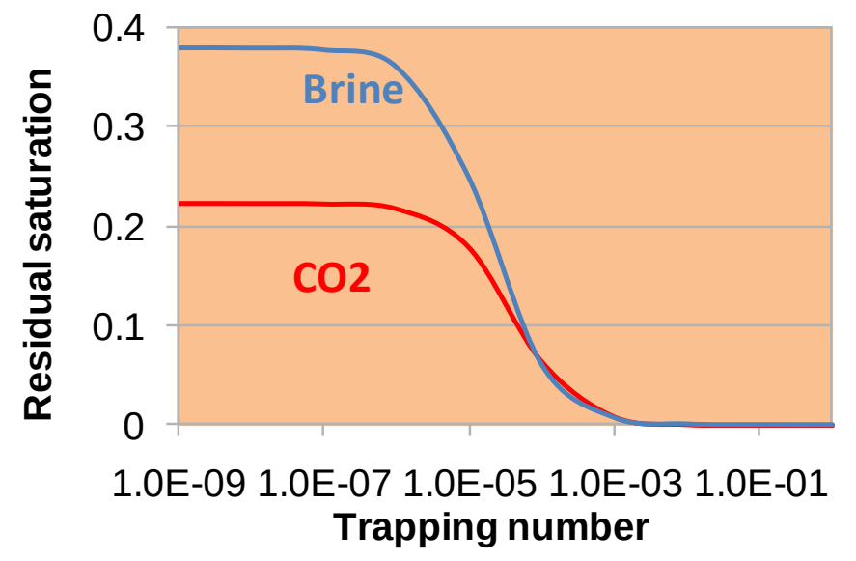
Trapping number (sum of N_c and N_B) (Pope, *et. al* 2000)

$$N_{Tl} = \frac{\left|\vec{k}\cdot(\vec{\nabla}\Phi_l + g(\rho_{l'}-\rho_l)\vec{\nabla}D)\right|}{\sigma_{ll'}}$$

5. Calculate Residual Saturation vs. Trapping Number

$$S_{lr} = \min\left(S_l, S_{lr}^{high} + \frac{S_{lr}^{low} - S_{lr}^{high}}{1 + T_l(N_{Tl})^{\tau_l}}\right)$$

where *T* and τ are trapping parameters obtained from lab data.

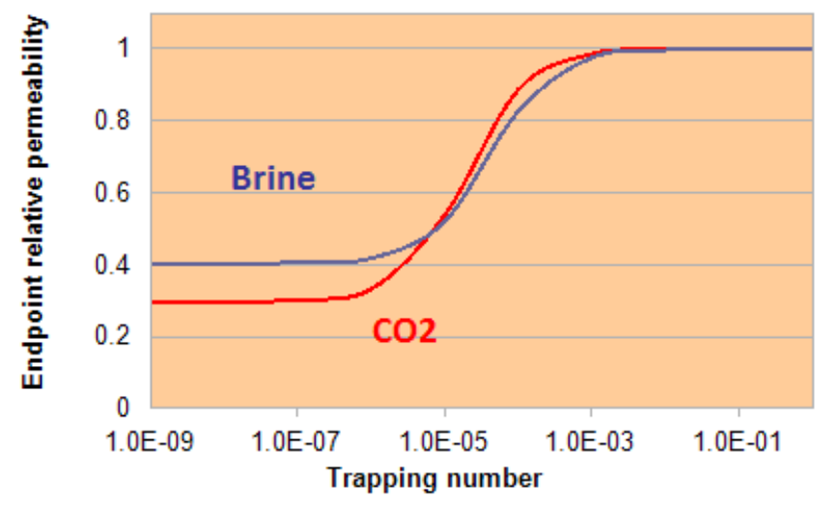


Model Description

6. Shift Relative Permeability vs. Trapping Number

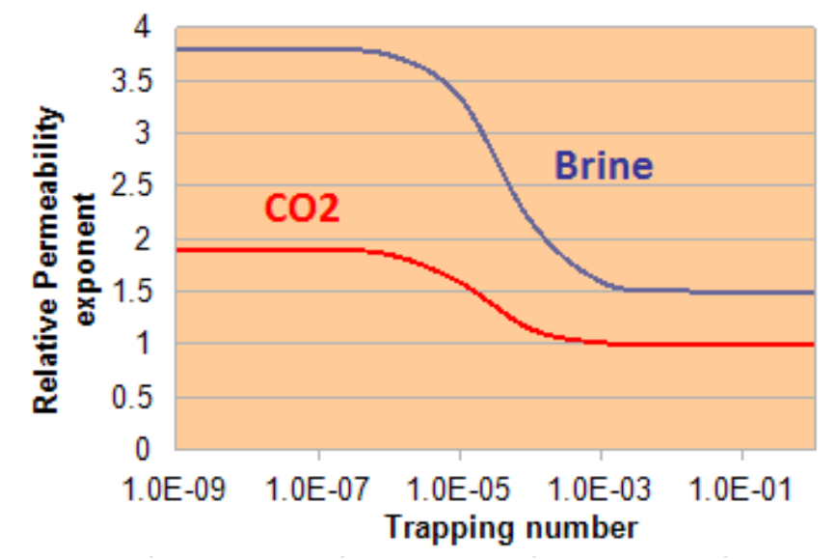
6a. Scale endpoint relative permeability with the shift in residual saturation due to trapping number

$$k_{rl}^0 = k_{rl}^{0low} + \frac{S_{l'r}^{low} - S_{l'r}}{S_{l'r}^{low} - S_{l'r}^{high}}\left(k_{rl}^{0high} - k_{rl}^{0low}\right)$$



6b. Scale relative permeability exponent with the shift in residual saturation

$$\lambda_l = \lambda_l^{low} + \frac{S_{l'r}^{low} - S_{l'r}}{S_{l'r}^{low} - S_{l'r}^{high}}\left(\lambda_l^{high} - \lambda_l^{low}\right)$$



