Air Injection: Heavy Oil Field Potential and Simulation

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In Situ Combustion Classic Schematic

7-9% of the contacted oil is consumed to maintain propagation of the in-situ oxidation process.
Recovery Mechanisms: Heavy Oils

- Thermal effects are the main recovery mechanism in heavy oils and bitumen (i.e. steam/hot water displacement, combustion front displacement).

- Flue gas drive (i.e. pressure maintenance, gasflood, oil stripping, oil swelling, etc.) is the main driving mechanism in light oils.

Displacement efficiency 100%

No oil and water left behind the front
Process Variations (1)

- **Dry Combustion**: Only air or enriched air is injected
- **Wet Combustion**: Water is injected along with air to create steam and provide additional heat transport and oil displacement
- Steam-Oxygen Co-injection: Air-Assisted Steam Injection
- **Cyclic Combustion**: CSS but injecting air or steam-air mixtures
- **COFCAW**: Combination of Forward Combustion and Waterflooding
- **Pressure Cycling Combustion**: Pressure up-Blow down process
Process Variations (2)

- **THAI**: Toe-to-Heel Air Injection
- **THAI-CAPRI**: Catalytic version of THAI
- **EnCAID**: EnCana Air Injection and Displacement process
- **COSH**: Combustion Override Split production Horizontal well process
History of air injection application

1888: Academician D.I. Mendeleev—idea of in-situ coal gasification process

1930s: A.B. Sheinman and K.K. Dubrovai—first attempts to initiate in-situ oxidation of oil

1967: Successful heavy oil in-situ combustion (ISC) applications (at the Pavlova Gora field in Krasnodar and at Shodnitza field in Ukraine)
North American experience

In the 1960s and 1970s approximately 40 air injection heavy oil full field or pilot projects were undertaken in the world, mostly in the North America.
California, USA

- California has an estimated 3.5 billion barrels of oil reserves. 75% of those reserves are heavy oil (API gravity 10 to 20).
- These deposits were discovered early, between 1880 and 1920.
- Full field air injection projects in the heavy oil fields of California, in the San Joaquin Valley.
- A wide range of thermal techniques have been applied to producing this large resource.
- 60-70% of the original oil still remains in place.
California, USA

- Largest project was the West Newport field producing 3,000 barrels/day from 100 producers.

- Others projects included:
  - Lost Hills, producing 800 b/d from 40 producers
  - Midway Sunset – Potter, producing 1,200 b/d.

- While some of the projects were clearly successful, recovering up to 50% of the original oil in place, overall the results did not live up to expectations.
The ISC problems that occurred and caused less than optimal recovery:

- emulsions,
- subsurface scale,
- corrosion and gas buildup at producers,
- the failure to ignite or control the flame front,
- gravity segregation.
Alberta, Canada

- Canada has an estimated **2.5 - 3 trillion barrels of heavy oil and bitumen deposits**, 175 billion barrels of which is proved.
- Most of these deposits are in Alberta.
- At one time, there were **16 air injection projects in Alberta and Saskatchewan**.
- More failures, than successes.
- Problems:
  - sand production, corrosion, gas locking and difficult emulsions.
Other ongoing heavy oil ISC applications

• Romania
  • Suplacu de Barcau field, Petrom
• India
  • Balol and Santhal fields, ONGC
• Russia, Tartar Republic
  • Mardovo-Karmalskoye field
Why reconsider air injection today? (1)

- Thermally, it is the most efficient oil recovery process
- Availability of air (cheap injection fluid)
- Proven technology in different reservoir settings (shallow heavy oil and deep light oil reservoirs)
- High displacement efficiency
- It can be applied in cases where waterflooding or steam injection are not effective
- It can be applied after other EOR processes (e.g. CO2 injection, chemical injection, etc.)
Why reconsider air injection today? (2)

- Size of the resources
- Better understanding of the process mechanisms (oxidation kinetics, relative permeability effects of liquid-blocking gas flow).
- Better access to the reservoir with horizontal wells
- Better production procedures and equipment
Air injection potential risks

INJECTION SIDE:
• Eventual O₂ back production

Measures:
Well bore isolation
No tubing leaks
Second injection line to purge water or N₂

PRODUCTION SIDE:
• O₂ breakthrough risk

Measures:
Production monitoring
Down hole gas gauges

Operational and safety issues are not regarded any more as obstacles for field application.
Tartar Republic, Russian Federation

Mordovo-Karmalskoye field of natural bitumen was pilot produced since 1974

By 2007 there were drilled 364 wells

MK field includes 3 domes (South, North and Southwest)

The South and South-West domes - ISC process

The North dome - steam injection
Mordovo-Karmalskoye field

Other production techniques:

✓ Steam-air injection (was tested in 1978-1981);

✓ Steam-gas injection (was tested in 1981 - 1995 on the North dome);

✓ Thermal-cyclic injection (negative effects were the gas breakthrough through the most permeable layers and steam gravity override);

✓ Thermal wave treatment (carried out on the South dome).
Mordovo-Karmalskoye field

Specific characteristics:

- presence of thin water saturated zones inside the bitumen deposit
- lack of the horizontal bottom boundary of the reservoir
- presence of free gas:
  \[\text{N}_2 - 9.5\%, \quad \text{C}_1 - 45.1\%, \quad \text{C}_2 - 24.7\%, \quad \text{C}_3 - 12.5\%, \quad \text{iC}_4 - 0.9\%, \quad \text{nC}_4 - 2.5\%, \quad \text{iC}_5 - 1.5\% \text{ and } \text{nC}_5 - 1.6\%\]
- high paraffin content: varying from 3.1 to 24.1% (in the South-East dome)
Reservoir simulation model
(thermal reservoir simulator STARS)

- Initial reservoir temperature - 8°C;
- Reservoir pressure - 45 bar;
- BHP for production wells – 37 bar;
- Oil (bitumen) viscosity - 6815 cp;

- Thermal conductivity for oil - 5.47·10^5 J/g-mole-°C;
- Thermal conductivity for water - 3.68·10^3 J/g-mole-°C;
- Thermal conductivity for gas - 2.93·10^3 J/g-mole-°C.

