Investigations into Oil Recovery and Drainage Rates during Vapour Extraction (VAPEX)

Hadi Zainee (Petronas), Abdullah Alkindi (Petroleum Development Oman) & Ann Muggeridge (Imperial)
Outline

• What is VAPEX?
  • Prediction of oil drainage rate
• Method
  • Experimentally validated numerical model
• Results
• Conclusions
• Acknowledgements
What is VAPEX?

Vapour Extraction

• Improve heavy oil recovery by injecting vaporised solvent
  » Horizontal injector and producer
  » Analogue of SAGD
• Oil viscosity reduced by diffusion driven mixing between oil and solvent
  More energy efficient than SAGD
  Better in thin reservoirs or those underlain by an aquifer
Butler & Mokrys (1989), analytical expression for oil rate:

\[
q_o = \sqrt{2 \ k \ h \ g \ \phi \ \Delta S_o \ \ N_s}
\]

\[
N_s = \int_{c_{\min}}^{c_{\max}} \frac{\Delta \rho (1-c_s) \ D}{\mu} \ d(\ln c_s)
\]

**But actual** \( q_o \) \( \gg \) Butler & Mokrys \( q_o \)


**Explanations include**

- Increased rate of mixing due to
  - Convective dispersion
  - Capillary films
  - Counter-current flow

- Higher effective drainage height
Prediction of Oil Drainage Rate

Alkindi (2009)

1. performed VAPEX experiments using analogue fluids
   - Glass bead pack representing 2D section of a reservoir
   - Producer at bottom & Injector mid-height
   - Could be rotated to give lower aspect ratio
   - Ethanol (solvent) and glycerol (oil)
   - All input data measured experimentally including longitudinal and transverse convective dispersion

2. Performed numerical simulations (STARS) using experimental data as input
   - To predict experimental behaviour
Prediction of Oil Drainage Rate

Alkindi (2009), results confirmed underprediction of oil rate by Butler & Mokryrs model

<table>
<thead>
<tr>
<th>Model height cm</th>
<th>Simulation cm³/hr</th>
<th>Measured oil drainage rate cm³/hr</th>
<th>Butler and Mokryrs drainage rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Molecular diffusion cm³/hr</td>
</tr>
<tr>
<td>30</td>
<td>0.46</td>
<td>0.48</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.38</td>
<td>0.41</td>
<td>0.23</td>
</tr>
</tbody>
</table>

» Using convective dispersion improves prediction, but still too low

• Numerical simulation predicted experimental results

⇒ need improved analytic model
This work

- Propose an improved analytic model to predict oil drainage rate

- Validate the predictions of oil rate as a function of
  - Density difference ($\Delta \rho$)
  - Viscosity ratio ($M$)
  - Permeability ($k$)
  - Reservoir thickness ($h$)
  - Reservoir aspect ratio ($h/L$)
Modified Butler-Mokrys model

Original model (Butler & Mokrys, 1989)
• \( \Delta \rho = (1-c_s)(\rho_0-\rho_s) \)
  » density difference between solvent and draining solvent-oil mixture

Modified model
• \( \Delta \rho = (\rho_0-\rho_s) \)
  » density difference between solvent and undiluted oil
  » \( N_s \) larger, \( \Rightarrow q_o \) larger

Why?
• Butler and Mokrys model assumes VE
  » Drainage driven by spread of solvent chamber, segregated flow \( cf. \) Dietz (1953)
Methodology

Numerical simulation using experimentally validated model of Alkindi (2009)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid size</td>
<td>$60 \times 1 \times 150$</td>
</tr>
<tr>
<td>Model dimensions ($x, y, z$)</td>
<td>$30 \times 0.5 \times 15$ cm</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.4</td>
</tr>
<tr>
<td>Permeability</td>
<td>43.3 D</td>
</tr>
<tr>
<td>Reference pressure</td>
<td>101 kPa</td>
</tr>
<tr>
<td>Reference temperature</td>
<td>20°C</td>
</tr>
<tr>
<td>Longitudinal dispersion coefficient</td>
<td>$8.9 \times 10^{-10}$ m$^2$/s</td>
</tr>
</tbody>
</table>