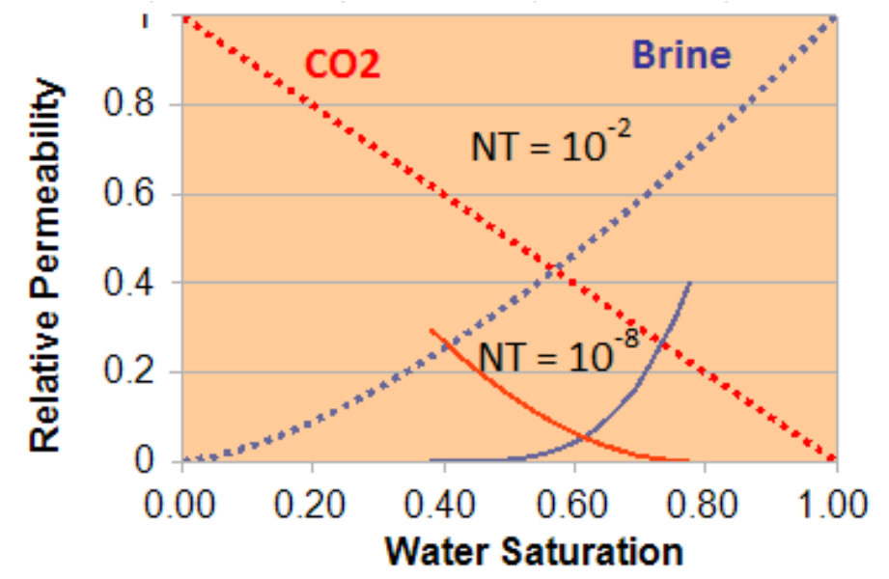
6c. Calculate normalized saturation

$$\bar{S}_w = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{gr}}$$

6d. Calculate relative permeability

$$k_{rw} = k_{rw}^0\bar{S}_w^{\,\lambda_w}$$

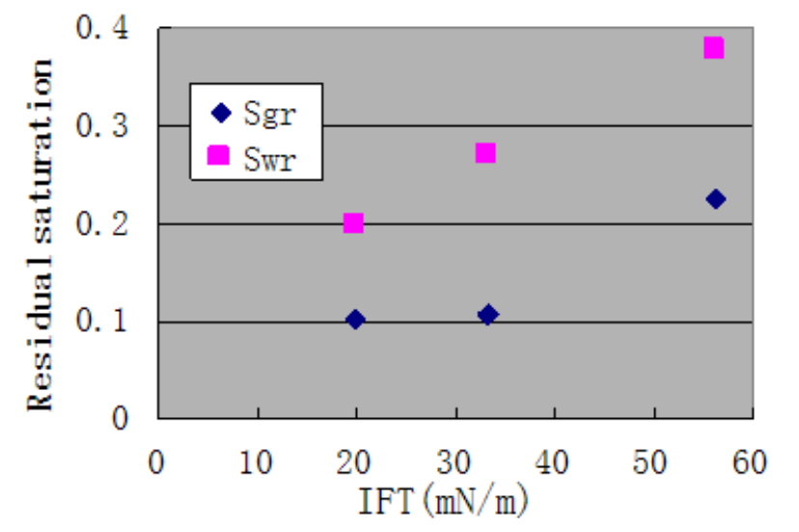
$$k_{rg} = k_{rg}^0\left(1-\bar{S}_w\right)^{\lambda_g}$$



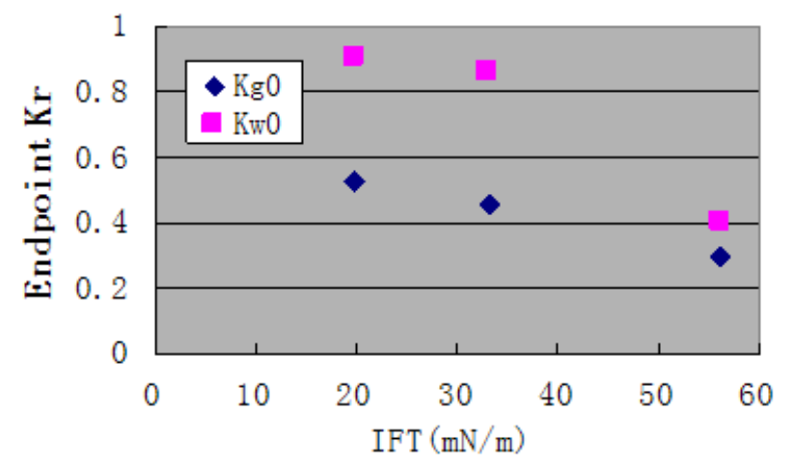
Model Validation

Three sets of relative permeability data at different pressure were available for a sample of sandstone rock at a temperature of 43 ºC and in-situ salinity of 27,096 ppm. (Bennion and Bachu, 2006)

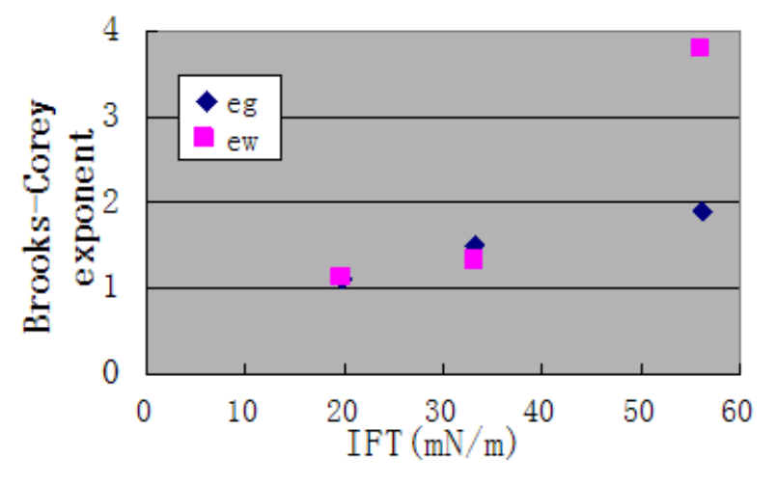
pressure(psi)	pressure(kPa)	IFT(mN/m)	trapping
200	1378	56.2	low
1000	6890	33.2	middle
2900	20000	19.8	high



