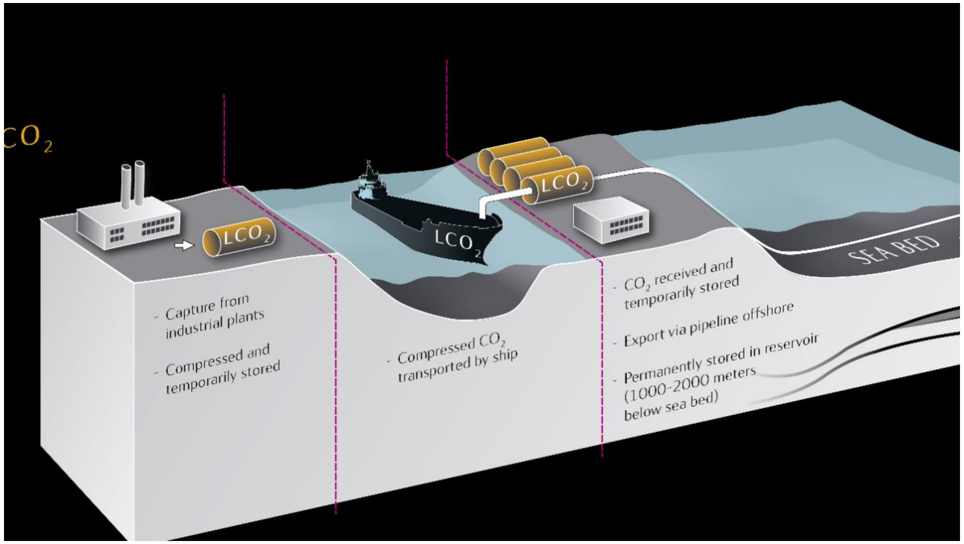
CO2-EOR simulations in OPM

OPM meeting 19th of October.

IRIS

Why CO2-EOR?

- PARIS COP21
- IEA: CO2-EOR - a stepping stone for CCS
- CCS full scale demo in Norway.



From: Statoil.com

Why CO_2-EOR simulations?

- Project planning and optimization.
  - Well placement and control strategies.
  - Many simulations with short / medium time scales. (years)
- Reservoir Characterization
  - Incorporating dynamic data to improve the reservoir model. Ex. TL mixing parameter.
  - Many simulations with short / medium time scales. (years)
- Monitoring
  - CO_2 leakage.
  - Long term CO_2 storage (hundreds of years).
- Improved recovery / storage.
  - Investigating mobility control alternatives. (CO_2-Foam etc.)

Why CO2-EOR simulations in OPM?

- Why do we need an open reservoir simulator?
- Why not use existing commercial simulators? Eclipse/ Intersect, tNavigator, CMG etc.

- OPM:
  - Test facility for new methods and new models.
  - Allows for tailored simulators for specific application.
  - Transparency of code.
  - Free to use.

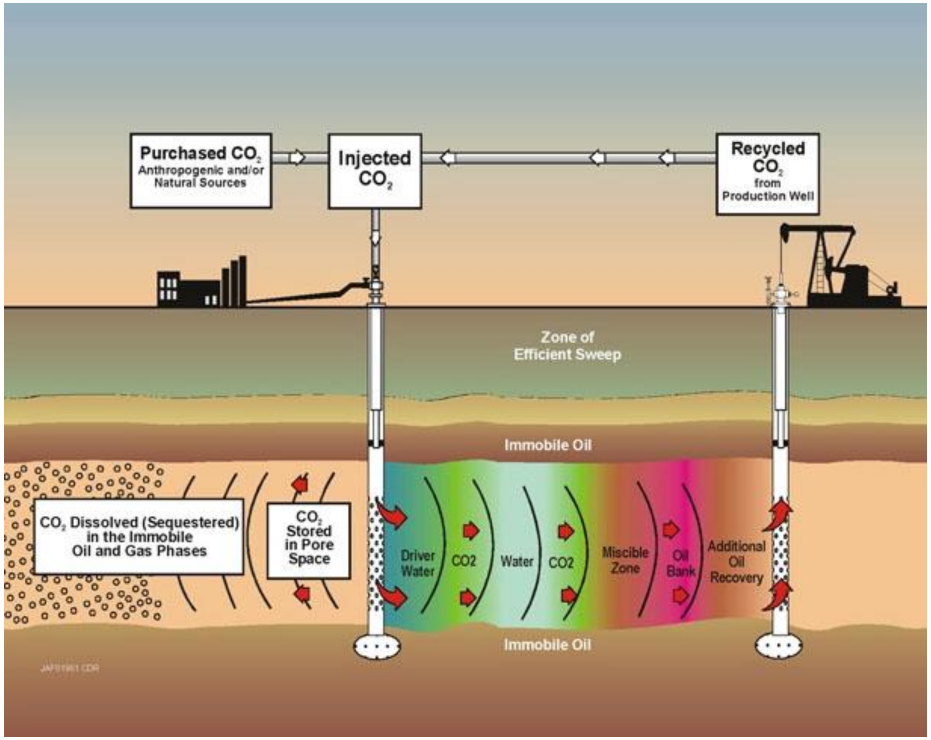
Main mechanism in CO_2-EOR.

› CO2 → OIL (Swelling of the oil phase)
  - Mobilize the oil (since the trapped oil contains less hydrocarbons)
  - Reduces viscosity of the oil
  - Increases density of oil (brings it closer to water)

› OIL → GAS (Extraction of lighter hydrocarbons)
  - Increases viscosity of the gas
  - Lowers the interfacial tension between the CO2 rich gas phase and the oil phase. → lower residual oil saturation.