Controlled reaction parameters:
- The activation energy (thermogravimetry);
- The frequency factor;
- The reaction enthalpy (thermogravimetry).
The current oil recovery factor in the ISC process area is 12% of STOOp.
The South dome of the MK field

Number of wells in production
The South dome of the MK field

Air injection, thousand m³/year
Modeling in-situ combustion

- Thermal simulator
- K value pseudo-compositional
- Four phases: water, oil, gas, solid
- N - components
- Chemical reactions
- Energy release and temperature modeling
Air injection

- **Kinetics, activation energy, reactive oil properties**
  - Differential Thermal Analyser (DTS) - low pressure (up to 100 bar)
  - Accelerating Rate Calorimeter (ARC) – up to 450 bar
  - Disc reactor, Ramped Temperature Oxidation (RTO) – res. pressures

- **Oxidation process, quantify performance, calibrate simulation model**
  - Combustion tube test – reservoir conditions flow test

- **Good conformance is critical**
  - State-of-the-art simulation
Chemical Reactions

- **Bond Scission Reactions (Oxidation Reaction)**

  Hydrocarbon + O₂ → Carbon oxides + Water + Energy

- **Oxygen Addition Reactions (Oxidation Reaction)**

  Hydrocarbon + O₂ → Oxygenated compounds + Energy

- **Pyrolysis Reactions (Thermal Cracking)**

  \[
  \text{Hydrocarbon}_{(\text{liquid})} \xrightarrow{\text{Energy}} \text{HC}_{(\text{liquid and/or solid})} + \text{HC}_{(\text{gas})}
  \]
Combustion model parameters

• Stoichiometric coefficients of reacting and produced components

• Reaction frequency factor (freqfac)

• Activation energy which determines dependence of the reaction rate on grid block temperature (J/gmol or Btu/lbmol)

• Reaction enthalpy (J/gmol or Btu/lbmol)
Oil combustion

Chemical reactions:
1) Cracking of C12-C17 -> coke + C7-C11
2) Cracking of C18+ -> coke + C7-C11
3) Burning of C12-C17 + O2 -> WATER + CO2 + energy
4) Burning of C18 + O2 -> WATER + CO2 + energy
5) Burning of coke + O2 -> WATER + CO2 + energy

Components:
H2O, N2, O2, CO2, C5-C6, C7-C11, C12-C17, C18+
and residual coke (solid component)
Oxidation reactions

Reactant Component + oxygen $\rightarrow$ $H_2O + CO_2 + \text{energy}$

Input parameters for reaction $k$:

- mass exchange (stoichiometry)
  - $s_{k,i_c}$ (reactant stoichiometry tric coefficient)
  - $s_{k,i_c}$ (product stoichiometry tric coefficient)

- reaction kinetics (reaction rate)

$$r_k = r_{f_k} e^{-eact/(T*R)} C_{1}^{o_k,1} ... C_{n_c}^{o_k,n_c}$$

where $C_{i_c}$ are concentration factors

- reaction enthalpy $H_k$
Reservoir simulation model  
(thermal reservoir simulator STARS)

<table>
<thead>
<tr>
<th>Components</th>
<th>Molar weights of components, lb/lbmole</th>
</tr>
</thead>
<tbody>
<tr>
<td>WATER</td>
<td>18</td>
</tr>
<tr>
<td>HEAVY OIL</td>
<td>675</td>
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<tr>
<td>LIGHT OIL</td>
<td>157</td>
</tr>
<tr>
<td>INERT GAS</td>
<td>40.8</td>
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<tr>
<td>OXYGEN</td>
<td>32</td>
</tr>
<tr>
<td>COKE</td>
<td>13</td>
</tr>
</tbody>
</table>
Reservoir simulation model
(thermal reservoir simulator STARS)

Air injection well pattern 345 of the MK South dome.
Oil saturation distribution

The cumulative oil production is 15.2 thousand tons of oil and 35.7 thousand tons of liquid.

In total there was injected 96 billion m$^3$ of air into 12 injection wells.
Reservoir simulation model

Pair of wells: 345 - injector, 344 – producer

Reservoir temperature two months after the start of air injection (°C)
Reservoir simulation model

Pair of wells: 345- injector, 344 – producer

Reservoir pressure two months after the start of injection (kPa)

Viscosity change in the dynamically refined grid cells
Dynagrid

- SPE 79683
  - Initial paper Dynagrid in 2002
  - Compositional simulator GEM
- SPE 86969
  - Applications in STARS
- Dynagrid suitable for low mobility fluids
- Accurate calculations
- Speed
Conclusions

✓ The valuable field development experience from the bitumen MK field.

✓ The reservoir simulation model of the South dome of the MK field is established and is used to simulate the ISC process.

✓ The important kinetic parameters (activation energy and reaction enthalpy) were measured in the laboratory.

✓ The dynamic gridding (DynaGrid) is used in the simulation model to achieve higher accuracy when modelling front movement and better material balance calculations in thermal and chemical reaction processes.
Conclusions cont.

- History matching of the long lasting ICS process in the bitumen deposit allows to calibrate process parameters and to improve reservoir characterization, to establish a useful simulation tool for ISC process _modelling, monitoring, evaluation and prediction._

- Simulations will allow _optimizing ISC process_ in the South and the South-West domes of the MK field.

- New thermal recovery methods, THAI process, drilling of advanced wells will be also evaluated.