Streamlines in IOR/EOR

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Outline

• IOR/EOR Key Modeling Concepts

• Streamline Simulation

• Applying SL to IOR/EOR
  • CO2/Miscible
  • Polymer / ASP
  • Thermal

• Wrap-up
Streamlines in IOR/EOR Floods

**IOR/EOR CONCEPTS**
IOR/EOR Concepts

- IOR—Improve sweep
  - Mobility control
  - Improved pattern balancing
  - Rate optimization
  - Infill wells / horizontals

- EOR—Mobilize trapped oil
  - Miscible flooding
  - SP/ASP/solvents/microbial
  - Thermal

\[ N_p = E_D \times E_V \times N \]

Volumetric Sweep Efficiency

Displacement Efficiency
IOR

- Improve sweep using streamlines
- Mobility control, improved pattern balancing, rate optimization, infill wells, horizontals...

\[ N_p = E_D \times E_v \times N \]

2D, steady state, homogenous
2D, SS, heterogenous
3D, heterogenous, compressible, gravity, ...

'30  '60  '80  present
Mobilize trapped oil

- Miscible flooding:
  - Locally $S_o \rightarrow 0$ above MMP, but serious issues with channeling/fingering of injectant due to reservoir connectivity

- SP/ASP/solvents/microbial
  - Drive M-ratio and $S_o$ down; key is to properly engineer concentrations/slug sizes

- Thermal
  - Drive M-ratio and $S_o$ down; key is delivery of heat to the reservoir by conduction and diffusion; steam flooding issues with condensation; ISC keeping front burning by proper air supply.

In all cases we have a “good” handle on 1D solutions. Not so for 3D.
Streamlines in IOR/EOR Floods

STREAMLINE SIMULATION
Modern SLS: Dual Grids

1. Eulerian “static” grid

2. Lagrangian “streamline” grid
Modern SLS: Dual Grids

Eulerian “static” grid
- diffusive properties: pressure, temperature

Lagrangian “streamline” grid
- directional properties: saturations, compositions
Modern SLS

- Heterogeneous rock properties (porosity, perm, NTG, rockregions, ...).
- 3 dimensional flow.
- Multi-phase flow
- Changing well conditions.
- Gravity effects.
- Compressibility.

- To solve realistic problems we turn to numerical streamline methods.
Initial Conditions

Trace Streamlines

Update Pressure

Geo

Move Saturations $t \rightarrow t + \Delta t$

New Initial Conditions

$P_{n+1}$

$S_{n+1}$

$S^n, P_{n+1}$

$S^n$ to $S^{n+1}$
EOR w/ SLs

• Put EOR-relevant physics along SLs:
  • Miscible flooding $\rightarrow$ oil viscosity/density function of composition
  • Polymer flooding $\rightarrow$ water viscosities a function of insitu polymer and salt concentration; adsorption; shear rate; perm reduction
  • Thermal flooding $\rightarrow$ oil viscosity function of temperature
  • Steam flooding $\rightarrow$ oil viscosity + condensation of water

• 1D model complexity must be weighted additional computational costs and numerical approximations inherent in the SL approach.
Miscible Flooding Using SLs

- Extensively documented in SPE literature, eg:
  - Using Analytical Solutions in Compositional Streamline Simulation of a Field-Scale CO2-Injection Project in a Condensate Reservoir (SPE 79690)
  - Compositional Streamline Simulation (SPE 77379)
  - Streamline Technology for the Evaluation of Full Field Compositional Processes; Midale, A Case Study (SPE 89363)
  - Streamline Simulation of Four-Phase WAG Processes (SPE 96940)
  - A three-phase four-component streamline-based simulator to study carbon dioxide storage (Comp. Geosci. 2009)
  - ...
Basic Ideas

• Model compositional displacements, but to maintain computational efficiency use simplified PVT model

• Model decreasing oleic density/viscosity with increasing gas miscibility; incl. 1st order gravity effects
  • Capture changing mobility ratio with increasing gas composition in oleic phase
  • 1st order fractional flow effects, sweep efficiency/channeling of free gas.
Example

• **1D Example:**
  • 8 component system: N2-C1, CO2-C2, C3-C4, C5-C6, C7-C8, C9-C13, C14-C24, C25+
  • WAG schedule: 2200 Mscf/DAY of gas followed by 2000 STB/day of water on a 6 month interval starting after two years of initial water injection.
  • 1D calibration parameters: $\beta=10 \omega=0.8$
Example: Alpine Field

• North slope of Alaska → interested in forecasting WAG

• 100x160x5; approx. 110 wells.