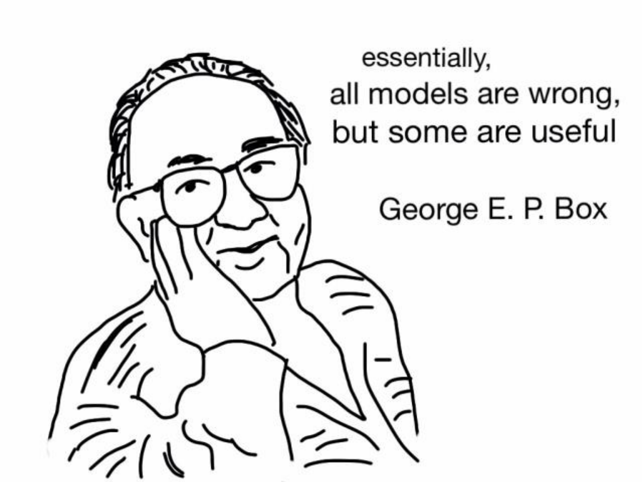
› Forms single phase locally at minimum miscibility pressure (MMP)

› CO2 → Water



Extended black-oil (solvent) simulator

- Gas and oil is represented by three-pseudo components (oil, solution gas, and injected solvent)
- Effective hydrocarbon relative permeability, viscosity and density.



- PROS
  - Use existing blackoil models.
  - Computationally more efficient than compositional simulators.
- CONS
  - Determining the relevant effective / upscaled quantities.
  - Can we trust the results?

- Papers:

  - M. R. Todd and W. J. Longstaff. The development, Testing and Application of a numerical simulator for predicting Miscible Flood Performance. 1972. SPE 3484
  - M. R. Todd. Modeling Requirements for Numerical Simulation of CO2 Recovery Processes. *SPE California Regional Meeting*. Society of Petroleum Engineers, 1979. SPE 7998
  - Killough, J. E., & Kossack, Fifth Comparative Solution Project: Evaluation of Miscible Flood Simulators. Society of Petroleum Engineers. C. A. 1987. SPE 16000
  - Karacaer, Caner. *Mixing issues in CO 2 flooding: comparison of compositional and extended black-oil simulators*. Colorado School of Mines, 2014.

Model formulation

› Effective hydrocarbon relative permeability

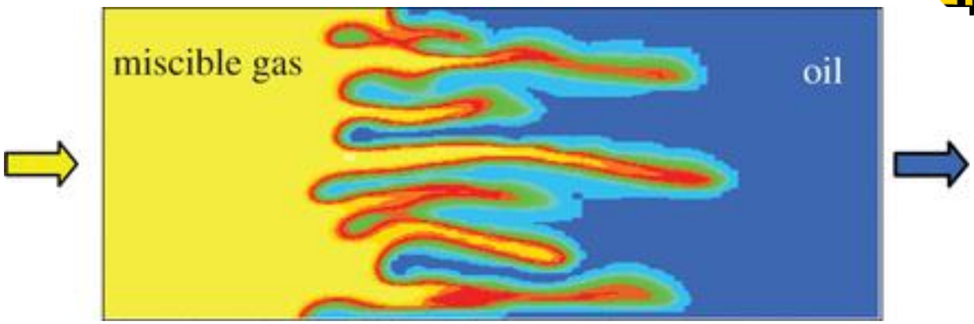
- $k_{roe} = M \cdot \left(\frac{S_o - S_{or}}{S_n - S_{gc} - S_{or}}\right) \cdot k_{rn}(S_n) + (1 - M) \cdot k_{ro}(S_w, S_g)$
- $k_{r*e} = M \cdot \left(\frac{S_g + S_s - S_{gc}}{S_n - S_{gc} - S_{or}}\right) \cdot k_{rn}(S_n) + (1 - M) \cdot k_{r*}$

$* = g:$ $k_{rg} = \frac{S_g}{S_g + S_s} k_{rgt}(S_s + S_g)$ (gas component)

$* = s:$ $k_{rs} = \frac{S_s}{S_g + S_s} k_{rgt}(S_s + S_g)$ (solvent component)

$M = M(pressure, solvent\ fraction)$: Miscibility function
$S_n = S_g + S_s + S_o$
k_{ro} : oil rel.perm
k_{rg} : gas rel.perm
k_{rn} : hydrocarbon to water rel.perm
S_{or} : effective residual oil saturation
S_{gc} : effective critical gas saturation

Model formulation



Muggeridge, Ann, et al. "Recovery rates, enhanced oil recovery and technological limits." *Phil. Trans. R. Soc.* (2014)

› Effective viscosities

- $\mu_{oe} = \mu_o^{1-\omega} \cdot \mu_{mos}^{\omega}$
- $\mu_{se} = \mu_s^{1-\omega} \cdot \mu_m^{\omega}$
- $\mu_{ge} = \mu_g^{1-\omega} \cdot \mu_{msg}^{\omega}$

μ_{mos} : fully mixed viscosity of oil and solvent (using the ¼ power mixing rule)

μ_m : fully mixed viscosity of oil, gas and solvent (using the ¼ power mixing rule)

μ_{msg} : fully mixed viscosity of solvent and gas (using the ¼ power mixing rule)

