Relative Permeability for Water and Gas through Fractured Cement

Presented by:
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Acknowledgments

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• Tamas Varga, XCT imaging
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Relative permeability through fractured cement

• Motivation
  • A well’s cemented annulus represents a significant leakage risk
  • Multiphase flow up a fractured interface is nonlinear and subject to local conditions

• Previous work
  • Relative permeability, originally developed for porous media, is the dominant model used to describe multiphase flow
  • Relative permeability of fractures has developed for rock or artificial surfaces (brick, glass plates) but not cement!

• Our approach
  • Fractured cement cores in laboratory
  • Measured absolute and relative permeability of salt water and air through fractures
  • Injected a tracer to characterize dispersion through the fracture

• Are existing models sufficient to estimate leak rates?
Relative permeability for fractured media is variable and dependent on media

• Summary of data, figure from:
  • Huo and Benson, 2016, Transport in Porous Media 113: 567-590
    • DOI 10.1007/s11242-016-0713-z

• Each color is a relative permeability curve for fractured geo-media

• Graph on right are data which are not represented by standard models
Fractures generated with shear force in hydraulic press

- Ordinary Portland Cement was cured for 28 days at 100% relative humidity; cement cores were shrink wrapped
- Offset metal plates were positioned at the top and bottom of cores; force was applied (~150 lbf.) until a shear fracture occurred
  - Produced heterogeneous natural fracture with connected pore
- Second core was offset and failed twice
  - Generated a complex heterogeneous fracture network
Stainless steel end caps fixed to each end of core

- Cement samples housed within
  - Stainless steel end caps fitted with pressure ports
  - Shrink wrap and ring clamps
- Water and air injected across the inlet surface through separate ports
- Fluid exits through single outlet port (phases separated in effluent line)
- Resistivity measured across the cement with electrodes attached to the end caps
  - Resistivity calibration check with water saturation for each experiment
Multiple measurements were taken made at steady state

- Pumps supplied air pressure through precision flow controllers to:
  1. Core directly (air)
  2. Reservoir (supplied constant water pressure to core)
- Water used = 0.1 M NaNO$_3$
- Gas used = air
- Beaker on scale used as a phase separator for effluent
- Data:
  - Air effluent: flow monitor
  - Water effluent: Change in mass (scale) and time
  - Water saturation: resistivity across core
Absolute permeability was calculated using Reynolds equation

- Effective aperture (b) calculated using water saturated flow discharge data

\[ Q = \frac{W b^3}{12 \mu} \left( \frac{P_i - P_o}{L} \right) \]

- Effective absolute permeability calculated using established relationship between aperture and permeability

\[ k_i = \frac{b^2}{12} \]

- Effective aperture for multiple fracture monolith 1.3 x simple fracture monolith

<table>
<thead>
<tr>
<th>Monolith</th>
<th>Aperture (cm)</th>
<th>( k_i ) (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>simple fracture</td>
<td>0.0153</td>
<td>1.94 x 10⁻⁵</td>
</tr>
<tr>
<td>multiple fracture</td>
<td>0.0206</td>
<td>3.54 x 10⁻⁵</td>
</tr>
</tbody>
</table>
Fractures in cores were characterized with XCT

- X-ray Computed Tomography (XCT) was used to characterize the fractures
- For simple fracture, used image (image a) to measure fracture width (W)
- Core dimensions:
  - Diameter = 5.08 cm
  - Length = 10 cm
- Data from the single fracture core (left) was used to generate a computer segmented fracture model
Fracture segmentation of data from XCT used to model aperture size distribution

- Aperture size range from 150 to 800 µm
- Heterogeneous distribution of fracture aperture thickness

- Note:
  - Aperture used to develop gamma function for Brooks-Corey/Burdine model
Models used included X-curve, Corey curve, and Brooks-Corey curve

**X-curve**
- Relative water permeability ($k_{rw}$)
- Relative gas permeability ($k_{rg}$)
  - $S_e =$ effective water saturation

**Corey curve**
- Relative water permeability
- Relative gas permeability

**Brooks-Corey model (Burdine)**
- Relative water permeability
- Relative gas permeability
  - $\lambda =$ characterization of pore-size distribution from pore size data

\[

k_{rw} = S_e \\
k_{rg} = (1 - S_e)
\]
\[

k_{rw} = S_e^4 \\
k_{rg} = (1 - S_e)^2 \cdot (1 - S_e^2)
\]
\[

k_{rw} = (S_e)^{\frac{2+3\lambda}{\lambda}} = (S_e)^e \\
k_{rg} = (1 - S_e)^2 \left(1 - S_e^{\frac{2+\lambda}{\lambda}}\right)
\]
Relative permeability curves: X, Corey, Brooks-Corey

• X-curve
  • Idealized fracture flow
  • One phase replaces the other

• Corey curve
  • Phase interference occurs

• Brooks-Corey curve (Burdine)
  • Similar to Corey curve but accounts for pore size distribution