• Compare full-physics simulation to SL’s+simplified PVT.
Example: Alpine Field
Alpine Field Production

Alpine Field Rates 100x160x6 WAG System

FDiff
SLines

Gas
Oil
Water
Alpine Well Production

Time 8691.0 days (2024/02/19 - 2024/08/18) - 3ds1_1

Alpine Well Rates 100x160x6 WAG System

- A015P103
- A040P080
- B001P090
- B043P130
Polymer Flooding (IOR)

- Compressible phase densities
- 4 components: oil, water, polymer, salt
- Immiscible flow
- Water viscosity a function of polymer & salt concentrations, shear rate
- Adsorption
- Permeability reduction due to adsorption

1D Oil & Water Production

1D Pressure
Ex: Polymer (Case 1)

- Water
- Oil
- Pressure

Graphs showing flow rates and pressure over time.
Ex: Polymer (Case 2)
SP / ASP Model

- Surfactant
  - Add dependence of oil/water relperms on surfactant concentration (as IFT↓ due to surfactant \(\rightarrow\) Sor↓);
  - Add support for transport of microemulsion phase

- Alkaline-Surfactant
  - In situ generation of surfactant \(\rightarrow\) add chemical reactions
  - SPE 1421095 \(\rightarrow\) 10 mass balance equations (water, oil, surfactant, polymer, total anions, total divalent cations, sodium, hydrogen, alkali, soap)

Modify 1D transport solutions to generate 3D SP/ASP solutions.
Ex: Thermal Flooding

- **Added difficulty:**
  - heat advection along streamlines
  - head conduction

- **Operator splitting**
  - $\Delta t$: Pressure $\rightarrow$ Transport $+$ heat convection $\rightarrow$ heat conduction

\[
\frac{\partial U}{\partial t} = \alpha \nabla^2 T
\]

Pressure

Mass & energy transport along SL
Ex: Heterogeneous Q5 Spot

Saturation Field

Streamline (50X50)  STARS (50X50)  STARS (200X200)

Temperature Field

Streamline (50X50)  STARS (50X50)  STARS (200X200)
Hybrid SL/FV

- Cyclic Steam Injection
  - Transport steam/hot water into reservoir via SLs
  - Solve soak-period by traditional FV
  - Transport steam/water/oil from reservoir via SLs

Settings:
- \( BHP_{\text{inj}} = 6000 \text{kPa} \)
- \( P_{\text{init}} = 4500 \text{kPa} \)
- \( K = 500 \text{mD} \) (homogeneous)
- \( f_{\text{steam}} = 0.8 \)

From: Z. Zhu / Efficient Simulation of Thermal Enhanced Oil Recovery Processes, PhD, Stanford 2011
Cyclic Steam Injection

50X50 SL

50X50 STARS MPFA
(Shiralkar 1991)

Temperature
(Injection)  (Soak)  (Produce)

SL  FV  SL

From: Z. Zhu / Efficient Simulation of Thermal Enhanced Oil Recovery Processes, PhD, Stanford 2011
SLs in EOR/IOR

- Usually, SLs numerically more efficient than FV simulation
  - Simulate on finer grids with more geological detail and/or...
  - Perform sensitivity/uncertainty studies
• Per-Pattern Displacement Metrics
  • Most attractive part of SL is the ability to perform flood design using per-pattern metrics

\[ N_p = E_D \times E_V \times N \]