ω : is the Todd-Longstaff mixing parameter

› Other implemented effects

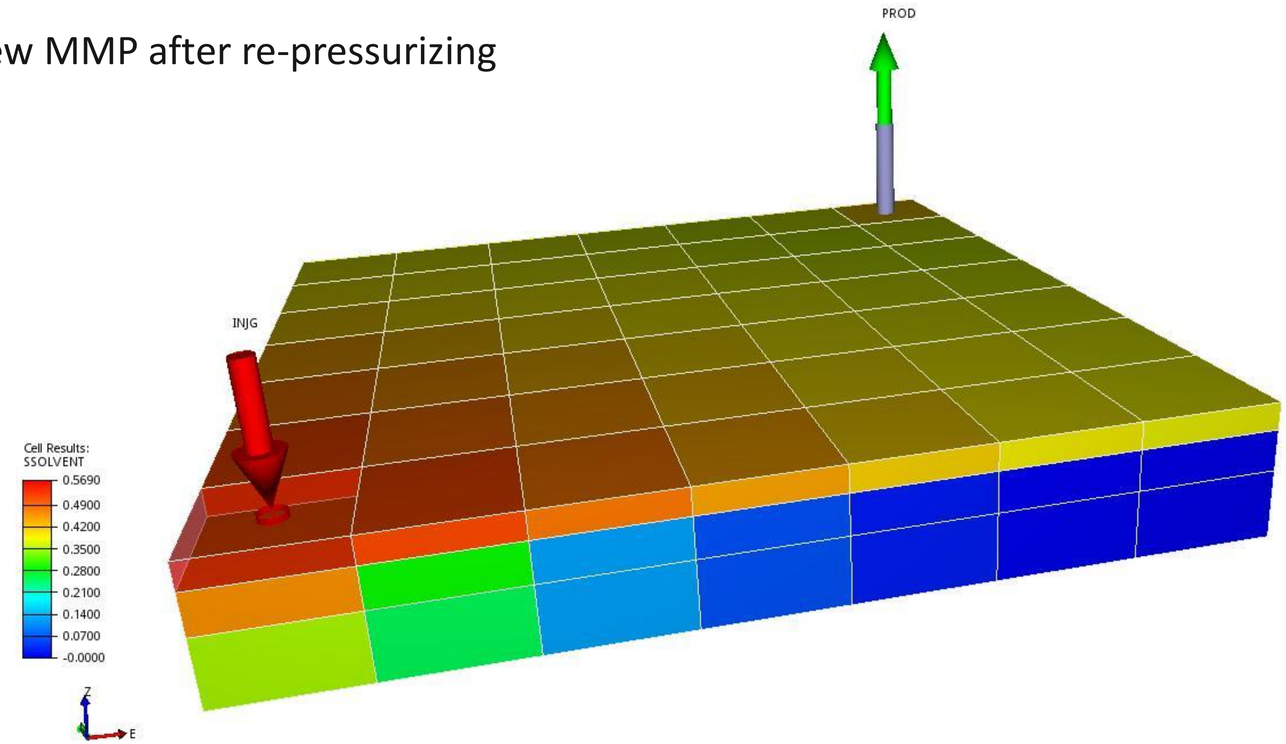
- Effective densities
- Reduced effective residual oil saturation / critical gas saturation due to water blocking oil filled pores
- Pressure effects on capillary pressure, viscosity and density miscibility
- Pressure dependent Todd-Longstaff parameter

Comparison SPE 5:

› Comparison of 4-component miscible simulators and compositional simulators

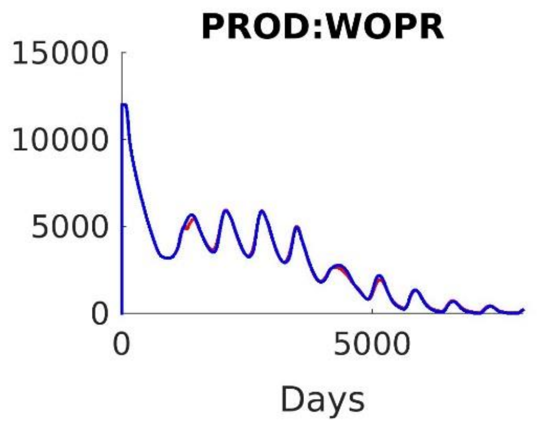
› Three cases. Where average reservoir pressure is:

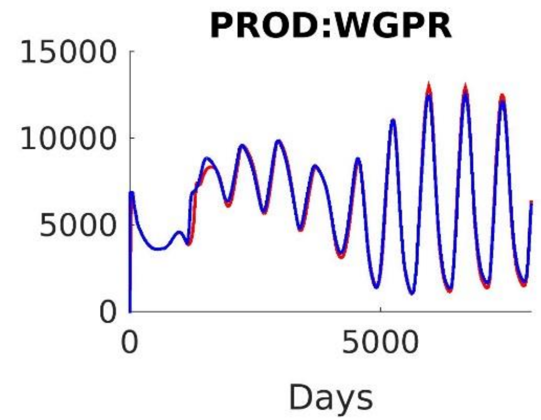
1. Much lower than MMP (immiscible case)
2. Near or above MMP
3. Below first, new MMP after re-pressurizing



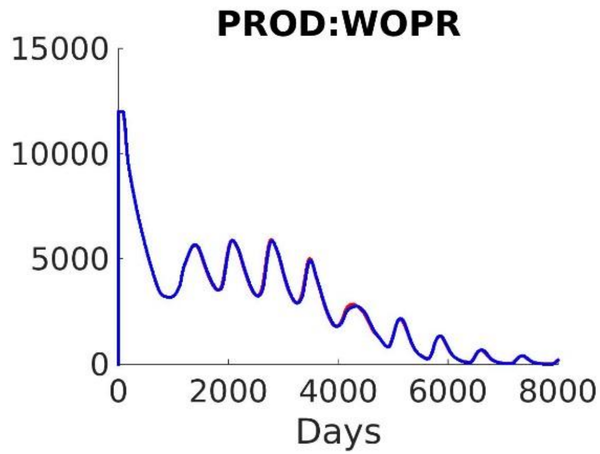
Comparison SPE 5: (OPM-FLOW, Eclipse)

