Effects on Brittleness of Temperature Difference Between Hydraulic Fracturing Fluid and Shale Formation – Study on Woodford Shale*

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Search and Discovery Article #50878 (2013)**
Posted October 31, 2013

*Adapted from poster presentation given at AAPG 2013 Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013
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Abstract

Objectives: A newly derived fully coupled thermo-hydro-geomechanics one-dimensional simulation is used to study the time-dependent evolution of the fracture aperture during hydraulic fracturing of the anisotropic Woodford Shale. The study aims at quantifying the effects of the spacing of natural fractures and the temperature gradient between the hotter reservoir rock and the colder fracturing fluid on the efficiency of the fracture job. The results can then be used to optimize hydraulic fracturing design for the shale reservoir.

Procedures: It has been observed during geological characterization that many natural fractures exist in the Woodford Shale and they are roughly vertical. During the hydraulic fracturing operation, they may reactivate and join to form fractures with almost parallel branches. Due to the large vertical and lateral extent of the hydraulic fracture, a section sufficiently far from the wellbore, fracture tips, and fracture joints can be modeled using the 1D solution.

Results: It was found that with an average natural fracture spacing of 1.2m, a fracturing fluid with the same temperature as the reservoir rock would create a nominal fracture aperture of 0.84 mm. Furthermore, this fracture will gradually closes due to shale swelling from the fracturing fluid invasion into the formation so proppant transport will gradually degrade. On the other hand, with a fracturing fluid 60°C colder than the rock formation, the fracture will gradually widen due to shale contraction as the cold front penetrates into the formation. At the end of the pumping, the aperture with the colder fracturing fluid is approximately 70% larger than that created with the hotter fluid. It was also found that the fracture aperture monotonically increases with increasing natural fracture spacing.

Conclusions: It is noted that while a wider fracture aperture promotes proppant transport, it requires more fracturing fluid volume to fill the same fracture length. In other words, the same pumped fluid volume will create a shorter hydraulic fracture and the impression of a less brittle formation. Therefore, it is crucial that the natural fracture spacing is taken as an input in the design of hydraulic fracturing jobs. Furthermore,
based on the proppant size and transport characteristics, the temperature of the fracturing fluid must be controlled to optimize both proppant transport and fracturing efficiency.
A newly-derived fully-coupled thermo-hydro-geomechanics one-dimensional simulation is used to study the time-dependent evolution of the fracture width during hydraulic fracturing of the anisotropic Woodford Shale. The study aims at quantifying the effects of the spacing of natural fractures and the temperature gradient between the hotter reservoir rock and the colder fracturing fluid on the efficiency of the fracture job. The results can then be used to optimize hydraulic fracturing design for the shale reservoir.

**Abstract**

**Understanding Brittleness**

**Overview of Woodford Shale**

**Figure 1.** Gas and oil shale plays of the United States (Source: EIA).

**Figure 2.** Number of Woodford Shale wells in Oklahoma (Cardott 2012).

**Figure 3.** Gas and oil production of Woodford Shale. (Cardott 2012).

**Figure 4.** Glass, easy to propagate fractures.

**Figure 5.** Tire, hard to propagate fractures.

**Figure 6.** Perception of brittleness of rock.

**Early attempts to characterize brittleness – Brittleness Index**

\[
\text{BI} = \frac{\text{Quartz} + \text{Dolomite}}{\text{Quartz} + \text{Dolomite} + \text{Calcite} + \text{Clays} + \text{TOC}}
\]

**Figure 7.** Mineralogical interpretation (Wang and Gale 2009), easy for log-based implementation, but is not based on geomechanics

\[
\text{BI} = \frac{1}{2} \left( \frac{E-1}{8-1} + \frac{v-0.4}{0.15-0.4} \right) \times 100\%
\]

**Figure 8.** Empirical interpretation on Barnett Shale (Rickman et al. 2008), easy for log-based implementation, but is not based on geomechanics

\[
\text{BI} = \frac{\text{reversible energy (W_reversible)}}{\text{total energy (W_total)}} \times \frac{\text{Area DCE}}{\text{Area OABCE}}
\]

**Figure 9.** Mechanics interpretation (Hucka and Das 1974), but requires cores and lab testing

**Figure 10.** Fracture width and length formula based on isotropic elasticity (Perkins & Kern 1961 and Nordgren 1972). Young’s modulus and Poisson’s ratio influence the brittleness of the rock by controlling the width and length of hydraulic fractures. But effects of $E$ are much stronger than $v$, they should not be lumped together as in previous approaches.

\[
W = \left(1 - \frac{2}{E} \right) \frac{h_f}{E} \left( P_{frac} - S_{min} \right)
\]

\[
L = 0.68 \left[ \frac{E Q^3}{\mu (1-v^2) h_f^4} \right]^{1/5}
\]

**What about anisotropy?**

**Figure 11.** Abaqus simulation shows that fracture width is mainly controlled by Young’s modulus $E_1$ in the lamination direction (Tran et al. 2012).

Does temperature difference between fracturing fluid and shale formation influence brittleness too???
Mechanical Anisotropy of Woodford Shale

Natural Fractures

Figure 12. Location of the Wyche Quarry and the drilled well (Google Map).