Per Pattern (Inj + associated prod’s)
Per Injector Conformance Plot

Conformance Plot for Injector P9-7

Pattern Oil Production Volume

Pattern Injection Volume/Mass/Heat/…
Improve IOR/EOR Floods

- Example: SPE 132774

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Improved Polymer-Flood Management Using Streamlines

Torsten Clemens, SPE, and Joseph Abdev, SPE, MV; and Marco R. Thiele, SPE,
Streamsim Technologies/Stanford University

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Summary

Recently, modern streamline (SL) simulation has been extended to polymer flooding. In this work, we extend the applicability of SL simulation further for efficient management of polymer-injection projects. We first present our method and then demonstrate the applicability of our approach using a Romanian field as an example. Owing to the price of polymers, an optimized injection strategy is needed, and an understanding of the streamline simulation is essential for such projects.

Polymer flooding has been used to further improve recovery from viscous-oil fields. In this case, a water-soluble polymer is mixed with the injected water to increase the water viscosity and thereby lower the mobility ratio. A number of successful polymer floods have been reported in the literature (Needham and Doe 1987; Littman 1988; Putz et al. 1994; Dong et al. 2008). More than 250,000 B/D of additional oil is being produced by polymer injection from the Daging field, and incremental oil recovery of up to...
OMV – Romanian Waterflood

- 40 years waterflood, 100+ wells
- Porosity: 30 %
- Permeability: 700 mD
- Oil density: 974 kg/m³
- Oil viscosity: 100 cp
- Water viscosity: 0.5 cp
- Reservoir temperature: 53 °C
- Water salinity: 23000 ppm
- Initial reservoir pressure: 90 bar

Field Oil Rate - Simulated

due to polymer history

from SPE 132774
Best use of polymer? → best patterns, max concentration, slug size.
Utility/Efficiency Factors

- Polymer injection projects are OPEX driven:
  - Per pattern efficiency factor
  - Per pattern utility factor

\[
EF = \frac{\text{cumulative mass polymer injected [kg]}}{\text{cumulative ultimate oil produced [bbl]}}
\]

\[
UF = \frac{\text{cumulative mass polymer injected [kg]}}{\text{cumulative incremental oil produced [bbl]}}
\]
Pattern Performance Plot

Cumulative polymer injected in kg vs. Cumulative Oil Production

from SPE 132774
Cumulative polymer injected in kg

Per Pattern Utility Factor

Cumulative oil production in bbl

Cumulative incremental oil produced

Cumulative polymer injected in kg

Per Pattern Utility Factor

Cumulative oil production in bbl

Cumulative incremental oil produced

Cumulative polymer injected in kg
Workflow Using Patterns

1) Improve waterflood

2) Disregard patterns with low EF for base slug size/concentration

3) Pattern sensitivity to concentration/slug size

4) Pick individual pattern operating conditions based on UF

5) Full field using optimal individual strategies
Sensitivity of Individual Patterns

Different slug sizes at a fixed concentration

Different concentrations at fixed slug size
Polymer Simulation Results

Cumulative polymer injection

Cumulative polymer injected decreased…

Cumulative oil production

…cumulative oil recovery increased

Base water flood

from SPE 132774
Conclusions & Wrap-up

- Advances in SL’s over the past 10 years have moved SL’s into mainstream engineering workflows.

- Most attractive feature of SLs for IOR/EOR is ability to
  - Define dynamic patterns (injector centered)
  - Quantify recovery on a per-pattern basis

- Per-pattern recovery metrics allow mean a step-change in flood management
  - Optimize EOR injection volumes locally.
  - Optimize volumetric sweep by better rate management.
Follow-Up Reading

• Streamline Simulation (SPE 2011)—Getting Up to Speed Series (online only)

• Improved Polymer-Flood Management Using Streamlines, SPEREER April 2011, (SPE 132774)

• Revisiting Reservoir Flood-Surveillance Methods Using Streamlines SPEREER April ‘08 (SPE 95402)

• Using Streamline-Derived Injection Efficiencies for Improved Waterflood Management, SPEREER April ‘06 (SPE 84040)