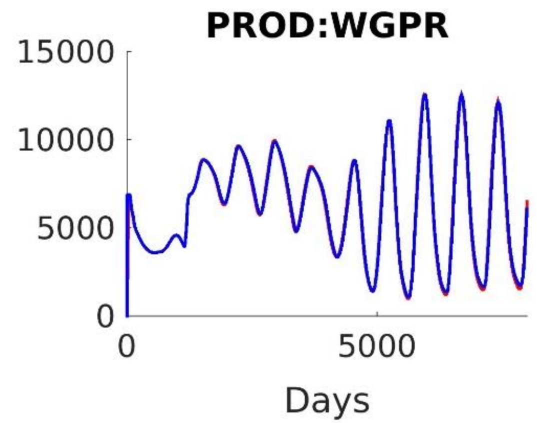
SPE 5 case 1





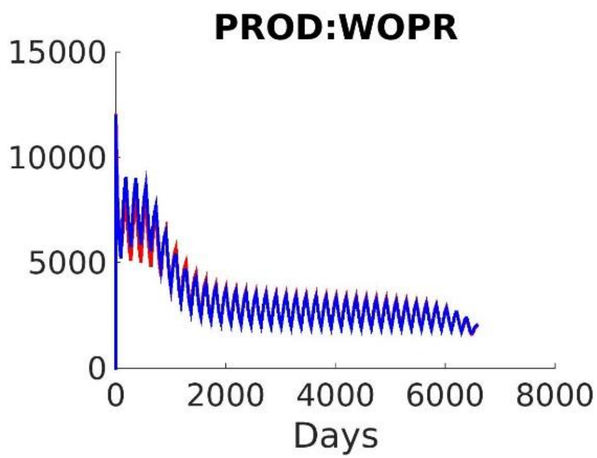
SPE 5 case 1:
With no mixing effect on the densities

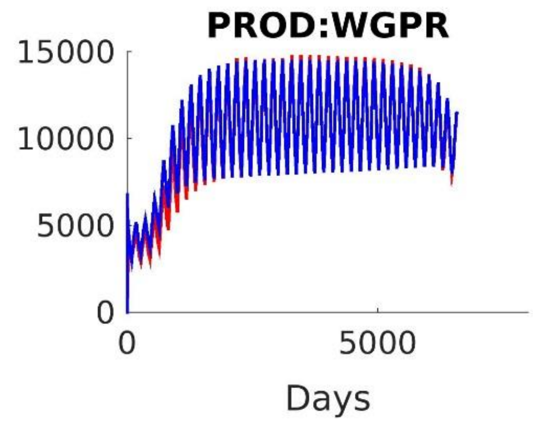




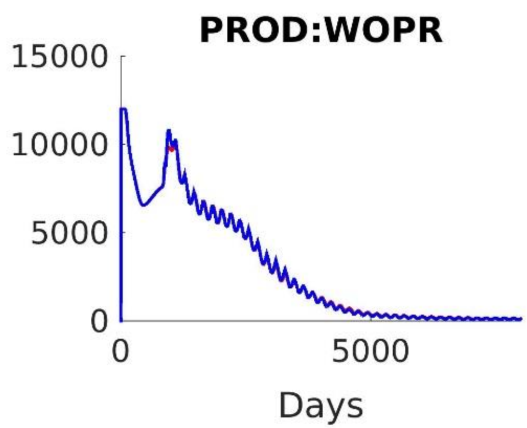
Comparison SPE 5: (OPM-FLOW, Eclipse)

