EOR Modelling within ECLIPSE

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ECLIPSE - EORs

Black-oil (ECLIPSE 100)
- Polymer
- Surfactant
- High pH (Alkaline)
- Brine – Low Salinity
- Solvent
- Foam

Compositional (ECLIPSE 300)
- CO2 Injection
ECLIPSE 100 - Polymer

Illustrative example

Base case: water flooding

Water injection

Polymer injection

Effective water viscosity

Polymer adsorption

Permeability reduction

ECLIPSE EORs modelling
Main Objective

decrease the water mobility ➔ reduced viscous fingering ➔ better sweep of the reservoir (oil mobility unaffected). *Water is the polymer carrier*

Capabilities

- Water viscosity model (modified Todd-Longstaff)
- Polymer Adsorption – analytical or tabulated isotherms
- Permeability reduction
- Dead pore volume
- Shear thinning – Herschel Bulkley model
- Salinity dependent polymer properties (viscosity, adsorption)
- (Polymer + Solvent ongoing development)
Shear Thinning Effect

Herschel-Bulkley (yield-power-law model):

\[ \tau = \tau_0 + \mu_r \dot{\gamma}^n \]

Standard polymer

Shear thinning: \( n = 1 \) to 0.6

PAW (Injection of polymer solution slugs alternate with water injection)

Log K - layer from SPE10

ECLIPSE EORs modelling
Reduction of the residual oil saturation by injection of a surfactant solution
Objective: Reduce oil-water surface tension and change wettability towards more water-wet to improve oil mobility.

Features:

- Water phase as surfactant carrier – optional partitioning in oil phase
- Oil-water surface tension as a function of surfactant concentration
- Immiscible to miscible transition on kr as a function of capillary number and surfactant concentration
- Adsorption – analytical (new 2009.1) or tabulated isotherms
- Wettability change (oil wet to water wet) depending on adsorption
- Salinity dependent properties (adsorption, TPB flash) (new 2009.1)
- Diffusion

Ongoing development to handle the micro-emulsion (oil/water/surfactant mixture)
- Multiple salts injection
- Ions exchange reactions with rock and surfactant
- Effective salinity:
  - For surfactant adsorption and surfactant-water-oil phase behaviour
  - For polymer adsorption
- Ions transport

**Salts: e.g. NaCl + CaCl₂**

**Ion exchange**

**Effective salinity**

**Adsorption**

**Phase behaviour**
Surfactant Model – Salinity Effect on Adsorption

Without Salinity Effect
(low adsorption)

With Salinity Effect
(high adsorption)

Effective salinity

Surfactant adsorption

Surfactant concentration
Objective: In-situ generation of surfactants and reduction of surfactant and/or polymer adsorption

Features:

• Currently a simplified alkaline model available
• Alkaline tracer carried in the water phase
• Reduction of polymer/surfactant adsorption with alkaline concentration
• Oil-water surface tension as a function of alkaline concentration
• Alkaline adsorption – analytical or tabulated isotherms
Alkaline-Surfactant-Polymer (ASP) Flooding

Injection sequence simulated using ACTIONXs and UDAs

![Graph showing injection sequence with alkaline, surfactant, and polymer concentrations over time.]

- Alkaline conc.
- Surfactant conc.
- Polymer conc.

Log K (layer 3 of SPE10)

Alkaline-Surfactant-Polymer (ASP) Flooding

ECLIPSE EORs modelling
Alkaline-Surfactant-Polymer (ASP) Flooding

Injection sequence simulated using ACTIONXs and UDAs

Surfactant conc. limit
Alkaline conc. limit

Log K
Alkaline
Surfactant
Polymer
Objective: Change of wettability towards more water wet resulting in increased waterflood recovery.

Features:

- Saturation and rel. perm. end-points as a function of brine salinity
- Water-oil capillary pressure as a function of brine salinity
- Salinity dependent brine density and viscosity as std. brine option
- Based on SPE 102239
Low Salinity Model

Saturation end-point scaling:

\[ S_{or} = F_1 S_{or}^L + (1 - F_1) S_{or}^H \]
\[ S_{cw} = F_1 S_{cw}^L + (1 - F_1) S_{cw}^H \]

Relative perm. and cap. pressure:

\[ k_{rw} = F_1 k_{rw}^L + (1 - F_1) k_{rw}^H \]
\[ k_{ro} = F_1 k_{ro}^L + (1 - F_1) k_{ro}^H \]
\[ P_{cow} = F_2 P_{cow}^L + (1 - F_2) P_{cow}^H \]

\[ F_1 = f_1(C_{salt}) \in [0, 1] \]
\[ F_2 = f_2(C_{salt}) \in [0, 1] \]
ECLIPSE 100 – Solvent

Illustrative example

Injection of a solvent slug

Field Oil Production Rate

Field Solvent Production Rate

Oil viscosity decreases due to oil mixing with solvent

Oil density decreases due to oil mixing with solvent
Main Objective
To model mechanisms where injected fluids are miscible with the hydro-carbons in the reservoir (e.g. high pressure gas, LPG slug, alcohol slug, CO2)

