Hele-Shaw Cell of Varying Thickness for Modeling of Leakage Pathways

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Introduction

- Canada is the fourth largest producer of natural gas
- 98% of the national production of natural gas takes place in the provinces of British Columbia (BC) and Alberta
- A recent study shows that 28.5% of the wells drilled since 2010 in BC have exhibited wellbore leakage

Figure 1: Incidence rate of wellbore leakage in BC [1]
Wellbore leakage

- Unwanted flow of hydrocarbons from the reservoir or other hydrocarbon bearing formations along the wellbore
- Surface casing vent flow (SCVF): leakage occurs through the surface casing vent assembly
- Gas migration (GM): leakage occurs through a permeable formation or pathways intersected by the well

Figure 2: Schematic of wellbore leakage [2]
Leakage pathways

- Wellbore leakage occurs through pathways found in the cement sheath
  - Microannulus
    - at the cement/casing interface (a,b)
    - at the cement/formation interface (f)
  - Cracks (e)
  - Cement sheath (c)
- Microannuli can be created due to
  - Cement shrinkage (dry microannulus)
  - Debonding due to temperature or pressure cycling in the well (dry microannulus)
  - Poor mud displacement during primary cementing (wet microannulus)

Figure 3: Schematic of leakage pathways [3]
Wellbore leakage model

- Generate a representative microannulus using stochastic means
- The microannulus is unwrapped and flow through it can be modeled using the Hele-Shaw flow
- The thickness of the microannulus ($h$) at various points in the cell is obtained by sampling a cumulative distribution function (CDF) using inverse transform sampling

Figure 4: Schematic of an unwrapped section of microannulus
Gamma distribution

- A modified gamma distribution is used to represent the possible values of microannulus thickness
- A gamma distribution has two parameters, the shape parameter $k$ and the scale parameter $\theta$
- A third parameter, the bonding percentage is added to account for the probability of the cement sheath being bonded with the interface (either rock formation or casing). In this case there is no microannulus ($h = 0 \, \mu m$)

\[
MODIFIED\ CDF = B + (1 - B) \left[ \frac{1}{\Gamma(k)} \gamma(k, \frac{x}{\theta}) \right]
\]

Figure 5: Modified CDF for a gamma distribution with parameters $k = 2$, $\theta = 4$, $B = 0.5$
Methodology

- Microannulus thickness \((h)\) is obtained inverse transform sampling of a modified gamma CDF
- If bonding occurs \((h=0 \ \mu m)\), flow has the opportunity to leak through the cement sheath
  - The microannulus thickness is related to the cement permeability \((k)\) through the flow between smooth parallel plate and Darcy’s law
- Flow between two smooth parallel plates: \(Q = -\frac{Wh^3\Delta P}{12\mu L}\)
- Darcy’s law: \(Q = -\frac{kA\Delta P}{\mu L}\)
- Therefore: \(k = \frac{h^2}{12} \rightarrow h = \sqrt{12k}\)
- API recommendation: cement permeability should be below 0.1 mD [4]
  - \(h = 0.0346 \ \mu m\)
- Range of values for microannulus thickness are obtained from the literature and used to determine the distribution parameters
# Dry microannulus - Shrinkage

<table>
<thead>
<tr>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>External shrinkage: 1.2 vol. %, dependence on w/c ratio</td>
<td>Justnes et al. 1995 [5]</td>
</tr>
<tr>
<td>External shrinkage: 2 vol. % (no additives), down to 1 and 0.6-0.7 vol. 5 based on % CaCO3</td>
<td>Justnes et al. 1995 [5]</td>
</tr>
<tr>
<td>1-2% external shrinkage, dependence on w/c ratio</td>
<td>Lyomov 1997 [6]</td>
</tr>
<tr>
<td>Shrinkage increases with decreasing w/c ratio. Varied from 0.7 to 1.2 vol. % (external)</td>
<td>Justnes et al. 1996 [7]</td>
</tr>
<tr>
<td>Early stage of cement setting, massive shrinkage due to water expulsion (dependent on formation property)</td>
<td>Dusseault and Gray 2000 [8]</td>
</tr>
<tr>
<td>Stiffer formation (higher Young’s modulus) leads to a higher possibility of microannulus development (cementing is better if the rock is ductile)</td>
<td>Oyarhossein and Dusseault 2015 [9]</td>
</tr>
<tr>
<td>Higher Young modulus (formation) improves cement’s ability to resist debonding (from)</td>
<td>De Andrade et al. 2015 [10]</td>
</tr>
<tr>
<td>External volumetric shrinkage: less than 1%, no evidence of full microannulus development was found but rather some unbonded surface. 0.5 % bulk shrinkage, retraction of 20 microns for 7 ID and 8.5 OD cement sheath.</td>
<td>Nelson and Guillot 2006 [11]</td>
</tr>
</tbody>
</table>
## Dry microannulus – Temperature and pressure cycling

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<tr>
<td>Mean h: 20 microns, std dev. 4 microns</td>
<td>Lavrov 2018 [12]</td>
</tr>
<tr>
<td>0 to 40 microns</td>
<td>Bois et al. 2011 [13]</td>
</tr>
<tr>
<td>0 to ~20-30 microns, nearly 100% of cases below 50 microns. Large microannulus: 25 microns</td>
<td>Garcia Fernandez et al. 2019 [14]</td>
</tr>
<tr>
<td>100 to 1000 microns (0.1 to 1 mm)</td>
<td>Skorpa and Vralstad 2016, Noor-Corina 2020 [15,16]</td>
</tr>
<tr>
<td>0 to 80 microns at casing-cement interface, 0 to 0.15 microns at cement rock interface</td>
<td>Wise et al. 2020 [17]</td>
</tr>
<tr>
<td>Fracture thickness: 17,20 microns or 25-500 microns</td>
<td>Todorovic 2016 [18]</td>
</tr>
<tr>
<td>Effective aperture of fracture: 12 to 35 microns</td>
<td>Huerta et al. 2009 [21]</td>
</tr>
<tr>
<td>Equivalent microannulus thickness: 8.1 to 12.8 microns based on pipe roughness</td>
<td>Noor-Corina 2020 [16]</td>
</tr>
<tr>
<td>Calculated microannulus: 56 and 65 microns, other sample 13 to 22 microns</td>
<td>Aas 2016 [22]</td>
</tr>
</tbody>
</table>
# Dry microannulus – Bonding percentage