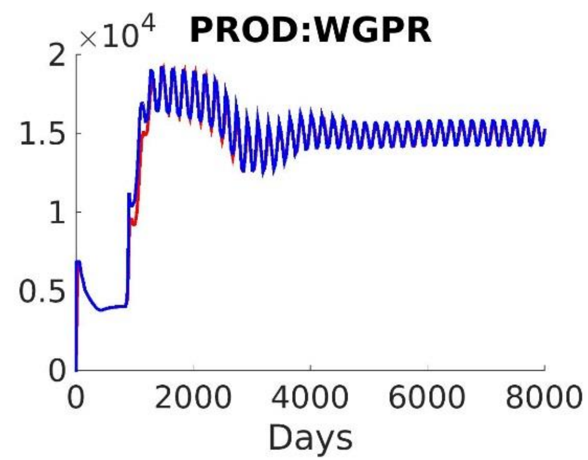
SPE 5 case 2





SPE 5 case 3



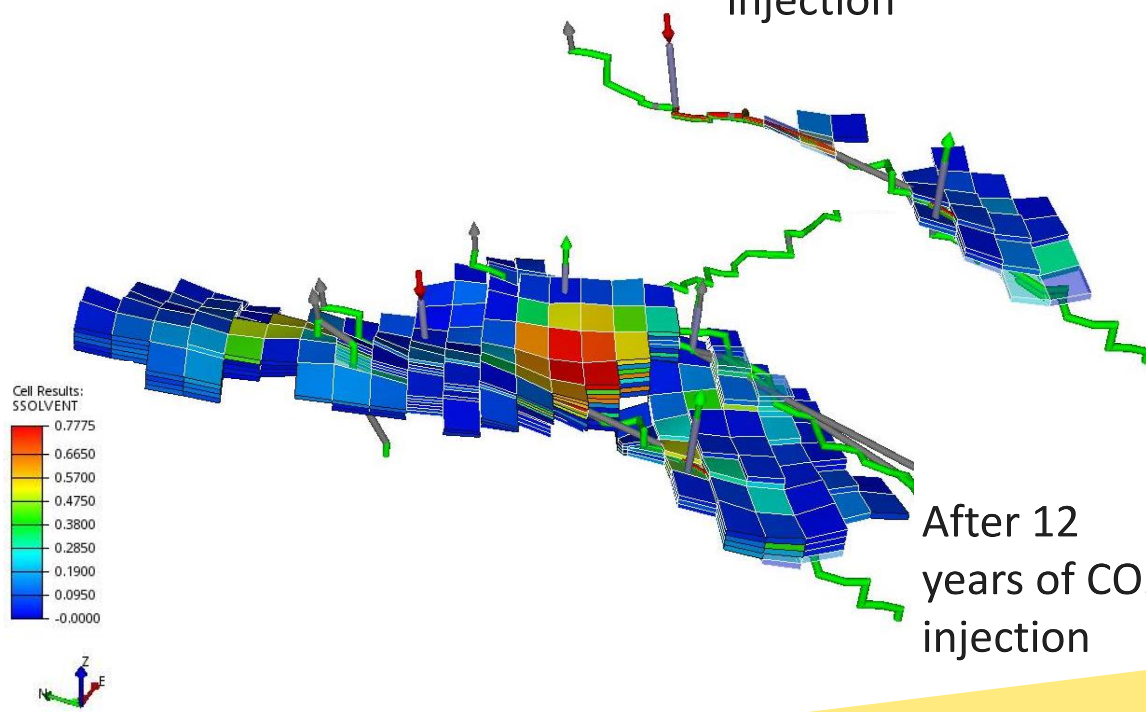


Field example 1 (Model 2)

› Setup

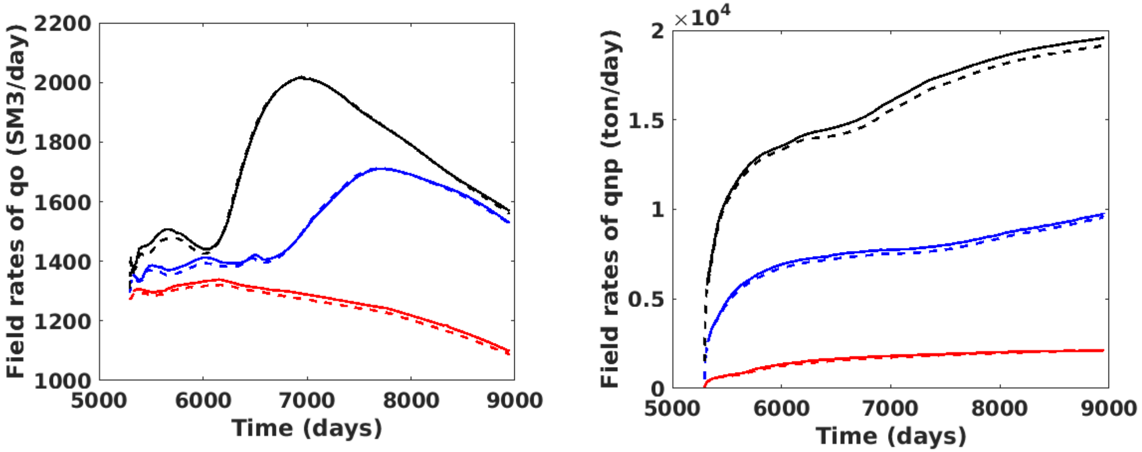
- Run 5295 days of history.
- LRAT controlled production wells.
- CO2 injected from day 5479
- Linear ramp between 100-250 Barsa to model pressure dependency in the miscibility
- The pressure dependency in the Todd-Longstaff parameter is neglected.

After 0.5 years of CO2 injection



After 12 years of CO2 injection

Good match with Eclipse



Comparison of production rates of oil and CO2 between Flow (dots) and Eclipse (solid) when injecting 0.1M (red), 0.5M (blue) and 1.0M (black) of CO2.

Performance Model 2

- Comparison with Eclipse (only the co2 injection part)

Case	Flow	Eclipse	
1	1380	5000	0,28
2	1710	8950	0,19
3	1800	8600	0,21

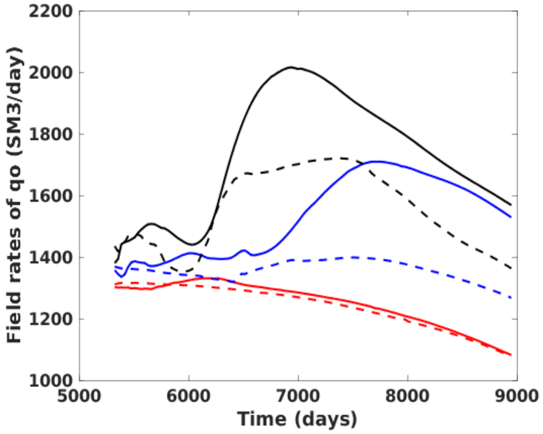
- MPI (history and co2 injection, only Flow)