Capabilities
- 4-phase (water, oil, gas and solvent) or 3-phase (solvent fully mixed with oil or gas)
- Immiscible to miscible transition handling (via user specified miscibility function)
- Screening of high water saturation (in miscible gas drive residual oil is higher with higher Sw)
- Viscosities and densities mixing (Todd and Longstaff and 1/4th power mixing rule)
- PVT, kr and cap pressure as functions of the miscibility pressure (user specified)
ECLIPSE 100 – Foam

Illustrative example

- Reduction in gas mobility
- Foam decay
- Foam concentration
- Foam adsorption
Main Objective:
To control gas mobility to slow down the breakthrough of injected gas or gas production.

*Gas is the foam carrier, foam is as an active tracer.*

Capabilities

- Foam adsorption: isotherm as a function of foam concentration (similar to surfactant)
- Foam decay (function of oil and water saturations)
- Gas mobility reduction
- Shear effect (similar to polymer)
CO2 as an EOR agent

- Reduce crude oil viscosity and increase in water viscosity
- Swelling of crude oil and reduction of oil density
- Acid effect on carbonate and shell rocks
- Miscibility

Main Objective
To model the chemical reactivity between CO2 (as a critical fluid) and the liquid phases (solubility of CO2 in the aqueous phase)

Capabilities
- Modelling of the phase equilibrium between CO2 and the aqueous phase
- Solubility of CO2 in the aqueous phase (viscosity and density in particular)
**Objective:** Modelling three-phase compositional effects of CO₂ behaviour

**Features:**

- **CO₂SOL/H₂SSOL:** three-phase models with CO₂/H₂S solubility in the water phase
- **GASSOL:** generic three-phase model where any component can dissolve in the water phase
- General gas-oil compositions, but no water in oil/gas phase
- Isothermal conditions
CO2SOL/H2SSOL and GASSOL

Assumptions:

• Solubility data entered as a function of
  – pressure (GASSOL + CO2SOL + H2SSOL)
  – temperature (CO2SOL)
  – salinity (CO2SOL)
  – composition (CO2SOL + H2SSOL)

• Gas phase fugacities calculated from Peng-Robinson EOS

• Molecular diffusion of components can be modelled
CO₂ Storage: Trapping Mechanisms

1: Hydrodynamic Trapping

2: Solubility Trapping

\[ CO_2 + H_2O \rightarrow H_2CO_3 \]
\[ H_2CO_3 + H_2O \rightarrow HCO_3^- + H^+ + H_2O \]
\[ HCO_3^- + H_2O \rightarrow CO_3^{2-} + H^+ + H_2O \]

3: Residual Trapping

4: Mineral Trapping (In progress)

e.g. 3K – Feldspar + 2H₂O + 2CO₂
\[ \rightarrow \text{Muscovite} + 6\text{Quartz} + 2H_2CO_3^- + 2K^+ \]

K – Feldspar (KAlSi₃O₈)
Muscovite (KAl₂(AlSi₃O₁₀)(FOH)₂)
Quartz (SiO₂)

ECLIPSE EORs modelling
ECLIPSE - EORs
Reducing the residuals

New in 2008.1
- Non-Newtonian Rheology: Herschel-Bulkey model
- New functional model, and phase carrier

Future Enhancements
Alkaline:
- Modelling to be based on requirements gathering
Surfactant:
- Salinity and rock permeability effects on adsorption
- Phase behaviour for water/surfactant/oil mixture

Polymer:
- Salinity and rock permeability effects on adsorption
Solvent:
- Robustness, and numerical stability

E100 - POLYMER
To decrease the water mobility, reduced viscous fingering, better sweep of the reservoir

Capabilities
- Water viscosity model (Todd-Longstaff)
- Adsorption
- Permeability reduction
- Dead pore volume
- Shear thinning (with non-Newtonian rheology)

E100 - FOAM
To control/reduce gas mobility. Gas is the foam carrier

Capabilities
- Foam adsorption: isotherm as a function of foam concentration
- Foam decay (with oil and water saturations)
- Gas mobility reduction
- Shear thinning effects

E100 - SOLVENT
To model mechanisms where injected fluids are miscible with the hydro-carbons in the reservoir

Capabilities
- 4-phase or 3-phase (solvent fully mixed with oil or gas)
- Immiscible to miscible transition handling
- Screening of high water saturation
- Viscosities / densities mixing (T-L and 1/4th)
- PVT, kr and cap pressure functions

E100 - SURFACANT
To reduce oil-water surface tension so that water can displace more oil

Capabilities
- Capillary pressure decreases with surfactant concentration
- Immiscible to miscible transition for relative permeability (with Ncap and Cs)
- Adsorption / de-adsorption
- Wettability change on kr (oil wet to water wet)
- Partitioned tracer