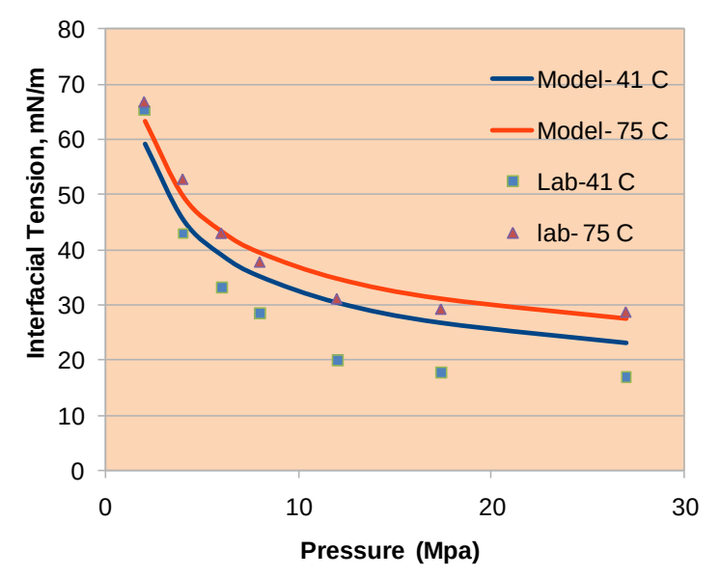
Residual saturations are lower at lower IFT