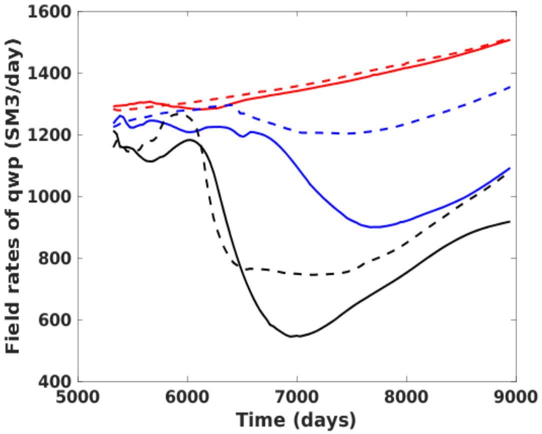
Case	np1	np2	np4
1	4136	3190	3423
2			
3			

*Intel Core i7-6700, 4(8) @ 3.4 GHz, 8M

** The run-time comparison is approximate. Different tuning may change the run time of both the simulators.

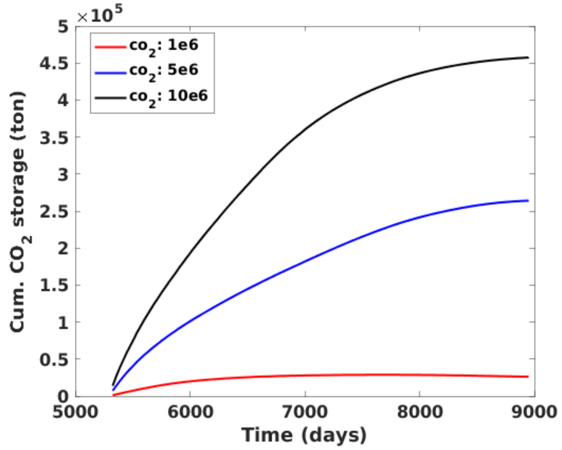
CO2 injection gives enhanced oil recovery.





Comparison of total field production rates of oil (left) and water (right) when injecting 0.1M (red), 0.5M (blue) and 1.0M (black) SM3/day of CO2 (solid) and Gas (dots) (0.2, 1 and 2 tons of CO_2 pr. Day).

CO2 storage potential.



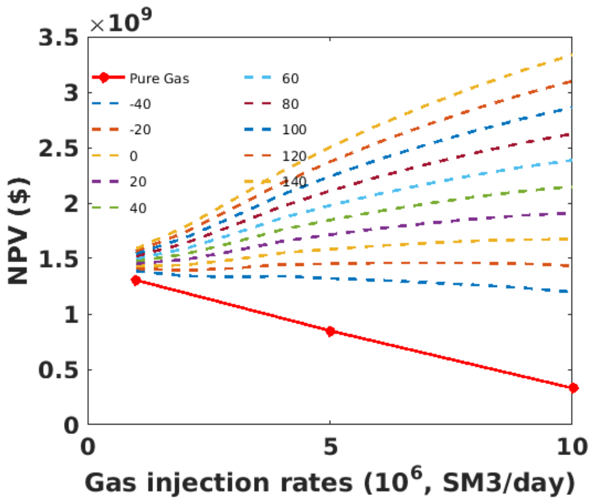


Table 1: Constant values for NPV calculation

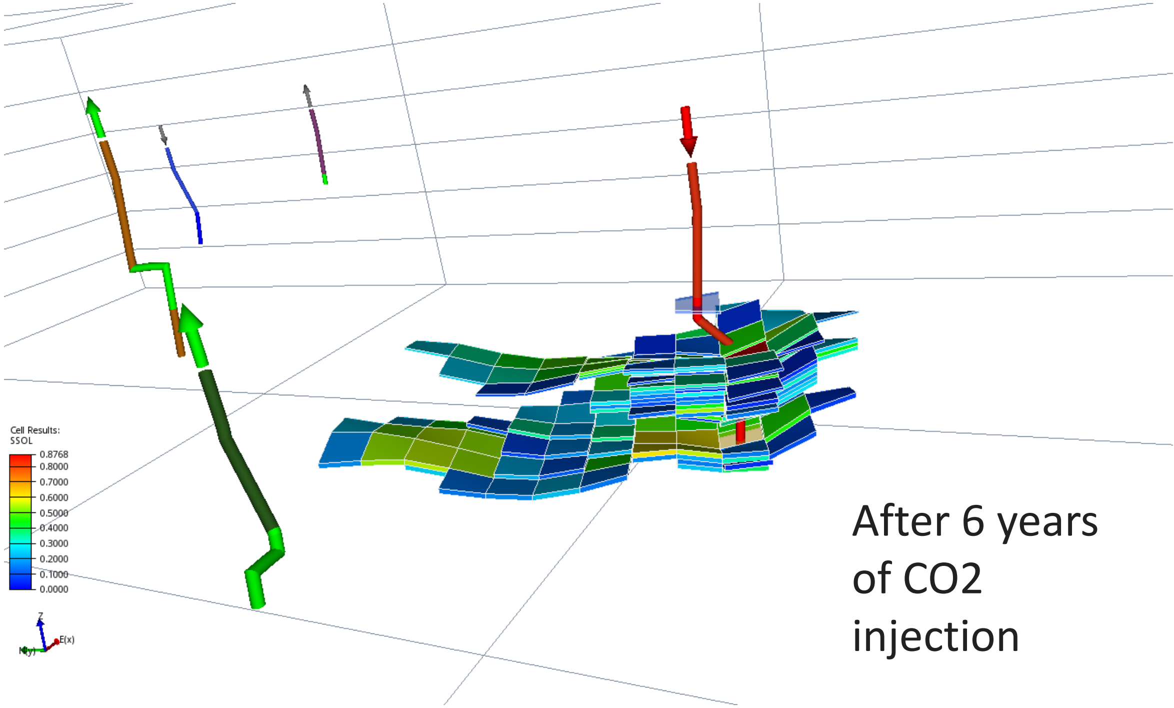
Oil price ($\$/SM^3$)	500
Gas price ($\$/SM^3$)	0.15
Gas injection cost ($\$/SM^3$)	-0.2
Water disposal cost ($\$/SM^3$)	-40
Water injection cost ($\$/SM^3$)	-30
CO_2 tax credit ($/ton)	60
CO_2 injection cost ($/ton)	0
CO_2 production cost ($/ton)	-10
Discount rate	0.1

