Modeling of the Snorre deep-divergence pilot
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Outline

• Snorre water diversion pilot
• Mechanisms of Sodium Silicate system
• Silicate modeling and History matching
• Challenges and potential improvements
In-depth water diversion – Sodium silicate

Goal: Establish flow restrictions in flooded areas to improve lateral and vertical reservoir sweep

- Silicate
  - Low temp – Flows like water
  - Reservoir temp - Gelling

- Dynamic gelling:
  - 2008-2009: Lab: > 25 bar
  - 2011: Single well test: 80-120 bar
  - 2013: Inter-well pilot

- Intolerant to seawater (need preflush)
  - Accelerated gelling
  - Precipitation
Pilot area

Thief zone challenge

Initial injection water front speed: approx. 6 m/d (2002-2003)

Water tracer injection (2008)
Tracer front speed: 9-11 m/d

Early and strong water break through
Modelling: Simulating and matching observed data

Reservoir transmissibility: $T = \frac{q}{\Delta p}$

Tracer-data – Post-flush tracer

Falloff-data
- **Green**: Observed Mar 2012
- **Orange**: Observed Mar 2014
- **Purple**: Simulated Mar 2012
- **Black**: Simulated Mar 2014

Change in water-cut

Black: Obs
Green: Sim (silicate and HM)
Red: Sim (no silicate)
Silicate mechanisms

Gelling:

Gelation time model from Stavland et al. (2011):

$$t_{\downarrow \text{g}} = A \cdot e^{\alpha[Si]} \cdot e^{\beta[HCl]} \cdot e^{\gamma[Ca^{2+}]} \cdot e^{Ea/RT}$$

The pilot designed such that:

$$t_{\downarrow \text{g}} \approx B \cdot e^{\alpha[Si]} \cdot e^{Ea/RT}$$

Precipitation:

Precipitation of Mg(OH)$_2$ from seawater in contact with silicate (high pH).

Pre and post flush: Desalinated water with KCl for ion exchange

During the operation: Desalinated water with HCl for pH stabilization
Simulation model

Permeability: thief zone scenario

Simulated silicate slug

Simulated temperature

Simulated salt concentration
Modeling of sodium silicate

• History matching approach
  - For history matching
  - Restriction included by multiplier boxes in time

• Silicate modeling approach – for prediction
  - Gelling: Temperature and silicate concentration dependent
    - Neglecting pH and salt concentration due to pilot design
  - Precipitation: salt and silicate concentration dependent

Using BASRA for assisted history matching: Statoil internal software – SPE113390
On average introduced late, but it does not really matter when weak restrictions are introduced.
Cross flow is one possibility

Salt (divalent cations) may back/cross flow into the thief zone during shut ins. That may give accelerated gelling for the silicate injected right after the shut-in.

(Could be prevented/mitigated for future operations)
Reservoir transmissibility

Pre-flush
Silicate injection
Post-flush

Temperature triggered gelling (mainly)

Drop in transmissibility after shut in period
Simulated salt concentrations close to the injector

Thief zone layer

Shut in of the injector in August 2013
Predictive modeling

Gelling and precipitation parameters:
- Silicate concentration triggering gelling
- Temperature triggering gelling
- Permeability reduction factors for gelling
- Silicate concentration triggering precipitation
- Salt concentration triggering precipitation
- Permeability reduction factors for precipitation

Adsorption/loss parameter
- Amount of adsorption of silicate (depends on silicate concentration)

7 generic silicate modeling parameters

Goal:
- Calibrate by the pilot
- Use for evaluating new field candidates

Effect of cross-flow had to be modeled by multiplier boxes
- May be avoided for future operations
Calibrated silicate modeling parameters

Ensemble of matching simulations (blue curves). The ensemble is also matching the other pilot responses.

Histogram for calibrated silicate modeling parameters – based on the matching ensemble.

In this example - the logarithm of the permeability reduction factor for precipitation.
Predictive approach - Formed obstructions

Gelling and precipitation introduced by the Predictive approach by September 1st, 2015:

Red: Gelling
Blue: Precipitation

Early cross-flow restrictions not in the figure.
Main flow restriction seems to have formed in this area between 100-230 days after the start of silicate injection.

Indications of early moderate flow restriction due to cross-flow of salts. Mitigating actions are possible for future operation.

Consistency between the two modeling approaches

Perm reduction factor ~0.1
Perm reduction factor ~0.0001
Summary – Pilot observations

• Deep placement of flow restriction leading to flow diversion
  – Deep placement supported by: Transmissibility reduction, fall off-data, step-rate tests
  – Diversion supported by: Delay of water tracers, reduction in water cut

• Reduced liquid throughput
  – Cross-flow of salts part of the reason
Summary – Silicate modeling

• History matching
  − Able to model location and strength of the introduced flow restrictions.
  − Able to history match pilot responses
  − Similar results using the two different approaches

• Predictive approach
  − Calibrated silicate modelling parameters obtained
    • May be used in evaluation of new silicate-based water diversion candidates
    • Further calibration to lab experiment results and/or new field implementations
Challenges and improvements for the modeling

• Modeling of the **effect of salts** on gelling (or preferably use a salt tolerant chemical)
  - Modeling the effect of potential cross-flow of salts
  - Determining size of pre flush
• Better modeling of **silicate consumption/loss**
  - Integrated part of the silicate modeling
• Still **uncertainty** in the **silicate modeling parameters**
• Demonstrate **good business cases for new field implementations**
  - Use developed modeling techniques for finding candidates and maximize IOR volumes in an economical context
    • Low oil price and cost

**Good ideas and contributions are welcome 😊**
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The Snorre asset

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Papers for the interwell pilot:
• Skrettingland et al. (2014) – SPE169727
• Skrettingland et al. (2016) – SPE179602