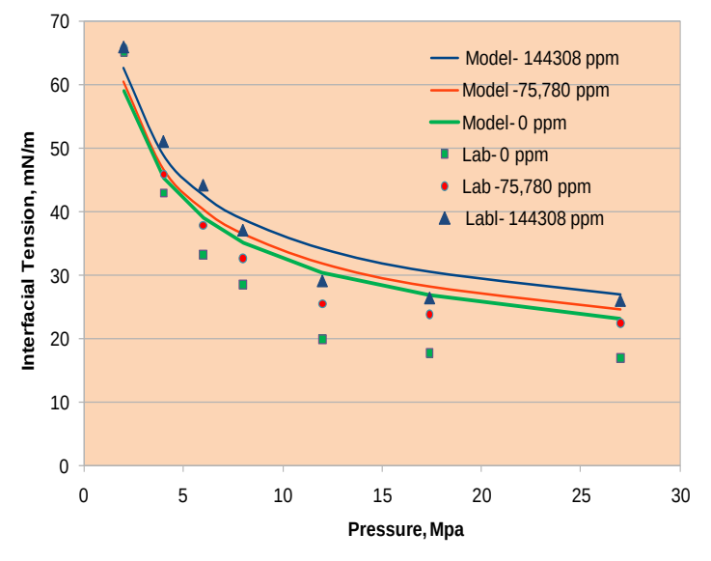
Endpoint Krs are higher at lower IFT



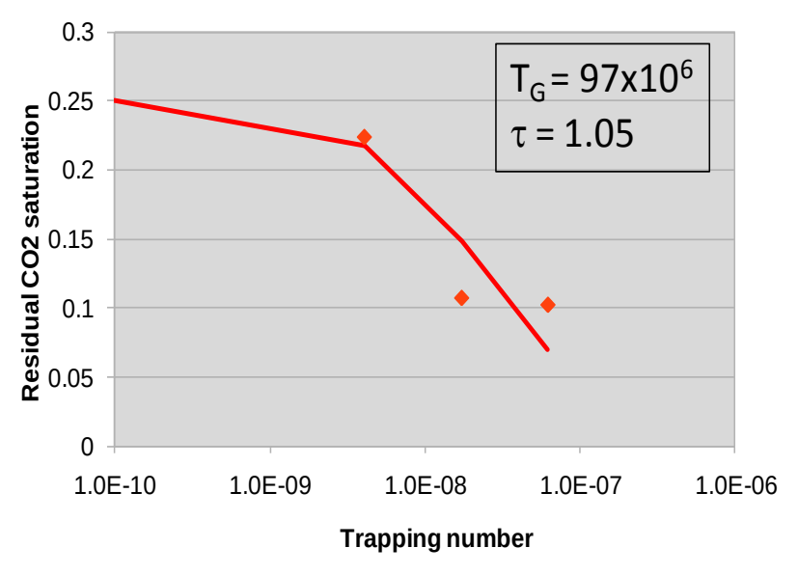
Exponents are lower at lower IFT



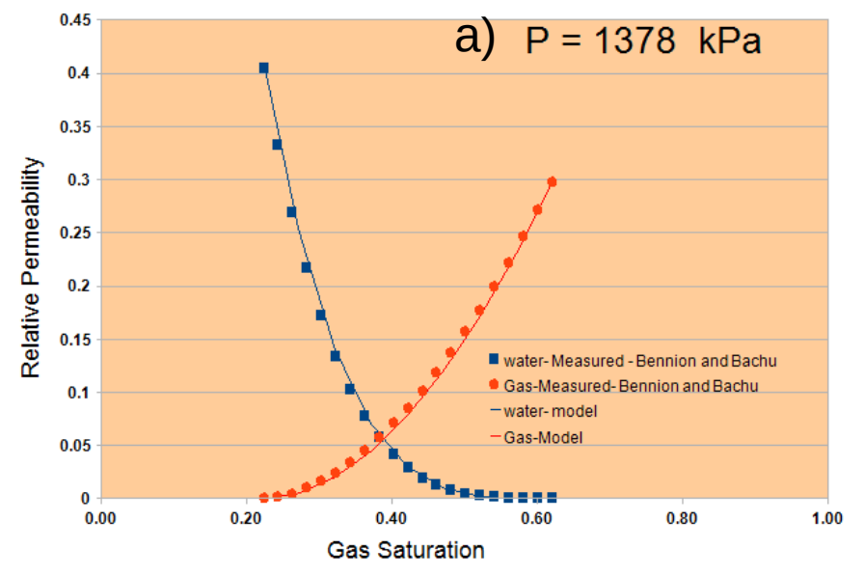
T and P Effect on IFT

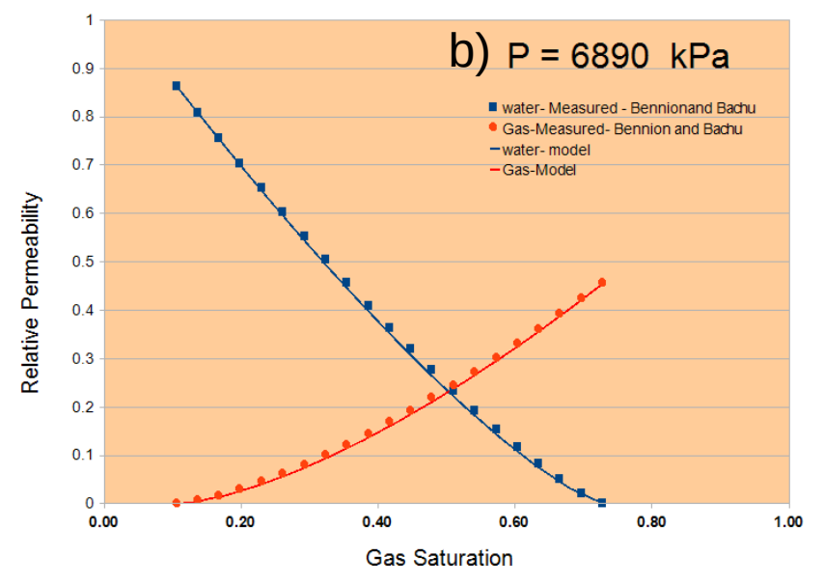


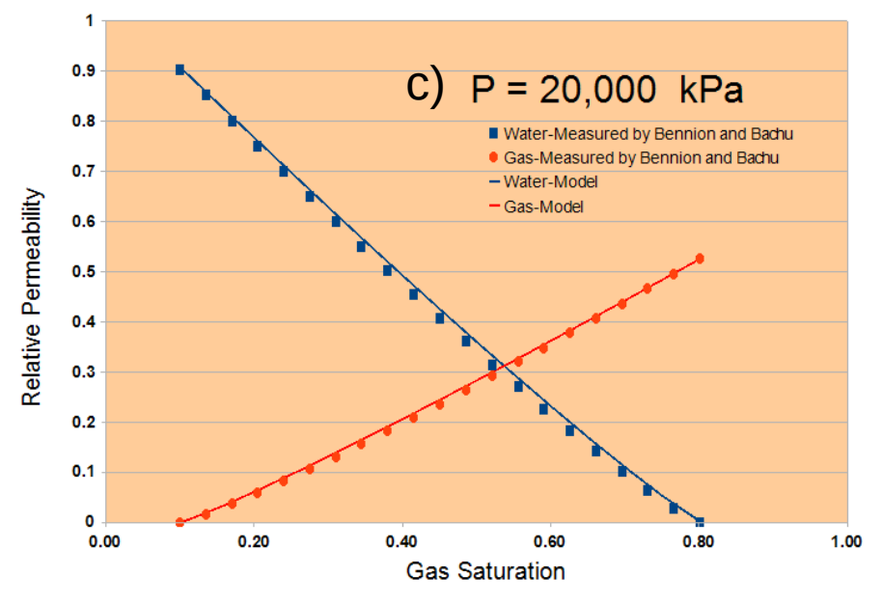
Salinity and P Effect on IFT



CO_2 Residual Saturation vs Trapping Number



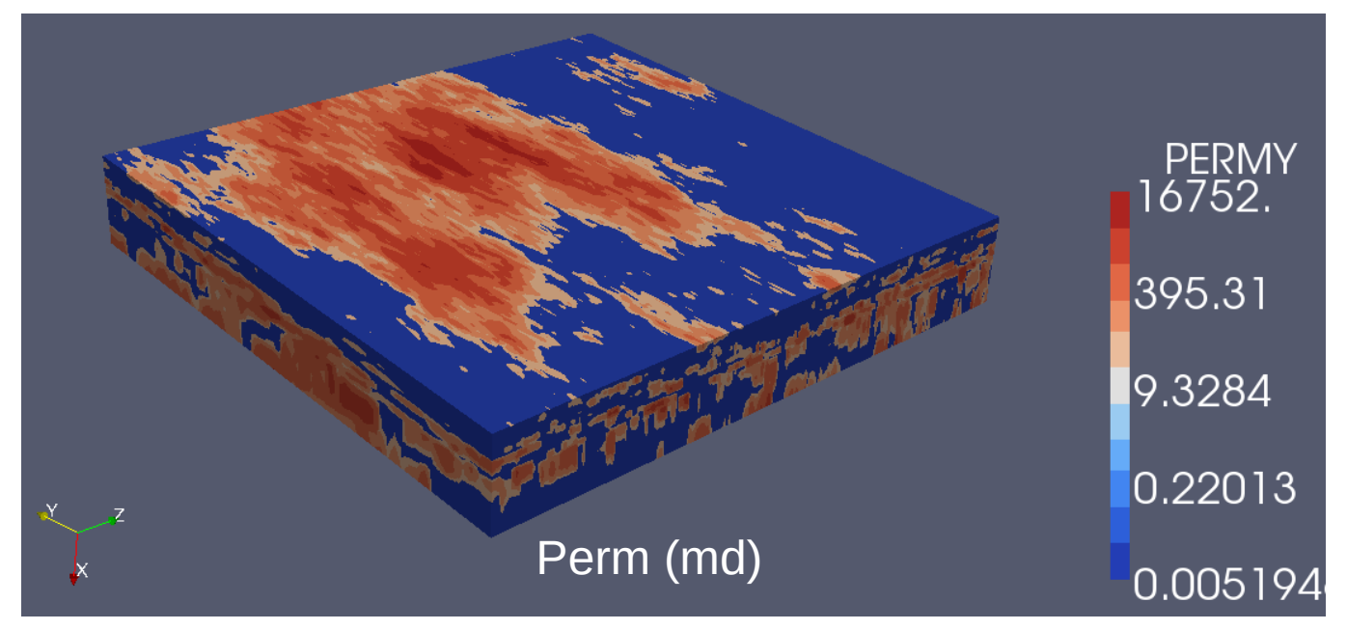


