Modelling blow-out from a CO$_2$ well

Erik Lindeberg
SINTEF Petroleum Research

Objective

To model multi-phase CO$_2$ flow in a blow-out situation taking into account
- Phase changes occur along the well
- Heat is exchanged between the rock and the flowing CO$_2$
- Accurate modelling of the strong adiabatic cooling due to expansion (while reservoir condition has been simplified)
- Suggest possible experiments that could verify modelling
Application on the Sleipner CO₂ injection well 15/9-A16

Two phase flow at the well head is the typical injection situation.
Basic equations

- **Bernoulli equation:**
  \[
  \frac{dp}{dz} = g \rho \sin \alpha + \rho v \frac{dv}{dz} + f \frac{\rho v^2}{4r}
  \]

- **Energy balance in the fluid:**
  \[
  \frac{dH}{dz} + v \frac{dv}{dz} + g \sin \alpha + \frac{Q}{dm/\,dt} = 0
  \]

- **Heat flow:**
  \[
  Q = KF \tau, \quad F = F(D,t,r)
  \]

- **Combining heat flow and the adiabatic contribution**
  \[
  \frac{d\tau}{dz} = s - \frac{KF \tau}{\left(\frac{dm/\,dt}{c_p}\right)} = s - b \tau, \quad \text{where} \quad b = \frac{K F}{\left(\frac{dm/\,dt}{c_p}\right)}
  \]
  \[
  \tau = \left(\tau_0 - s\right) e^{b dl} + s
  \]

- **Boldizar (1958):**
  \[
  F \approx 4\pi / \ln\left(\frac{4Dt\gamma}{r^2}\right), \quad \gamma = 0.5772.. \quad \text{(Euler's constant)}
  \]
Solution method

- Numerical solution by discretizing the well into length steps (typically < 1000). At each step the flow equation is solved analytically.
- A rate is applied at the perforation and the corresponding pressure is calculated at the well head.
- Phase regimes has to be located to avoid a single step to cross the phase boundary.
- The rate is iteratively altered until the desired blow-out pressure is reached (typically 1 atmosphere).
Well features

Perforation depth: 1092 m (from well head)
Length: 3100 m
Radius: 0.1 m
Adiabatic section: 160 m (platform leg)
Reservoir conditions: 106 bar, 37 °C
Perforation depth: 1092 m (from well head)
Length: 1092 m
Radius: 0.1 m
Adiabatic section: 160 m (platform leg)
Reservoir conditions: 106 bar, 37 °C
Temperature and pressure profiles

- Geothermal gradient
- Deviated well
- Vertical well
Phase diagram for CO₂ in the p and T space

- Triple point
- Critical point
- Melting curve
- Sublimation curve
- Dew point curve

Pressure, bar

Temperature, °C

Solid
Liquid
Gas
p-T path along deviated well

- Pressure, bar
- Temperature, °C
- Solid
- Liquid
- Gas
- Triple point
- Critical point
- Melting curve
- Sublimation curve
- Dew point curve
- Reservoir condition

SINTEF Petroleum Research
Condensed phase fraction in well

- Vertical well
- Deviated well

Depth, m

Mass fraction condensed phase, (liquid or solid CO₂)
CO$_2$ heat capacity, $c_p$, and total density of as function of depth.
CO₂ densities along the well

![Graph showing CO₂ densities along the well depth](image-url)
Solubility of H₂O in CO₂

If CO₂ is saturated at reservoir conditions - free water will be present in the well
Phase diagram for CO$_2$ in the p and T space

- **Triple point**
- **Critical point**
- **Melting curve**
- **Sublimation curve**
- **Dew point curve**
- **Hydrate curve**

**Legend:**
- Solid CO$_2$ ice
- Liquid
- Gas
## Summary of some cases

<table>
<thead>
<tr>
<th>Well</th>
<th>Reservoir conditions</th>
<th>Blow out</th>
<th>Mass rate</th>
<th>Blow out speed</th>
<th>Blow out temp.</th>
<th>Depth sublimation</th>
<th>Depth gas+liquid</th>
<th>Depth hydrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>106</td>
<td>37</td>
<td>Well head</td>
<td>244</td>
<td>1165</td>
<td>-81.2</td>
<td>4.7</td>
<td>671</td>
</tr>
<tr>
<td>Deviated</td>
<td>106</td>
<td>37</td>
<td>Well head</td>
<td>181</td>
<td>935</td>
<td>-79.3</td>
<td>5.8</td>
<td>848</td>
</tr>
<tr>
<td>Vertical</td>
<td>106</td>
<td>37</td>
<td>Sea floor&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>284</td>
<td>183</td>
<td>-45.8</td>
<td>704</td>
<td>428</td>
</tr>
<tr>
<td>Deviated</td>
<td>106</td>
<td>37</td>
<td>Sea floor&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>195</td>
<td>150</td>
<td>-47.5</td>
<td>874</td>
<td>620</td>
</tr>
<tr>
<td>Vertical</td>
<td>130</td>
<td>37</td>
<td>Well head</td>
<td>313</td>
<td>1586</td>
<td>-97.1</td>
<td>3.7</td>
<td>465</td>
</tr>
<tr>
<td>Deviated</td>
<td>130</td>
<td>37</td>
<td>Well head</td>
<td>225</td>
<td>1374</td>
<td>-96.1</td>
<td>26.2</td>
<td>698</td>
</tr>
<tr>
<td>Johansen</td>
<td>220</td>
<td>100</td>
<td>Well head</td>
<td>268</td>
<td>1232</td>
<td>-74.8</td>
<td>2.2</td>
<td>389</td>
</tr>
</tbody>
</table>

<sup>1</sup) Sea depth 82 m giving a blow out pressure of ~ 8.2 bars
p-T path along deviated well “Johansen”

Temperature, °C

Pressure, bar

- Solid
- Liquid
- Gas

- p-T path along well
- Triple point
- Critical point
- Melting curve
- Sublimation curve
- Dew point curve
- Johansen reservoir conditions
Conclusions

- The injection well approaches adiabatic conditions relatively fast, *i.e.* the transient heat effect can then be neglected.
- Stored CO$_2$ will be water saturated (0.01 – 0.02 mole fraction H$_2$O) and solubility will decrease up along the well.
- At clogging due to hydrates (or unlikely dry ice) heat transfer from the rock will melt the plugs and cause the release pulse step release.
- The recent fast CO$_2$ release tests in Germany from a pipe:
  - 10 000 tonne per 10 hours = 278 kg/s are in the range of typical blow-out rate from wells.
  - This test lack the gravity effect.
  - Are approximately adiabatic.
  - This suggest similar tests to be performed on an abounded well.