Left: Cumulative CO_2 storage at the CO_2 injection rates of 1e6, 5e6 and 10e6 SM3/day.
Right: Comparison of NPV values at different CO_2 capturing credits vs. pure natural gas injection.
The right figure shows that CO_2-EOR is more economical beneficial for this field than pure gas injection.

Field scale example 2 (Model 2.2)

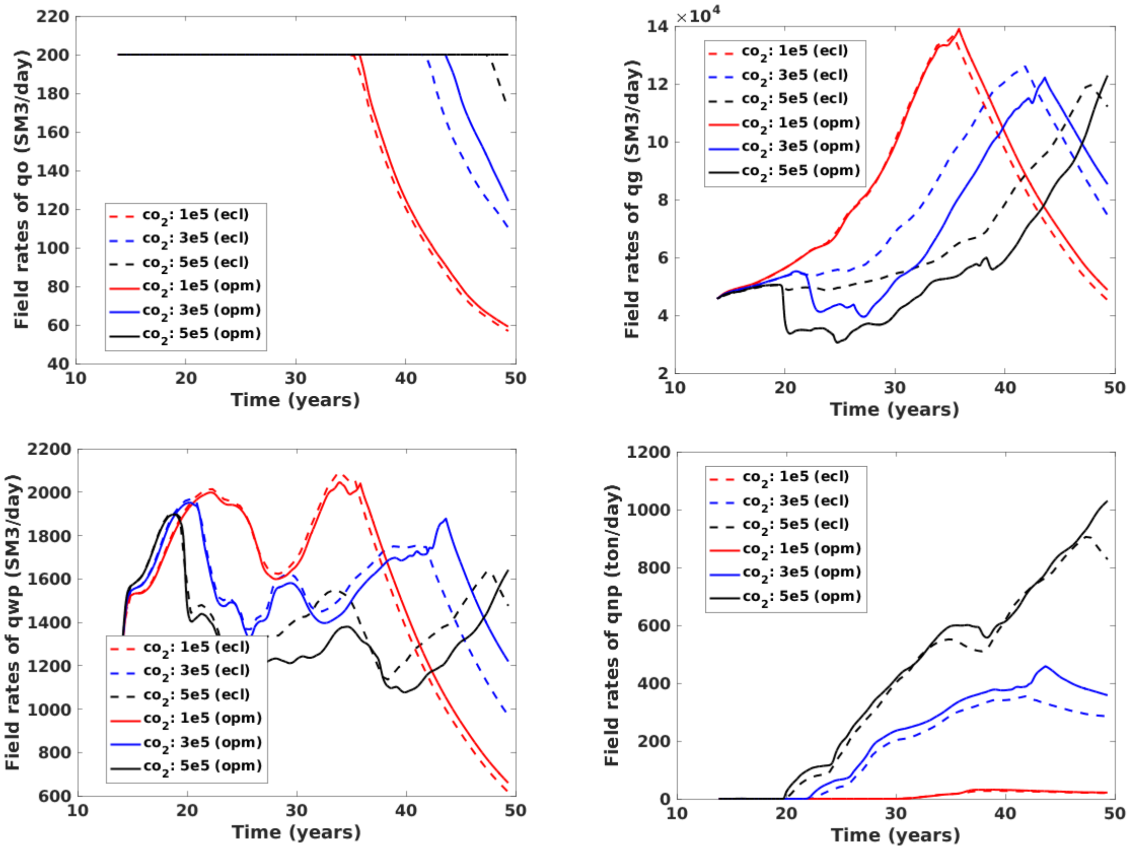
› **Setup**

- Run 14 years of history.
- Change to ORAT controlled production wells.
- CO_2 injection for 50 years
- Linear ramp between 100-195 Barsa to model pressure dependency in the miscibility
- The pressure dependency in the Todd-Longstaff parameter is neglected.