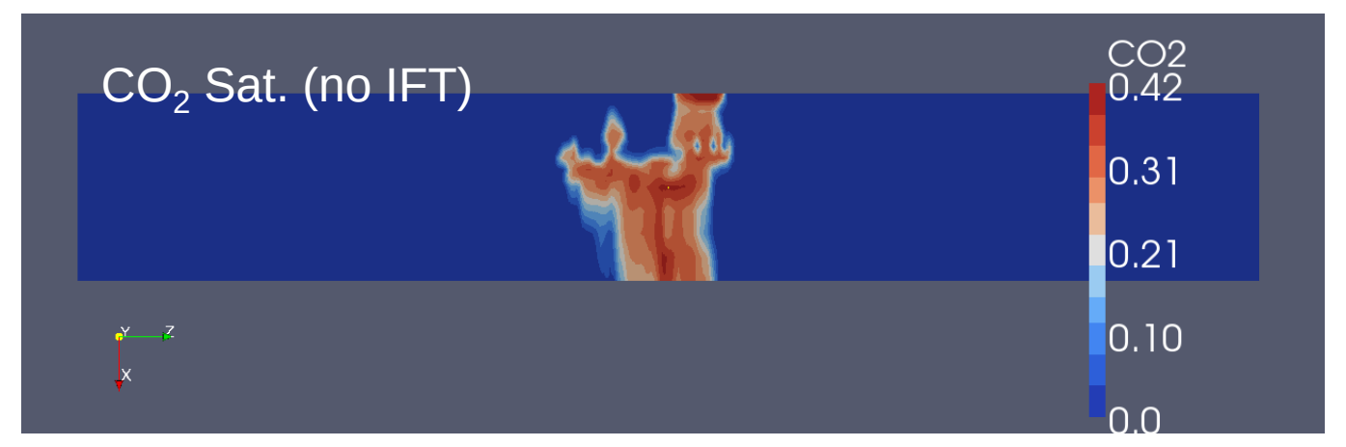


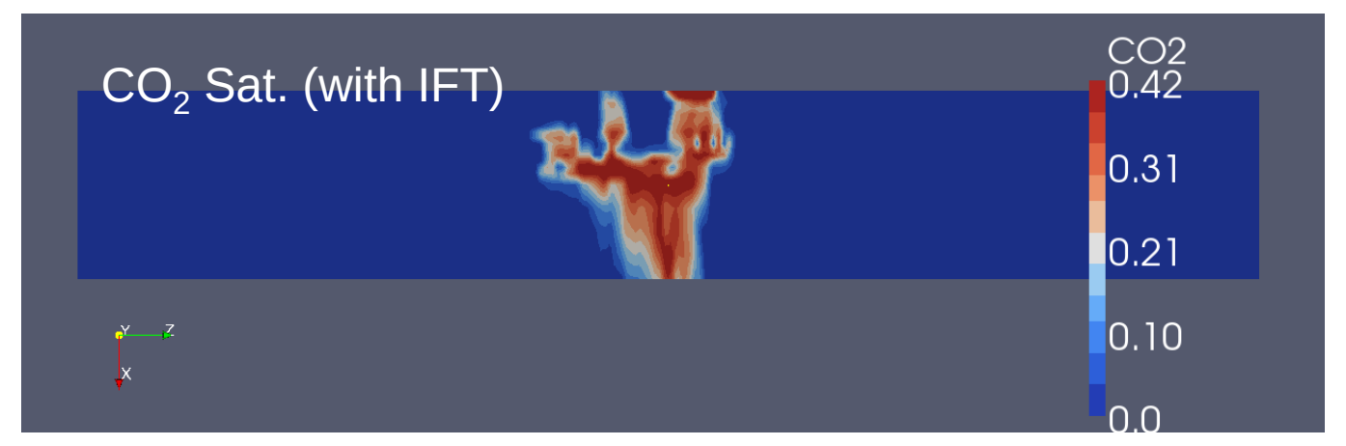
Relative Permeability vs Pressure(IFT): a), b), c)
(Bennion and Bachu, 2006)

Case 1: Effect of IFT on CO_2 Plume

Four CO_2 injectors are positioned in the center of the aquifer with a constant injection pressure of 2900 psi and continuous injection for 3 years followed by 7 years of no injection. The boundary conditions of the model are constant pressure of 2500 psi.

