Characterizing Mechanical and Flow Properties using Injection Falloff Tests

Presented by
Dave Cramer / March 28, 2011
Agenda

• Review the basics of fracture injection / fall-off tests.
• Describe fracture closure analysis for determining in-situ stress and non-ideal fracture closure mechanisms.
• Describe after-closure analysis for determining reservoir flow behavior, reservoir flow capacity \((kh/u)\) and initial reservoir pressure \((p_i)\).
• Discuss integration of this information for enhanced control of hydraulic fracturing.
The process starts with the creation of a small hydraulic fracture, typically requiring less than 5 barrels for a shale gas interval.
Hydraulic Fractures Open Normal to the Least Principal Stress

This stress regime is typical for deeply buried reservoir rock.
Drivers of Bottomhole Pressure Behavior

Initially, rock mechanical properties and in-situ stress influence the pressure fall-off response. Later, pressure fall-off behavior is dominated by reservoir flow properties and pore fluid pressure.
Fracture Closure

Asperities on opposing fracture faces touch in the initial stages of fracture closure. The adjacent void space imparts residual fracture conductivity.
Flow Regimes in Hydraulically Fractured Wells with Residual Fracture Conductivity

Achieved in the after-closure period.
Radial flow solutions can be used to derive far-field $kh/u$.

From Cinco-Ley

During the pseudo-radial flow period, the area of investigation is well beyond the region of the fracture.
Assumed Case for Modeling Purposes: Fracture-Enhanced Wellbore in Cylindrical Reservoir

**Hydraulic Diffusivity**

\[ \frac{k}{\phi \mu c_T} \]

= fluid mobility / fluid storativity

**Fractured-Well Type Curve**

\[ t_D = 0.000264 \frac{k t}{\phi \mu c_T} x_F^2 \]

Start of pseudo-radial flow \( t_D > 1 \)

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*Hydraulic diffusivity determines the speed that pressure changes induced by production or injection are transmitted through the reservoir.*
To facilitate doing long-duration tests, memory gauges are used to monitor and record the pressure fall-off downhole or more commonly at the wellhead.
Overbalanced Perforating

Maintaining the wellbore pressure above reservoir pressure prevents gas influx into the wellbore and enables closed-chamber analysis under certain conditions.
Propagating a Hydraulic Fracture

Injection time and volume are kept short to minimize fracture dimensions and satisfy the conditions of an impulse event.
Even with a small injection, reservoir investigation is significant.
Pressure Fall-off History

Hydrostatic pressure is added to the observed wellhead pressure value to compute bottomhole pressure.
Diagnostic Log-Log Plot of Pressure Fall-Off

Derivative plot is used for identification of fracture closure behavior and after-closure reservoir flow regimes.
## Log-Log Graph Characteristic Slopes

### Diagnostic slopes depend on the derivative type used.

<table>
<thead>
<tr>
<th>Log-Log Graph</th>
<th>Before Closure</th>
<th>After Closure</th>
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<tbody>
<tr>
<td></td>
<td>Bilinear</td>
<td>Linear</td>
<td>Bilinear</td>
<td>Pseudolinear</td>
<td>Pseudoradial</td>
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<td>( \Delta p_{wf} \text{ vs. } t )</td>
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<td>1/2</td>
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<td>( \Delta p_{awf} \text{ vs. } t_a )</td>
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<tr>
<td>( \partial \Delta p_{wf} / \partial t \text{ vs. } t )</td>
<td>–3/4</td>
<td>–1/2</td>
<td>–7/4</td>
<td>–3/2</td>
<td>–2</td>
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<tr>
<td>( \partial \Delta p_{awf} / \partial t_a \text{ vs. } t_a )</td>
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<tr>
<td>( t \partial \Delta p_{wf} / \partial t \text{ vs. } t )</td>
<td>1/4</td>
<td>1/2</td>
<td>–3/4</td>
<td>–1/2</td>
<td>–1</td>
</tr>
<tr>
<td>( t_a \partial \Delta p_{awf} / \partial t_a \text{ vs. } t_a )</td>
<td>1/4</td>
<td>1/2</td>
<td>1/4</td>
<td>1/2</td>
<td>0</td>
</tr>
<tr>
<td>( t^2 \partial \Delta p_{wf} / \partial t \text{ vs. } t )</td>
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<td>3/2</td>
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<td>( t_a^2 \partial \Delta p_{awf} / \partial t_a \text{ vs. } t_a )</td>
<td>1/4</td>
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</table>

