Quantitative Analysis of HFTS-2 Completion Designs Using Cross-well Strain Measurements

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HFTS 2

- A DOE-funded project to improve the understanding of hydraulic fractures and enhance productivity
- 3 permanent fibers installed – 2 horizontal and 1 vertical fiber
- 4 Horizontal wells were stimulated sequentially
- Presence of parent well depletion

https://www.osti.gov/servlets/purl/1855739a
### Completion Designs

- 11 completion designs without considering phasing angles
- 8 designs with sufficient implemented stages

<table>
<thead>
<tr>
<th>Design (CxP)</th>
<th>PPC</th>
<th>Perf Taper Design</th>
<th>PC spacing (ft)</th>
<th>Stage length (ft)</th>
<th>Proppant per cluster, bls</th>
<th>Fluid per cluster, bbls</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 x 24 (base line)</td>
<td>4</td>
<td>None</td>
<td>32</td>
<td>190</td>
<td>84,025</td>
<td>1,859</td>
</tr>
<tr>
<td>6 x 18</td>
<td>3</td>
<td>None</td>
<td>31</td>
<td>190</td>
<td>84,273</td>
<td>1,883</td>
</tr>
<tr>
<td>6 x 15</td>
<td>2.5</td>
<td>2H,3T</td>
<td>31</td>
<td>190</td>
<td>84,145</td>
<td>1,874</td>
</tr>
<tr>
<td>6 x 12</td>
<td>2</td>
<td>None</td>
<td>33</td>
<td>195</td>
<td>60,007</td>
<td>890</td>
</tr>
<tr>
<td>9 x 18</td>
<td>2</td>
<td>1H,2M,3T</td>
<td>32</td>
<td>290</td>
<td>84,151</td>
<td>1,904</td>
</tr>
<tr>
<td>10 x 15</td>
<td>1.5</td>
<td>1H,2T</td>
<td>31</td>
<td>311</td>
<td>79,367</td>
<td>1,749</td>
</tr>
<tr>
<td>10 x 20</td>
<td>2</td>
<td>None</td>
<td>32</td>
<td>317</td>
<td>78,410</td>
<td>1,779</td>
</tr>
<tr>
<td>12 x 24</td>
<td>2</td>
<td>None</td>
<td>12/16</td>
<td>140/190</td>
<td>37,971</td>
<td>825</td>
</tr>
</tbody>
</table>
Primary Objectives of HFTS 2

Evaluate and identify the key drivers impacting Stimulation Distribution Effectiveness (SDE)

- Normal Stage Length (NSL) vs. Extended Stage Length (ESL)
  - 6 clusters vs. 9/10 clusters
- Increasing Aggressive Limited Entry (ALE) by reducing the number of perforations per cluster
  - 6 clusters: 4 → 3 → 2.5 → 2
  - 9/10 clusters: 2 → 1.5
- Tapered perforation configurations to mitigate fluid heel-ward bias
  - Uniform perf. number per cluster vs. more perf. at the toe side
Objectives

Gap:
LF-DAS based cross-well analysis has been primarily restricted to qualitative interpretations

Our objectives:
• Quantify fracture width using a novel Green’s function-based inversion algorithm
• Diagnose the impact of stage lengths, aggressive limit entry and tapered configurations and give a recommendation for optimal completion designs
Summary of Stages

Approximately 120 stages spanning 4 treatment-monitoring well pairs

Analysis Order:
1. B4H → B3H
2. B1H → B4H
3. B2H → B3H
4. B2H → B4H
Low-frequency strain recorded at the monitoring well is inverted to obtain the width of fractures at the monitoring well location.
Attributes in the Far Field

Fracture Unevenness (Frac UE) from cross-well strain

\[
\text{Frac UE} = \frac{\text{Deviation}}{\text{Mean}} = 100 \times \left( \frac{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}}{n - 1} \right) \left( \frac{\sum_{i=1}^{n} x_i}{n} \right)
\]

\(X_i\) is the maximum fracture width of each frac hit at the monitoring well.

The larger the Frac UE, the more non-uniform distribution of fracture width.

- **Width Density**: Total maximum fracture width / stage length
- **Frac Density**: Number of fracture hits per stage / stage length
Fracture Unevenness (Frac UE): Describes the number of fractures compared to the number of clusters per stage (Frac Efficiency) and the uniformity of the maximum fracture widths.

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 3</th>
<th>Stage 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>No frac hit</td>
<td>No frac hit</td>
<td>Better Frac UE</td>
</tr>
</tbody>
</table>
Uniformity Index in the Near Wellbore

Cluster efficiency
In-well DAS measurement: Calculate In-well Unevenness based on fluid distribution across targeted perforation clusters.