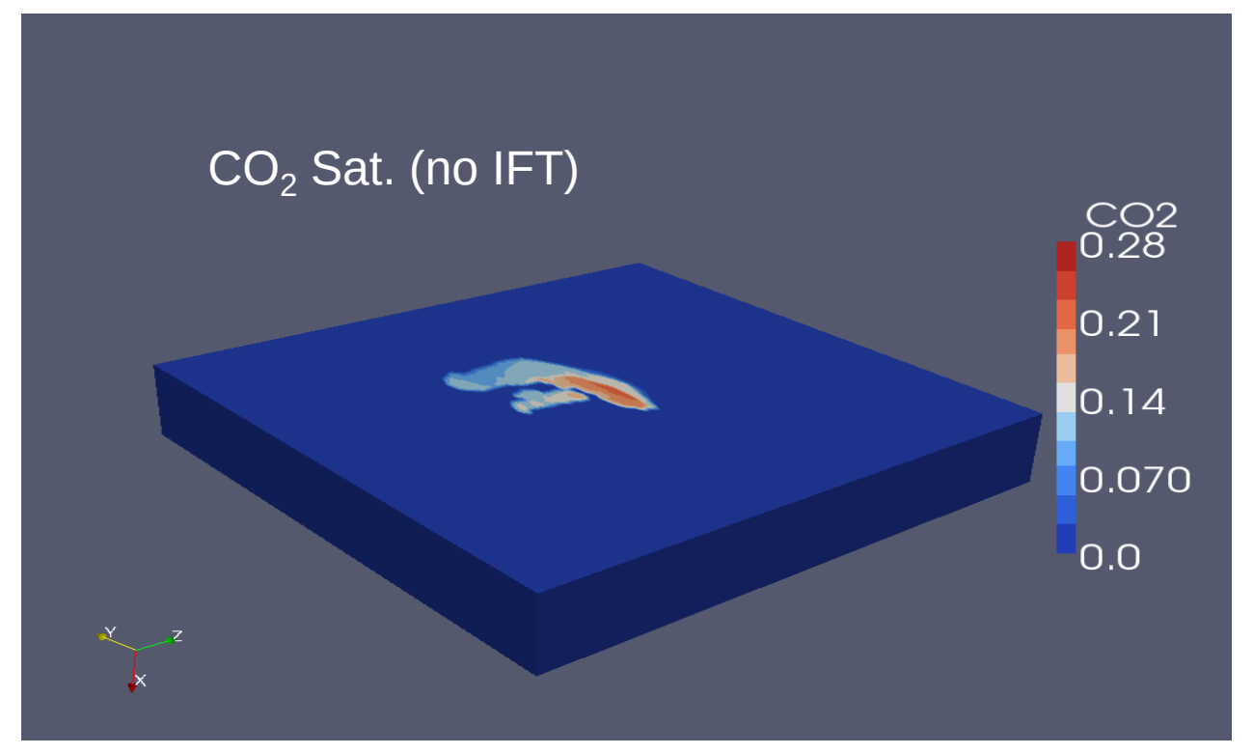


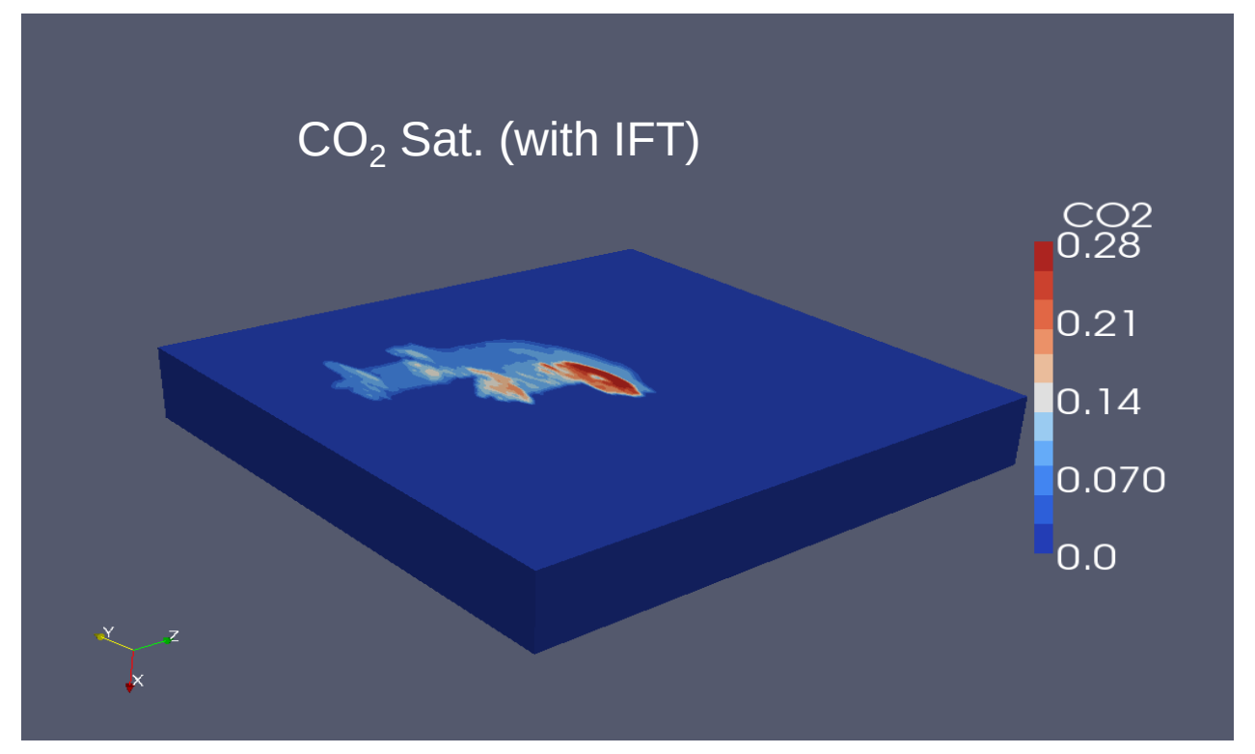




Aquifer size	**32500 ft × 32500 ft ×500 ft**
Mesh	**120×220×40**
Dip Angle	**10 degree**
Depth (top corner)	**5000ft**
Aquifer temperature	**160 F**
Initial pressure	**2500 Psi**
Kv/Kh	**0.1**
Porosity	**0.30**
Well position	**four wells at the center of aquifer, perforation low**
Vertical well length	**256 ft**
S_{wr} , S_{gr}	**0.379, 0.225**
Injection pressure	**2900 psi**
Injection period	**3 years injection, 7 years redistribution**