Analogue fluid properties (ethanol=solvent, glycerol=oil)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol density (kg/m$^3$)</td>
<td>790</td>
</tr>
<tr>
<td>Ethanol viscosity (mPa s)</td>
<td>1.2</td>
</tr>
<tr>
<td>Glycerol density (kg/m$^3$)</td>
<td>1261</td>
</tr>
<tr>
<td>Glycerol viscosity (mPa s)</td>
<td>1390</td>
</tr>
</tbody>
</table>
Use numerical model validated by comparison between experimental and simulation results (Alkindi, 2009)
Results:
Sensitivity to density difference

Good agreement between modified analytic model and simulation
- Original Butler & Mokrys model underpredicts rate
- Oil drainage rate increases with solvent oil density difference
- Convective dispersion is not important at high density differences
  » Consistent with experimental results of Alkindi et al. (2011)
Results:

Viscosity ratio and permeability

Good agreement between modified analytic model and simulation

- Original Butler & Mokrys model underpredicts rate
- Oil drainage rate
  - Increases with square root of permeability
  - Decreases as viscosity ratio ($M$) increases
  - Analytic model breaks down for $M<1000$

\[ q_o = \sqrt{2 \ k \ h \ g \ \phi \ \Delta S_o \ N_s} \]

\[ N_s = \int_{c_{\text{min}}}^{c_{\text{max}}} \frac{\Delta \rho (1-c_i) D}{\mu} \ d(ln \ c_i) \]

\[ N_s = \Delta \rho \ D \int_{c_{\text{min}}}^{c_{\text{max}}} \frac{1}{\mu} \ d(ln \ c_i) \]

\[ N_s = \Delta \rho K_L \int_{c_{\text{min}}}^{c_{\text{max}}} \frac{1}{\mu} \ d(ln \ c_i) \]

Sensitivity plot for square root of permeability ($\sqrt{k}$)

Sensitivity plot for viscosity ratio ($M$)
Results:
Aspect ratio and thickness

No dependency of oil drainage rate on aspect ratio for $h/L < 1$
- Consistent with Butler & Mokrys model

Butler & Mokrys breaks down for $h/L > 1$
- Flow no longer gravity dominated

Oil drainage rate dependency on thickness
- Best matched with an exponent of 0.28
  » Butler & Mokrys and modification both predict an exponent of 0.5

$$q_o = \sqrt{2 \ k \ h \ g \ \phi \ \Delta S_o \ N_s}$$

$$N_s = \int_{c_{\text{min}}}^{c_{\text{max}}} \frac{\Delta \rho (1-c_s) D}{\mu} d(\ln c_s)$$

$$N_i = \int_{c_{\text{min}}}^{c_{\text{max}}} \frac{1}{\mu} d(\ln c_s)$$

$$N_i = \Delta \rho K_L \int_{c_{\text{min}}}^{c_{\text{max}}} \frac{1}{\mu} d(\ln c_s)$$
Conclusions

Presented an improved analytic model for predicting oil drainage rate during VAPEX

- Modification of the Butler & Mokrys (1989) model
- Use density difference between pure oil and solvent

Investigated the analytic model predictions using numerical simulation

- Numerical model originally validated by comparison with experiments of Alkindi (2009)

- The modified Butler & Mokrys model predicts simulation results for
  - Viscous oils, $M > 1000$
  - Thin reservoirs, $h/L < 1$

- Convective dispersion is not important in VAPEX at high density differences
Discussions and Recommendations

All simulations performed using FCM liquids on the laboratory scale
  • Numerical model assumptions consistent with Butler & Mokrys derivation

Further work is needed to investigate more realistic conditions
  • Field length scales
  • Sub-miscible fluids
  • A vapourised solvent
Acknowledgements

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