DAS Acoustic In-well Measurement

Fluid Distribution per Cluster

In-well Unevenness = (100 – Uniformity Index)

- Where the Uniformity Index = 100*(1 - \(\frac{\text{Deviation}}{\text{Mean}}\))
Normal and Extended Length Design

- More uneven fracture growth associated with ESL designs
- More non-uniform fluid allocation associated with ESL designs

Cross-well Fracture Unevenness

- B4H fracturing $\rightarrow$ B3H monitoring

In-well Unevenness
(100 – Uniformity Index)
Taper Designs

• Taper design does not provide more even fracture growth for NSL designs

• Taper design does not provide more uniform fluid allocation for NSL designs

• B4H fracturing → B3H monitoring
Taper Designs

Cross-well Fracture Unevenness

- Taper design provides more even fracture growth for ESL designs
- Taper design provides more uniform fluid allocation for ESL designs

B4H fracturing → B3H monitoring

In-well Unevenness (100 - Uniformity Index)

- Better performance with Taper design
- 9/10 cluster designs show better performance compared to 6 cluster designs

None

Yes

Better performance
Cross-well Design Analysis

- Similar Width Density and Frac Density observed in parent well and non-parent well zone
- Increased Frac UE observed with the application of 12 x 24 design

- B1H fracturing → B4H monitoring
- 6 x 24 Base design and 12 x 24 reduced cluster spacing

B1H → B4H Attribute Results

- Depletion vs. No depletion
- Frac Uneveness
- Wall Density (mm/ft)
- Frac Density (num Fracs/ft)

Stage number

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
Cross-well Design Analysis

- B1H fracturing → B4H monitoring

Zone of no parent well depletion

6 x 24 Base Design and 12 x 24 reduced cluster spacing

- Same Width Density and Frac Density achieved with both designs
Cross-well Design Analysis

- B1H fracturing → B4H monitoring

**Zone of parent well depletion**

6 x 24 Base Design and 12 x 24 reduced cluster spacing

- Same Width Density and Frac Density achieved with both designs
Aggressive Limit Entry

1. No noticeable improvement associated with tapered design and aggressive limit entry for 6 clusters per stage (NSL)
2. Noticeable Improvement associated with aggressive limit entry and tapered design for 10 clusters per stage (ESL)

Zone of no parent well depletion

Map View

Better performance

Without depletion

B1H B3H B4H B2H

Design (cluster x perf)

Frac Unevenness

Reduced CS

Tapered

Increasing ALE

12 x 24 6 x 24 6 x 15 6 x 18 10 x 15 10 x 20 9 x 18
Aggressive Limit Entry

1. No noticeable improvement associated with tapered design and aggressive limit entry for 6 clusters per stage (NSL)
2. Noticeable Improvement associated with aggressive limit entry and tapered design for 10 clusters per stage (ESL)

Zone of parent well depletion

Map View

Better performance

With depletion

B1H  B2H  B4H  B3H
Completion Design Optimization

- Non-depletion zone, well spacing of 660 ft, and same cluster spacing
- The 6 x 24 (Base) and 9 x 18 (Tapered) designs achieve:
  - More even fracture growth
  - More fracture width per ft
  - More fractures per ft
Conclusions

Through our quantitative cross-well LF-DAS analysis we identified:

- Consistency between our in-well and cross-well evaluation, demonstrating the correlation between far-field fracture development and in-well stimulation distribution effectiveness.
- Extended Length designs benefit from more Aggressive Limited Entry and Tapered practices across all treatment-monitoring well pairs.
- Optimal performance was achieved with 6 x 24 (Base) and 9 x 18 (Tapered) designs.

The application of quantitative cross-well based analysis enables:

- Reduced surveillance cost by monitoring multiple well completions with a single fiber.
- Avoid logistical challenges associated with permanent fiber-optic surveillance installations within the treatment well.
- Temporary wireline fiber deployments to evaluate completion design programs.
Acknowledgement

The authors would like to acknowledge the Advanced Geomechanics Fracture & Reservoir Application Consortium (AGFRAC) at Texas A&M University for providing tools to conduct this research work.
Thank you!
Solve fracture width using measured strain

- Strain at point \(j\) induced by fracture \(i\)

\[
\epsilon^i_j(x_{sj}, y_{sj}, z_{sj}) = G(x_{sj} - x_{fi}, y_{sj} - y_{fi}, z_{sj} - z_{fi}) w_i
\]

- Assume linear-elastic rock deformation

\[
\epsilon_j(x_{sj}, y_{sj}, z_{sj}) = \sum_{i=1}^{N} G(x_{sj} - x_{fi}, y_{sj} - y_{fi}, z_{sj} - z_{fi}) w_i
\]

- System of equations

\[
Gw = \epsilon
\]

\[
\begin{bmatrix}
G_{11} & \cdots & G_{1i} & \cdots & G_{1N} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
G_{ji} & \cdots & G_{ji} & \cdots & G_{jN} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
G_{Mi} & \cdots & G_{Mi} & \cdots & G_{MN}
\end{bmatrix}
\begin{bmatrix}
w_1 \\
\vdots \\
w_i \\
\vdots \\
w_N
\end{bmatrix}
= 
\begin{bmatrix}
\epsilon_1 \\
\vdots \\
\epsilon_j \\
\vdots \\
\epsilon_M
\end{bmatrix}
\]