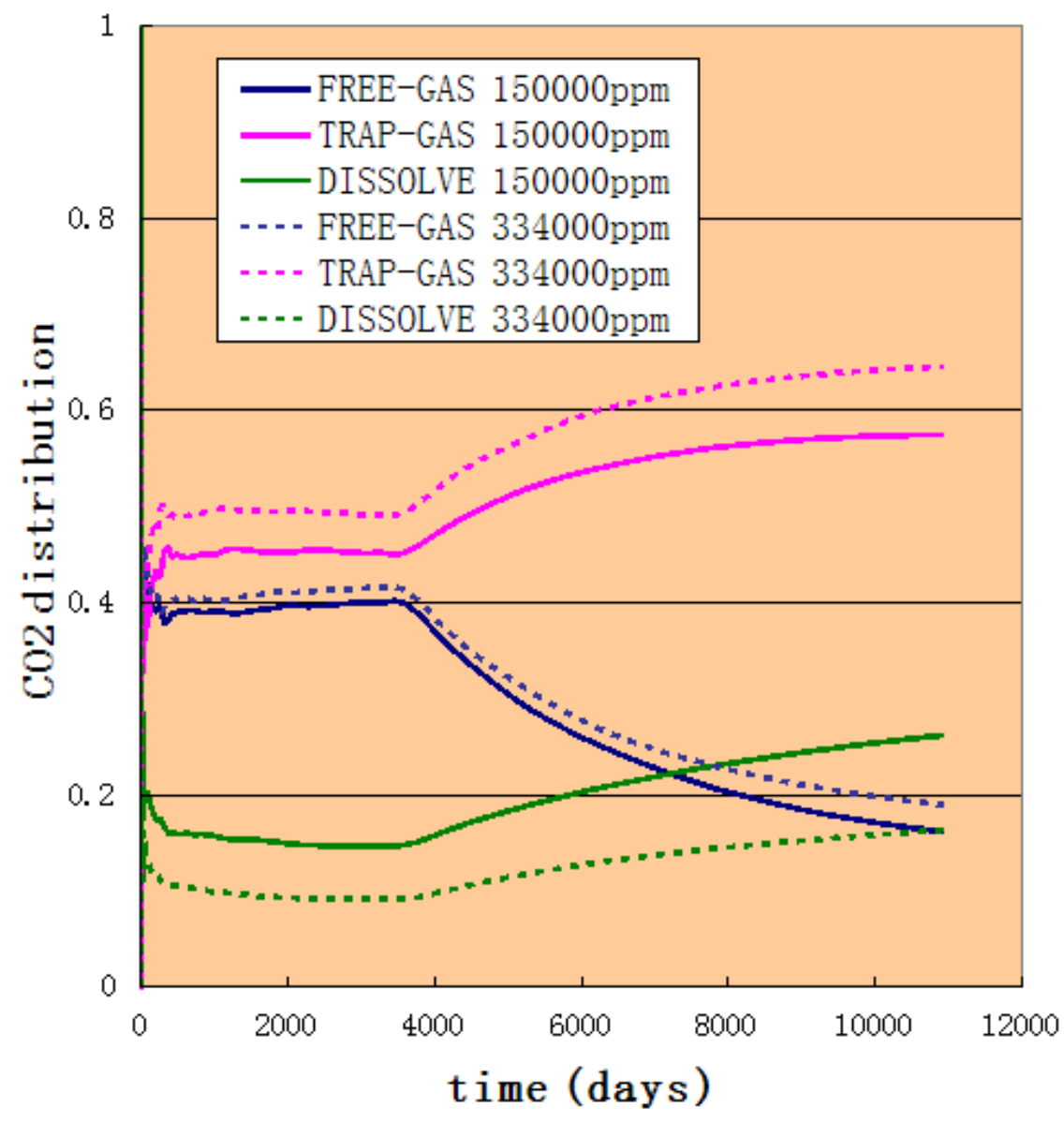
Final CO_2 Saturation Distributions





Case 2: Effect of Salinity on CO_2 Inventory

The injection well is located in the center of the model with a constant injection rate of 414 MSCF/D.
The initial aquifer pressure is 1000 psi and the boundary condition is no flow at all sides of the model.