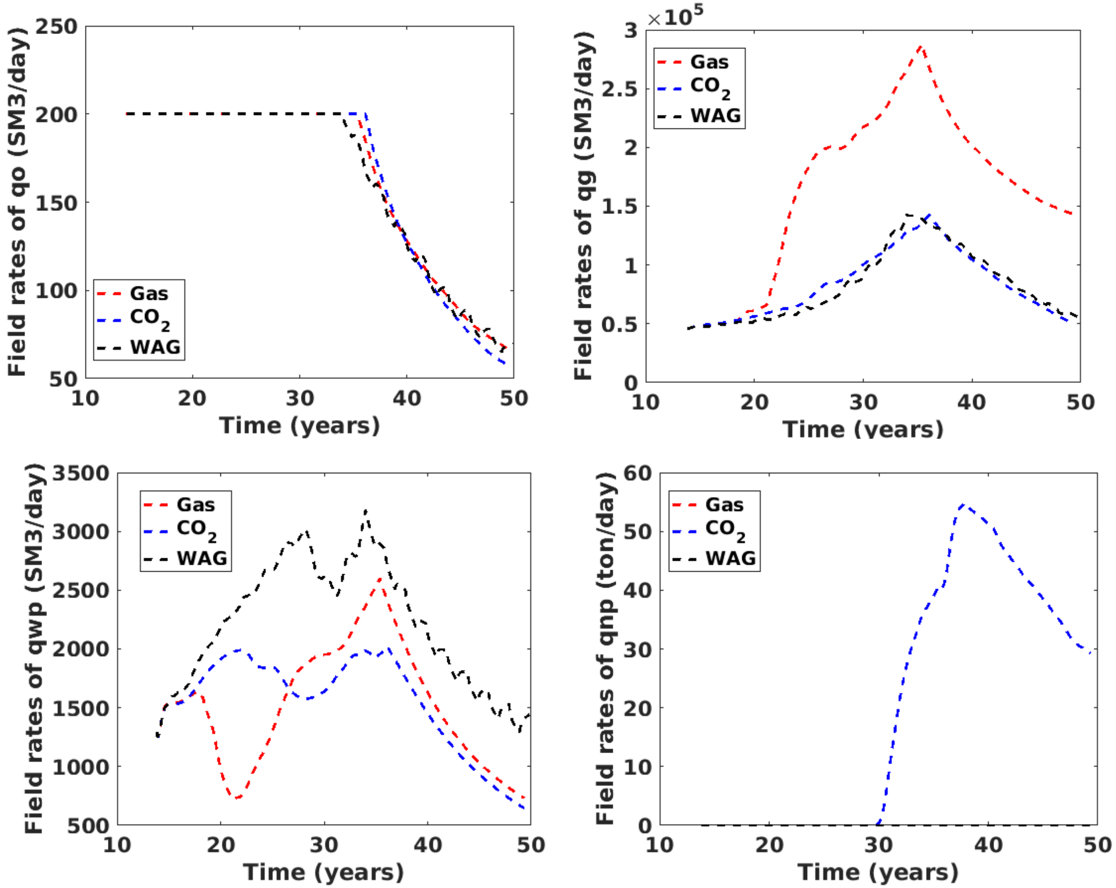


After 6 years of CO_2 injection

Comparison with Eclipse results.



Comparing Gas injection, CO2 injection and WAG



NPV calculations on the second field example.

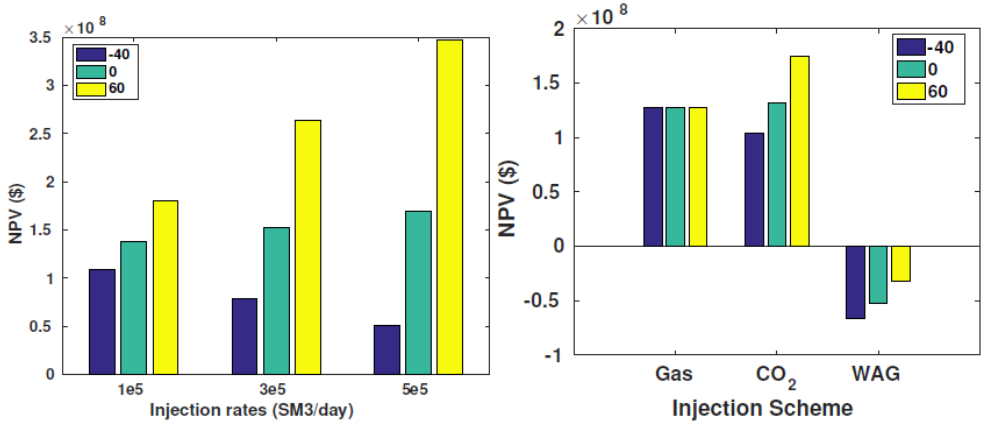


Figure 7: Comparison of NPV calculated at different CO_2 injection cost for different CO_2 injection rates(right) and schemes (left) and. Each colored bar represents a different CO_2 injection cost (unit: \$/ton).

Table 1: Constant values for NPV calculation

Oil price (C_o)	500 (\$/SM^3)
Gas price (C_g)	0.15 (\$/SM^3)
Gas injection cost (C_{gi})	-0.2 (\$/SM^3)
Water disposal cost (C_{wp})	-40 (\$/SM^3)
Water injection cost (C_{wi})	-30 (\$/SM^3)
CO_2 injection cost (C_{ni})	-40 , 0, 60 (\$/ton)
CO_2 recycling cost (C_{np})	-10 (\$/ton)
Discount rate (d)	0.1

Performance Model 2.2

- Comparison between Flow and Eclipse (only 10 years of co2 injection)

Case	Flow	Eclipse	
1	2442	17919	0,14
2	3300	13310	0,25
3	3232	10347	0,31

*Intel Core i7-6700, 4(8) @ 3.4 GHz, 8M

** The run-time comparison is approximate. Different tuning may change the run time of both the simulators.

Summary

- Flow-solvent. Extended black-oil model for CO2-EOR simulations
- Benchmarked against Eclipse on two field models.
- Approximately 3-5 times faster than Eclipse.
- Run in parallel. (still some issues)
- Basis for implementing new models and methods.

Some research questions.

- Does the TL mixing model capture the essential physics?
  - How to determine ω?
  - $\omega = \omega$(geology, pressure, history, velocity, …)?
- CO2 → Water. Is this important?
- Can we make a predictive / useful simulator for CO2-EOR without going all the way down to a fully resolved compositional model?

Ruben Juanes, MIT