E300 - CO2 as an EOR agent
To model the chemical reactivity between CO2 and the liquid phases (solubility of CO2 in the aqueous phase)

Capabilities
- Modelling of the phase equilibrium between CO2 and the aqueous phase
- Solubility of CO2 in the phases (viscosity and density effects)
ECLIPSE Thermal
– Introduction to ECLIPSE Thermal
– Recent Thermal Projects Involving AbTC
– Developments and Future Plans

Mark Wakefield
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The ECLIPSE THERMAL Project

1992  Project started  (Paul Naccache)
      Dead oil + steam
      First client: BEB in Germany

1995  First commercial release E500

Continued development including live oil, well models, chemical reactions, solvers …

Continued client support and integration into ECLIPSE/Petrel suite

<table>
<thead>
<tr>
<th>Process</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamy oil</td>
<td>Non-equilibrium phase behaviour</td>
</tr>
<tr>
<td>CHOPS</td>
<td>Sand transport, worm holing (Visage)</td>
</tr>
<tr>
<td>Hot water injection</td>
<td>Viscosity reduction through heating</td>
</tr>
<tr>
<td>Cyclic Steam Stimulation</td>
<td>Viscosity reduction through heating</td>
</tr>
<tr>
<td>Steam Drive</td>
<td>Steam transporting more energy</td>
</tr>
<tr>
<td>SAGD</td>
<td>Formation damage</td>
</tr>
</tbody>
</table>
| VAPour EXtraction | Viscosity reduction via solvent
Asphaltene precipitation |
|------------------|------------------------------------------------|
| In-Situ Combustion, THAI™ | Viscosity reduction through heating
Fractional distillation / solvent flood
Consumption of heavy end
Steam flood
Cracking?
Coke blocking |
Some recent thermal projects involving AbTC include:

- ISC in Venezuela
- Multi segment well comparisons
- Foamy oil
Collaborating with Schlumberger Cambridge (SCR) to develop ISC models

- Combustion tubes data for simulation validation
- Oil analysis to determine a suitable reaction set and data (rates, enthalpies)

Asphaltene + \( \text{O}_2 \) → Gas + Water
Maltene + \( \text{O}_2 \) → Gas + Water

- Modelled using the REACTION feature
ISC in Venezuela

- Chemical reactions add source and sink terms to component conservation equations
- No additional solution variables
- Additional non-linearities to the system
  - Jacobian less well conditioned
  - More work for the linear solver
  - A new time scale (fast) which needs resolving

All leads to challenging models!
ISC in Venezuela

- Move from Lab to field time and length scales
- Maintain sufficient predictive power to assess well configurations, air enrichment and run sensitivities studies

Material supplied by Aubrey O'Callaghan, Jean Gossuin & Paul Naccache.
ICD modelled in ECLIPSE as segments with pressure losses (labyrinths, valves)
Multi Segment Well ‘vs’ Conventional Well

Conventional

Multisegmented

5 years

10 years

Steam Chamber and Drainage Areas

Data supplied by Carlos Damas et al.
Multi Segment Well Inflow Control Devices

Steam Chamber and Drainage Areas

Steam placement

No ICDs
Large numbers of persistent gas bubbles trapped in oil. Generated by de-pressurization of live heavy oils

Non-equilibrium behaviour, gas components take time to appear

Restricted gas mobility

Results in Oil components with ideal gas-like compressibility

\[
\text{Liquid Vol. } \sim 1 - C_p(P-P_{\text{ref}}) \quad \quad \text{Gas Volume } \sim \frac{1}{P}
\]
Non equilibrium behaviour modelled with a kinetic model using the reactions feature instead of a flash calculations.

<table>
<thead>
<tr>
<th>Component</th>
<th>Dissolved Gas</th>
<th>Trapped Gas</th>
<th>Free Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatility</td>
<td>Non-volatile</td>
<td>Non-volatile</td>
<td>non-condensable</td>
</tr>
<tr>
<td>Compressibility</td>
<td>Liquid Oil</td>
<td>Gas Oil</td>
<td>Gas</td>
</tr>
<tr>
<td>Phase</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Material supplied by David Law
ECLIPSE Thermal 2007.1 included the new JALS solver

- Constrained Pressure Residual (CPR) algorithm where a reduced pressure equation is additionally solved
- The additional pressure solve increases the CPU cost per linear iteration but can significantly improve the convergence rate
- Solver initially tested on a variety of heavy oil & thermal cases. Average CPU WARP / CPU JALS ~ 1.7
- Solver available in parallel
- The JALS solver is under development by John Appleyard, a member of the original ECLIPSE team
The JALS solver consistently requires less linear iterations leading to a healthy decrease in CPU time ~ 42% reduction.

- 16,750 active cells
- 2 multi-segmented wells
- 2 hydrocarbon components
The JALS solver powers through the period of poor convergence leading to a substantial reduction in CPU time \( \sim 9.8 \times \).

- 11,000 active cells
- 5 multi-segmented wells
- 2 hydrocarbon components