• Note:
  • No adjustment for irreducible water or trapped air for these plots
Relative permeability was calculated using modified Darcy’s equation

- Modified Darcy’s equation from Scheidegger 1974.
  - From *The Physics of Flow through Porous Media*, 3rd ed., University of Toronto

- Solved for relative permeability of water and gas

- Calculation for relative permeability of gas reduces influence of compressibility on $k_{rg}$

\[
Q = \frac{k_i k_{rw} A}{\mu_w} \left( \frac{P_i - P_o}{L} \right)
\]

\[
Q = \frac{k_i k_{rg} A}{\mu_g} \left( \frac{P_i^2 - P_o^2}{LP_o} \right)
\]

- $Q =$ discharge (cm$^3$ s$^{-1}$)
- $k_i =$ absolute permeability (cm$^2$)
- $k_{rw} =$ relative permeability water (cm$^2$)
- $k_{rg} =$ relative permeability gas (cm$^2$)
- $A =$ fracture area (cm$^2$)
- $\mu_w =$ water viscosity (Pa·s)
- $\mu_g =$ gas viscosity (Pa·s)
- $P_i =$ pressure at inlet (Pa)
- $P_o =$ pressure at outlet (Pa)
- $L =$ length (cm)
Phase interference is evident in relative permeability data

• Plot of simple fracture core relative permeability
  • Water phase flow is reduced and has a Corey curve like pattern
  • Air phase is less impacted by multiphase flow
single fracture adjusted for irreducible water fits <80% sat

- $k_r$ fit is slightly improved using Brooks-Corey compared to Corey
- Fit is best <80% effective water saturation
- Brooks-Corey and Corey under predict water flow when >80% effective saturation
$k_f$ single fracture adjusted for irreducible water and trapped air fits $>80\%$ sat

- $k_f$ fit is slightly improved using Brooks-Corey compared to Corey
- Fit is best $>80\%$ effective water saturation
- Brooks-Corey and Corey over predict water flow when $<80\%$ effective saturation
$k_r$ multiple fracture adjusted for irreducible water fits closer to X-curve

- $k_{rw}$ fits between Corey curve and X-curve
- $k_{rg}$ fits X-curve
- Larger and more complex fracture network reduces phase interference of flow
Small changes (drop) in air pressure can alter the $k_{rw}$ pattern to linear

- Pressure differential in the $k_r$ experiments ranged 100-200 kPa
- Small reductions in air pressure (<50 kPa) reduced air flow to zero producing unsaturated single phase flow
- Orientation for unsaturated flow was changed to vertical (top to bottom flow)
- Calculated $k_{rw}$ becomes linear
Relative permeability of simple fracture migrates from X-curve to Corey curve

• Plot of $k_{rg}$ versus $k_{rw}$

• As saturation decreases, simple fracture monolith changes to X-curve dominant to Corey curve dominant

• Multiple complex fracture remains most similar to X-curve
Dispersivity was investigated through the fracture

- A coil with multiple 3-way valves was inserted between the water reservoir and the simple fracture core
- Coil filled with 0.4 M KBr tracer
- Effluent line emptied to a fraction collector
- Fractions were collected during three tests
  - Water saturated
  - 80% water saturated
  - 66% water saturated
- Water analyzed for Br concentration
Dispersion decreased at lower saturation for simple fracture core

- Data was analyzed with CXTFit (Advection Dispersion Equation)
- Equilibrium CDE model
- Dispersion decreased at lower saturation
  - Water likely flowing in narrower range of pore sizes

<table>
<thead>
<tr>
<th>Fracture Saturation</th>
<th>Velocity (v; cm s(^{-1}))</th>
<th>Dispersion Coefficient (D; cm(^2) s(^{-1}))</th>
<th>Retardation Coefficient (R; dimensionless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated</td>
<td>1.6</td>
<td>3.7</td>
<td>1</td>
</tr>
<tr>
<td>80%</td>
<td>1.0</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>66%</td>
<td>0.5</td>
<td>0.9</td>
<td>1</td>
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</tbody>
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Conclusions and path forward

• Conclusions
  • Relative permeability of a cement fracture aperture 0.2 to 0.5 mm is crossover point of Corey-curve to X-curve
  • X-curve is limited in its utility to model cement relative permeability
  • Cement fracture aperture size and complexity influences which relative permeability model is most valid
  • Changes in sample orientation and small changes of air pressure can result in a dramatic change in measured relative permeability pattern
  • Using measured aperture for Brooks-Corey/Burdine model yields nominal improvement to curve fit compared to Corey

• Experimental avenues
  • Relative permeability change before and after fracture heal in a CO₂ rich system
  • Permeability change in a dynamic, flowing, CO₂ rich system
  • CO₂ heal effect on permeability between cement and casing and cement and rock