Figure 13. Natural fractures in the Woodford Shale are almost vertical, with an average distance of 1.2 m between fractures (Portas 2009).

Figure 14. At smaller scales, there are also extensive natural vertical fractures in chert beds between shale layers (Slatt and Abousleiman 2011).

Table 1. Measured acoustic velocities confirm the anisotropy of Woodford Shale (Tran 2010).

Table 2. Engineering poroelastic moduli from UPV analysis show the anisotropy in Woodford Shale (Tran 2010).

Figure 15. SEM study shows little preferred orientation of clay pallets in Woodford Shale. However, thin section study reveals the laminated nature of Woodford Shale. Schematic model for Young’s moduli $E_1$ in lamination direction and $E_3$ in transverse direction for a composite of homogeneous isotropic layers. Using Cauchy’s inequality it can be shown that $E_1$ is always greater than or equal to $E_3$; $E_1$ is equal to $E_3$ if and only if all layers are the same.

Figure 16. Ultrasonic Pulse Velocity (UPV) setup (Abousleiman et al. 2007).
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Model for Hydraulic Fracturing

Figure 17. Branching of hydraulic fractures due to the existence of natural fractures.

Figure 18. Anisotropic thermo-hydro-geomechanics model for a section of the multi-branch hydraulic fracturing pattern.

Table 3. Properties of the Woodford Shale used in simulation.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.19</td>
</tr>
<tr>
<td>Permeability</td>
<td>0.50 mD</td>
</tr>
<tr>
<td>Young’s modulus E1</td>
<td>14 GPa</td>
</tr>
<tr>
<td>Thermal conductivity κ</td>
<td>0.2 W/mK</td>
</tr>
<tr>
<td>Thermal expansion coefficient α T</td>
<td>0.00051 K⁻¹</td>
</tr>
<tr>
<td>Heat capacity c_p</td>
<td>1000 J/kg K</td>
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<tr>
<td>Density ρ</td>
<td>2000 kg/m³</td>
</tr>
<tr>
<td>Fluid pressure p_F</td>
<td>5000 psi</td>
</tr>
<tr>
<td>Fluid viscosity μ</td>
<td>1 cp</td>
</tr>
</tbody>
</table>

Thermo-Hydro-Geomechanics Governing Equation

\[ \sigma_{xx} = M_{11} \varepsilon_{xx} + \alpha_1 p + \beta T \]

- \( \sigma_{xx} \): stress in horizontal direction (Pa)
- \( \varepsilon_{xx} \): strain in horizontal direction
- \( p \): pore pressure (Pa)
- \( T \): temperature (K)
- \( M_{11} \): stiffness coefficient (Pa)
- \( \alpha_1 \): Biot’s pore pressure coefficient (Pa/K)
- \( \beta \): thermal factor (Pa/K)

Analytical Solution for Fracture Width

\[ w(t) = \frac{2(P_{frac} - S_{liq}) h}{M_{11}} + \frac{2\alpha_1(P_{frac} - P_0) h}{M_{11}} + \frac{2\beta_1(T_{frac} - T_0) h}{M_{11}} + f(t, P_{frac} - P_0, k_1, \ldots) + g(t, T_{frac} - T_0, \lambda_1, \ldots) \]

- \( w(t) \): fracture width
- \( P_{frac} \): fracture pressure
- \( P_0 \): formation pressure
- \( T_{frac} \): fracture temperature
- \( T_0 \): formation temperature

Effects on Brittleness of Temperature Difference Between Hydraulic Fracturing Fluid and Shale Formation

1. Temperature difference between fracturing fluid and shale formation significantly influence brittleness.
2. Effects of temperature difference between fracturing fluid and shale formation on fracture width are the same order of magnitude as effects of shale stiffness.
3. Hotter fracturing fluid leads to narrower and longer fracture, or more brittleness.
4. Narrower fracture however can hinder proppant transport and decrease fracture permeability.
5. Fracturing fluid temperature must be accounted for in hydraulic fracturing optimization.

Hydraulic Fracturing Optimization?

Effects of Fracturing Fluid Temperature

- \( T_{frac}=30°C \): Rock contraction due to cold fracturing fluid dominates shale swelling. Fracture widening.
- \( T_{frac}=40°C \): Shale swelling dominates rock contraction. Fracture closing.
- \( T_{frac}=50°C \): Shale swelling dominates rock contraction. Fracture closing.
- \( T_{frac}=60°C \): Shale swelling dominates rock contraction. Fracture closing.
- \( T_{frac}=70°C \): Shale swelling dominates rock contraction. Fracture closing.
- \( T_{frac}=80°C \): Shale swelling dominates rock contraction. Fracture closing.
- \( T_{frac}=90°C \): Shale swelling dominates rock contraction. Fracture closing.

Figure 19. Fracture width as a function of time from fracture opening (Abousleiman et al. 2013).

Figure 20. Fracture width evolution with time at different fracturing fluid temperatures

Figure 21. Importance of fracturing fluid temperature on fracture width (time = 1 hour). It can be seen that the effects of temperature is of the same order of magnitude as the effects of the Young’s modulus \( E_1 \) in lamination direction. \( E_1 \) is the main controlling mechanical factor (from Figure 11).