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Frac Model Calibration for Conventional and Unconventional Rocks

Leen Weijers
Outline

• Introduction
• Why Model?
• 1\textsuperscript{st} Calibration Cycle – Pressure Qualification
• 2\textsuperscript{nd} Calibration Cycle – Net Pressure Matching
• 3\textsuperscript{rd} Calibration Cycle – Fracture Mapping
• Frac Model Calibration Case Histories
• Conclusions
Conventional vs Shale Frac’ing

- 1947 – present
- Higher permeability sand – Moving the hydrocarbon molecule to the frac
- Vertical wells, mostly single stages
- Focus on conductivity

Diagram:
- Sand: 0.1 – 1,000 mD
- Shale: High pressure and temperature cook kerogen
Conventional vs Shale Frac’ing

- 1947 – present
- Higher permeability sand – Moving the hydrocarbon molecule to the frac
- Vertical wells, mostly single stages
- Focus on conductivity

- ~2000 – present
- Low permeability shale – Bringing the frac to the hydrocarbon molecule
- Multi-stage horizontal wells
- Focus on complexity – “2 miles of plumbing”
Why Model Hydraulic Fracs?

- Tier 1: “Get the job away”
- Tier 2: Optimize production economics

How?
- Improve proppant placement
- Improve well-to-fracture connectivity
- Height coverage optimization
- Conductivity vs half-length / complexity trade-offs ($F_{CD}$)
Why Model Hydraulic Fracs? Optimize Frac Dimensions

Simplified Design Metric:
Dimensionless Fracture Conductivity

\[ F_{cD} = \frac{k_f w}{k L_f} \]

= "Fracture Throughput" / "Reservoir Deliverability" = "Traffic Throughput" / "Traffic Inflow"

\( k_f w \): Fracture Conductivity, mD ft
\( k \): Formation Permeability, mD
\( L_f \): Fracture Half-Length, ft
Why Model Hydraulic Fracs? Optimize Frac Dimensions

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\[ L_f : \text{Fracture Half-Length, ft} \]
Using Indirect Measurements to Determine Dimensions

Injected Volume
Balloon Elasticity
Net Pressure $P_{net}$

Radius R

Injected Volume, Efficiency
Layer Rock Properties
Net Pressure $p_{net}$

Length L,
Height H,
Width w
Hydraulic Fracture Propagation – Physical Processes

- **Viscous fluid flow**
- **Fluid leakoff**
- **Elastic deformation**
- **Fracture propagation**
- **Proppant transport**

**Key relationships**

- (Darcy’s Law)
- (Mass balance)
- (Sneddon equation)
Fracture Modeling Evolution

Modeling without Real-Data Feedback

- Early designs (pre-1980) did not incorporate feedback from real data
- Frac modelers thought fracs would mostly stay in zone

Use predicted net pressure
Fracture Modeling Evolution

The 1st Model Calibration Cycle – Pressure Qualification

- Early designs (pre-1980) did not incorporate feedback from real data
- Frac modelers thought fracs would mostly stay in zone
- Observed net pressure trends could be evaluated

- Nolte (1979) linked net pressure progression over time to fracture growth modes
  - Mode I represents desirable in-zone growth

<table>
<thead>
<tr>
<th>Growth Mode</th>
<th>Description</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>No height growth</td>
<td>1/5</td>
</tr>
<tr>
<td>II</td>
<td>Height growth / fissure opening</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>Tip screen-out</td>
<td>1</td>
</tr>
<tr>
<td>IV</td>
<td>Unrestricted height growth</td>
<td>Negative</td>
</tr>
</tbody>
</table>

Nolte net pressure behaviors

Nolte growth modes
Fracture Modeling Evolution

The 2\textsuperscript{nd} Model Calibration Cycle – Net Pressure Matching

- Early designs (pre-1980) did not incorporate feedback from real data
- Frac modelers thought fracs would mostly stay in zone
- However, measured net pressure generally MUCH higher than model net pressure

![Graph showing measured and predicted net pressures with pump time and pump rate axes. The graph illustrates the difference between predicted and measured net pressures, emphasizing the need for accurate model calibration.](image-url)
Fracture Modeling Evolution

The 2nd Model Calibration Cycle – Net Pressure Matching

• Net pressure history match can be obtained by incorporating new physics into fracture models
  - Multiple fractures, tip effects
• With the right physics, inferred geometry has a better chance to be correct

Use measured net pressure with model net pressure

Matching measured net pressure with model net pressure
Multiple Fractures and Tip Effects