From Barree (SPE 107877)
G Function Plots for Fracture Closure Identification

The semilog derivative is the primary plot for identifying fracture closure.
G-Time Functions for Analyzing a Closing Fracture

\[ \Delta t_D = (t - t_p) / t_p \]
\[ g(\Delta t_D) = 4/3 \left( (1+\Delta t_p)^{1.5} - \Delta t_p^{1.5} \right) \]
\[ G(\Delta t_D) = 4/\pi \left( g(\Delta t_p) - g_0 \right) \]
\[ \eta = \left[ G(\Delta t_D)_C \right] \left[ 2 + G(\Delta t_D)_C \right] \]

where,
- \( t \) = total test time (pumping and shut-in)
- \( t_p \) = pumping time
- \( G(\Delta t_D) \) = G-Function time in previous slide
- \( G(\Delta t_D)_C \) = G-Function time at fracture closure
- \( \eta \) = fluid efficiency (i.e., fluid remaining in fracture relative to total fluid injection, at shut-in)

The G-Time Function linearizes the pressure response of a closing fracture under ideal conditions.
The 1st derivative plot is a secondary method for confirming fracture closure.
Poroelastic Equation for Estimating In-Situ Horizontal Stress

\[ \sigma_h = \left[ \frac{\nu}{1 - \nu} \sigma_v - \alpha_v P_r \right] + \alpha_h P_r + \sigma_t \]

Where,
- \( \sigma_v \) = overburden stress, psi = 10,752 psi (1.12 psi/ft; bulk density log)
- \( \nu \) = Poisson’s ratio = 0.23 (from dipole sonic log computation)
- \( \alpha_v \) = vertical Biot’s parameter = 1.0
- \( \alpha_h \) = horizontal Biot’s parameter = 1.0
- \( P_r \) = reservoir pore pressure, 4693 psi (0.49 psi/ft; DFIT)
- \( \sigma_t \) = external (tectonic) stress, psi = 0 psi (assumed)
- \( \sigma_h \) = minimum horizontal stress, psi = 6503 psi (predicted from above)
- \( \sigma_h \) = minimum horizontal stress, psi = 7269 psi (observed from DFIT)

The fracture closure method for deriving minimum in-situ stress can be used to evaluate and adjust the values derived from predictive equations.
After-Closure Flow Regime Type Curve

Pseudo-radial flow period

Pseudo-radial flow is indicated by 1.) the -1 slope trend in both ΔP & semilog derivative plots and 2.) equivalency of ΔP and semilog derivative values.
After-Closure Flow Regimes Plot Time Function

linear flow time function$^2 = F_L^2$

linear flow time function = $F_L = \frac{2}{\pi} \sin^{-1} \sqrt{\frac{t_c}{t}} \text{ for } t \geq t_c$

where,
$t = \text{total test time (including injection time)}$
$t_c = \text{time to fracture closure (including injection time)}$

Note: In gas reservoirs, the pseudo-time function ($t_a$) is used to adjust time.

*It’s the linear flow time function squared, which is a function of total test time and fracture closure time.*
The solution derived with the Radial Flow specialty plot shows good agreement with the Type Curve plot.
After-Closure Flow Regime Plot: Linear Flow

Pseudo-linear flow indicator: when pressure change and derivative both lie on the half-slope trend line & pressure change is 2x the value of the derivative. This test meets the criteria for pseudolinear flow. Reservoir pressure can be inferred from this analysis.

Certain types of naturally fractured reservoirs exhibit long-term linear flow.
Summary

- **Injection Fall-off Testing** is an efficient way to derive in-situ information on most rock types.
  - A modest-size hydraulic fracture is created and pressure fall-off during shut in period is analyzed for fracture closure and after-closure radial flow period.
  - Injection rate and volume are tailored for interval thickness and leak-off characteristics.

- **Identification of fracture closure** provides information on rock stress.
  - A combination of derivative-based diagnostic plots are used.
  - Non-ideal fracture propagation (e.g., fracture height growth, fissure opening, multiple fracture closures) can be identified and evaluated.

- **After-closure analysis** is used to derive rock transmissibility \((kh/u)\) and pore fluid pressure.
  - Radial flow is identified and evaluated by type curves and specialty plots.
  - Computations are based on well testing theory.

- **The resulting information** is employed to assist in controlling the hydraulic fracturing process.
  - The information is used in hydraulic fracture modeling to predict fracture geometry, proppant placement, fracture conductivity, etc.
  - Treatment design is modified as necessary to achieve treatment objectives.