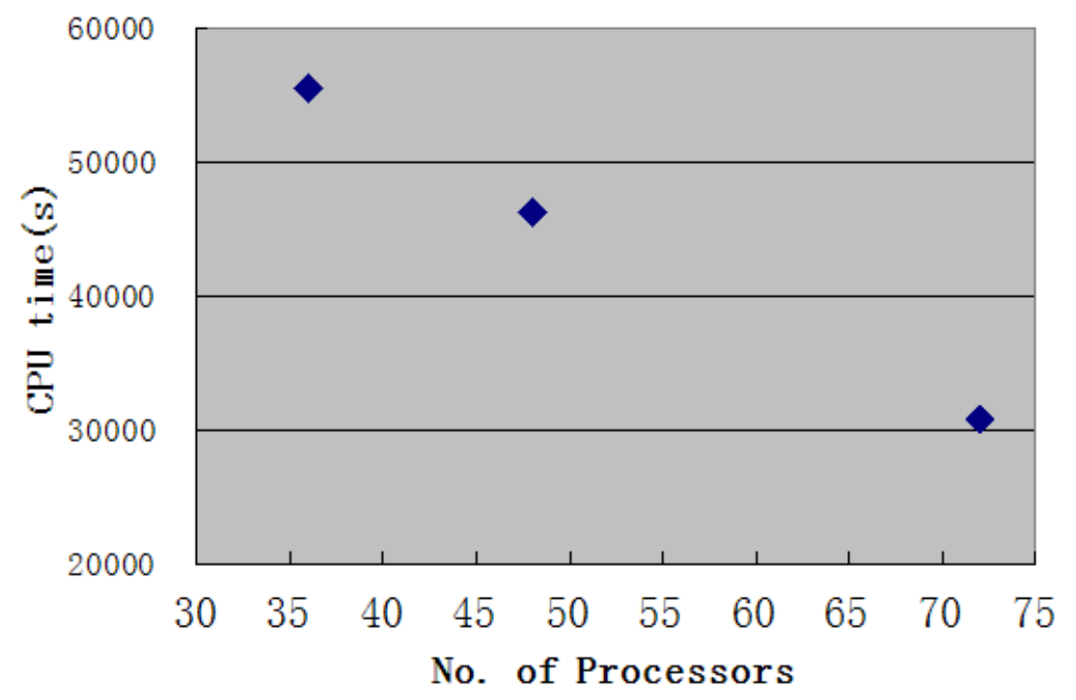


Aquifer size	**3500 ft ×3500 ft ×100 ft**
Mesh	**24 x 24 x 3**
Aquifer depth	**8300 ft**
Aquifer temperature	**110F**
Initial pressure	**1000 psi**
Horizontal Permeability	**50 md**
Kv/Kh	**0.1**
Porosity	**0.30**
Well position	**center of the model in bottom layer**
Vertical well length	**20 ft**
S_{wr} , S_{gr}	**0.379 , 0.225**
Salinity	**a) 150,000 ppm b) 334,000 ppm**
Injection rate	**414 MSCFD**
Injection period	**10 years injection, 20 years distribution**

Case 3: IPARS Parallel Scalability

We used over one million (160×160×40) grids with highly heterogeneous aquifer permeability. There are four injection wells in the center of the model with constant CO_2 injection rate of 300 MSCF/D for 20 years.

No. of Processors	Time (s)	Time (hr)
36	55,519.78	15.42
48	46,259.06	12.85
72	30,844.94	8.57

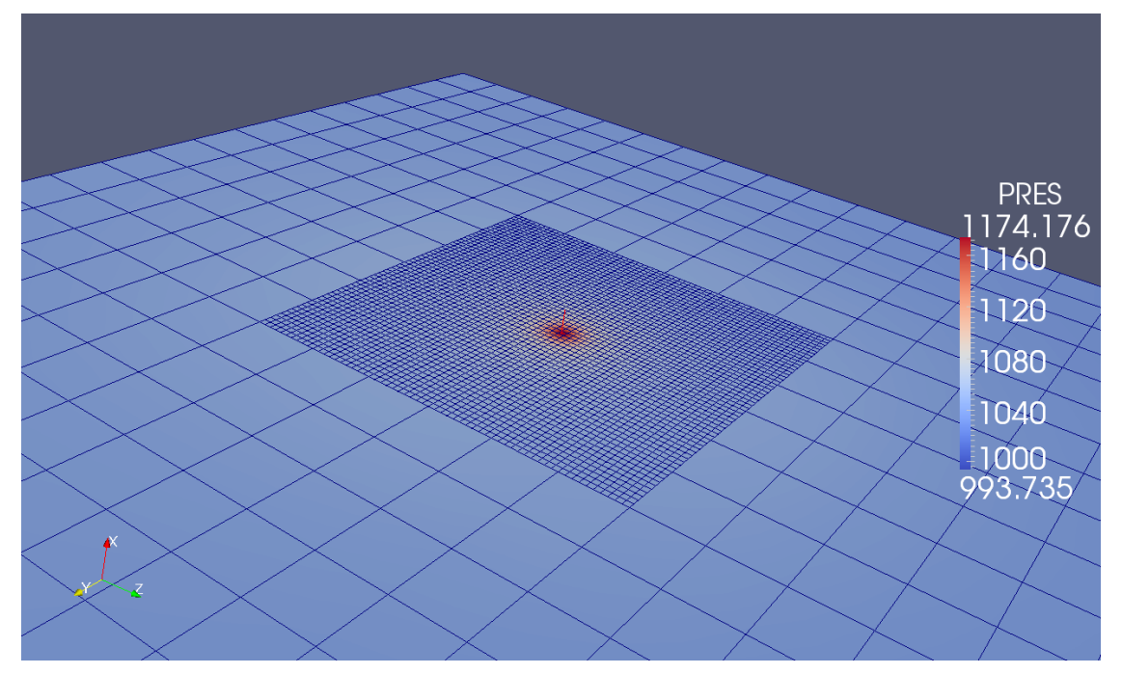


Aquifer size	**32500 ft × 32500 ft ×500 ft**
Mesh	**160×160×40 (1.024million)**
Depth (top corner)	**5000 ft**
Aquifer temperature	**112 F**
Initial pressure	**2500 psi**
Horizontal Permeability	**heterogeneous**
Kv/Kh	**0.1**
Porosity	**0.30**
Injection period	**20 year**

The Center for Subsurface Modeling has a 184 core Linux-based cluster (BEVO2) with 2 quad core 2.66 GHz Intel Xeon processors. Each node has 16GB of RAM.

Enhanced Velocity Method

IPARS has the capability of applying the enhanced velocity Mixed Finite Element method where non-matching multiblock grids are used to take advantage of different discretizations in different parts of the simulation domain and maintaining the flux continuity along the interfaces (See Poster SPE 141824).



Example of pressure during CO_2 injection into an aquifer. It is modeled as 4 coarse blocks and one refined block. The coarse grid size is 10 times the size of the fine grid.

- Discretizing flow in porous media via mixed finite element methods on non-matching multiblock grids
- Enhancing Velocity space along the interfaces to give flux-continuous approximation
- Locally refining grid to save CPU times compared to mesh refinement of the whole domain.
- Multiblock for different physical models and different discretization

Highlights

- Phase behavior, trapping number, and heterogeneity interact in a complex way that requires compositional simulation to understand and predict the behavior of high rate CO_2 injection
- Relative permeability model based upon trapping number was implemented and successfully tested for CO2/brine
- Key to the model is the dependence of CO_2 residual saturation on pressure (or IFT), viscous forces, and gravitational forces that are consistent with published lab data
- IPARS has a hysteresis model . However, we need to incorporate the effect of IFT variation.