- Shlyapobersky et al. (1992, 1998) first observed **process zone**
  - Fluid lag region
  - Cohesive zone ("bridging")
  - Plastic deformation
  - Opening of micro-fractures

- Multiple fractures first observed in minebacks / core throughs by Warpinski & Teufel (1984)
  - Multiple initiation points
  - Bifurcation
  - Complexities at fracture tip
Fracture Modeling Evolution

The 3rd Model Calibration Cycle – Fracture Mapping

• Net pressure history matching can be implemented by adding new physics to fracture models
• With the RIGHT physics, inferred geometry has a better chance to be correct
• However, pressure matching-inferred geometry often less confined

Use measured net pressure

Matching measured net pressure with model net pressure

Net pressure

Pump time

Wellbore

Pay
Fracture Modeling Evolution

The 3\textsuperscript{rd} Model Calibration Cycle – Fracture Mapping

- Change physical mechanisms in model to match BOTH net pressure and directly observed fracture geometry
  - Layer interface effects
- Obtained a predictive tool that is firmly linked to actual growth behavior

Use measured net pressure AND measured geometry
## Composite Layering / Width Decoupling

- Several researchers (Cleary 1980; Nolte and Smith 1981; Warpinski and Teufel 1984) speculated about additional confinement mechanisms observed in minebacks.
- Not incorporated in initial models.

<table>
<thead>
<tr>
<th>Increased fracture closure stress</th>
<th>Interface slippage</th>
<th>Composite layering</th>
</tr>
</thead>
</table>

**Confinement Mechanisms**

**Composite Layering Effect**
Case Study 1: Calibration w/ Pressure Data
Case Study 1: Calibration w/ Pressure & Micro-Seismic Data
Case Study 2: Calibration Critical for Well Spacing

Frac Model matches Microseismic Geometry

Propped Fracture Height

Frac Model Calibration

Spacing Scenario Evaluation

Economic Optimization

Optimum 1,900 – 2,300 ft

Li et al. 2017 (SPE paper 184848)
Calibration: Modeling and Measuring

Fracture Growth Models
Predictive
Incomplete Physical Understanding

Direct Diagnostics
Not Predictive
Reflected Physical Behavior

Calibrated models more realistically predict how fractures will grow for alternative designs
Fracture Propagation Models for the Future...

- 2D models
  - Perkins, Kern and Nordgren (PKN)
  - Khristianovitch, Geertsma and De Klerk (KGD)
  - Radial Model
- 3D models
  - Pseudo-3D models
  - Back-of-the-envelope models
  - Parameterized 3D models
  - Full 3D models
- Non-planar models
- Complex models
- Fully-coupled models
Complex Fracture Models: New Paradigm?

• Ideal work flow:
  – Characterize natural fracture network
  – Calibrate fracture properties from observed fracture network
  – Use calibrated model to design treatments in offset wells

• Practical application:
  – Match observed pressure, by modifying natural fracture network parameters
  – Result: “Garbage In = Garbage Out”

• Paradigm shift is hampered by a rational limitation: lack of data to populate geologically realistic models

Hydro-Frac interacts With Natural Fractures

Fractures from Micro-Seismic Data

Sophisticated Fracture Networks From Geological Characterization
Balancing Frac Models with Diagnostics

“It is Better to be Roughly Right than Precisely Wrong”, John Maynard Keynes

“Precisely Wrong”

Frac Model “Sophistication”

“Roughly Right”

Calibration Data “Quality / Intensity”

2D Frac Models

Fluid Test
Leakoff

Logs

Mechanical

Core Tests

Net Pressure

Flowing Core Tests

Out-of-Zone Stress Tests

Far-Field Frac Diagnostics

Interface Measurements

Wellbore Diagnostics

Gridded-3D
Frac Models

Parameterized-3D
Frac Models

Power-Law
Frac Model

Complex
Frac Models

Coupled
Frac Models

Pseudo-3D
Frac Models

“Back-of-the-Envelope”
Model

25
Conclusions

• Our industry has gone through a revolution, enabling economic frac designs in rocks with ~8 orders-of-magnitude change in permeability.

• The role of calibration in fracture propagation models is critical for value-creation.
  - Frac models have become practical tools through calibration.
  - Calibration is straightforward and cost-effective.

• “New” physical mechanisms reflect improved understanding.
  - Multiple fractures, tip effects and composite layering effects.

• Model sophistication should be matched with calibration quality.
  - Planar frac model paradigm remains valid.
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