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</thead>
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<tr>
<td>Cement/Casing interface: after temperature cycling, B = 77%, 82%. Cement/rock interface: B = 96%, 99%</td>
<td>De Andrade et al. 2014 [23]</td>
</tr>
<tr>
<td>Debonding at cement/formation interface may be due to large stiffness different between the two material</td>
<td>Wise at. al. 2020 [17]</td>
</tr>
<tr>
<td>B = 10% to 99% depending on rock type and drilling fluid, lower value of B for OBM, then WBM then pristine. 60-70% and 80% for WBM.</td>
<td>Opedal et al. 2014 [24]</td>
</tr>
<tr>
<td>Poor bonding quality in eccentric sections (on the narrow side)</td>
<td>Palacio 2020 [25]</td>
</tr>
<tr>
<td>Interface porosity, various rock type and drilling fluid. Worst with sandstone and WBM, best with sandstone and no mud. Rock and mud type very important. Interface porosity between 0.06% and 1.11% (interface pores volume/total sample volume)</td>
<td>Opedal et al. 2013 [26]</td>
</tr>
<tr>
<td>Higher B for shale than for sandstone, B changes based on number of thermal cycle. B between 97.5 and 96% for sandstone and 99.5 and 98.0% for shale.</td>
<td>De Andrade et al. 2015 [10]</td>
</tr>
<tr>
<td>Pressure cycling: cement/formation interface, no debonding observed, casing/cement, 99.1% bonding after cycling</td>
<td>Skorpa et al. 2018 [27]</td>
</tr>
<tr>
<td>Significant portion of wells are uncemented or have poor bonding (67% total, other 33% has fair, good or excellent bonding)</td>
<td>Waston and Bachu 2009 [28]</td>
</tr>
</tbody>
</table>
Dry microannulus – Distribution parameters

- Gamma distribution
  - mode = \((k - 1)\theta\)
  - mean = \(k\theta\)

<table>
<thead>
<tr>
<th>Type of microannulus</th>
<th>Mode [(\mu m)]</th>
<th>Mean [(\mu m)]</th>
<th>Bonding %</th>
<th>(k)</th>
<th>(\theta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debonding (temperature and pressure cycling)</td>
<td>20</td>
<td>40</td>
<td>50</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>0.5% -&gt; 41.7</td>
<td>1% -&gt; 83.6</td>
<td>30</td>
<td>1.995</td>
<td>41.9</td>
</tr>
</tbody>
</table>
Dry microannulus – Sampling rate

- On the physical mesh, how many times should the CDF be sampled to find the value of microannulus thickness?
- Magnitude of changes in the vertical direction are much less important than in the azimuthal direction.

Figure 6: Acoustic impedance maps of a well section. Adapted from [25]
Results - Example 1

- Dry Microannulus caused by temperature and pressure cycling
- Surface Casing of 244 mm outer diameter
- 4m long well section
- Pressure gradient: 2 kPa/m
- Parameter distribution
  - \( k = 2 \)
  - \( \Theta = 20 \)
  - \( B = 50\% \)
- Sampling points
  - In x direction: 10
  - In y direction: 5

Figure 7: Microannulus of varying thickness
Figure 8: Microannulus of varying thickness and contour of pressure drop along the length of the microannulus
Results - Example 2

- Dry Microannulus caused by temperature and pressure cycling
- Surface Casing of 244 mm outer diameter
- 4m long well section
- Pressure gradient: 2 kPa/m
- Parameter distribution
  - $k = 2$
  - $\Theta = 20$
  - $B = 50\%$
- Sampling points
  - In x direction: 10
  - In y direction: 5

Figure 9: Microannulus of varying thickness
Figure 10: Microannulus of varying thickness and contour of pressure drop along the length of the microannulus
Results - Example 3

- Dry Microannulus caused by cement shrinkage
- Surface Casing of 244 mm outer diameter
- 4m long well section
- Pressure gradient: 2 kPa/m
- Parameter distribution
  - $k = 1.995$
  - $\Theta = 41.9$
  - $B = 30\%$

Sampling points
- In x direction: 10
- In y direction: 5

Figure 11: Microannulus of varying thickness

Figure 12: Microannulus of varying thickness and contour of pressure drop along the length of the microannulus
Results - Example 4

- Dry Microannulus caused by cement shrinkage
- Surface Casing of 244 mm outer diameter
- 4m long well section
- Pressure gradient: 2 kPa/m
- Parameter distribution
  - $k = 1.995$
  - $\Theta = 41.9$
  - $B = 30\%$
- Sampling points
  - In x direction: 10
  - In y direction: 5

Figure 13: Microannulus of varying thickness
Figure 14: Microannulus of varying thickness and contour of pressure drop along the length of the microannulus
Summary and future work

• Short microannulus section were generated using a gamma distribution
  – Pressure drop across the section is presented

• What is the effect of varying various parameter on the effective permeability?

• Leakage pathways: wet microannulus
  – Flow through dehydrated mud

• Leakage pathways: Cracks
Thank you!
Questions/Comments?
References


References


References


