Reservoir Engineering Aspects of Unconventional Reservoirs — An Update

Tom BLASINGAME
Petroleum Engineering — Texas A&M University
College Station, TX 77843-3116 (USA)
+1.979.255.8808 — t-blasingame@tamu.edu
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Brief Biography — Tom Blasingame

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Brief Biography: **Blasingame**

- **Role:**
  - Professor, Texas A&M U.
  - Holder of the Robert L. Whiting Professorship
  - B.S., M.S., and Ph.D. degrees from Texas A&M U. (PETE)

- **Counts: (November 2013):**
  - 12 Ph.D. Graduates
  - Over 120 Technical Articles

- **Recognition:**
  - Distinguished Member of the Society of Petroleum Engineers (2000)
  - SPE Distinguished Service Award (2005)
  - SPE Distinguished Lecturer (2005-2006)
  - SPE Uren Award (2006)
  - SPE Lucas Medal (2012)
  - SPE DeGolyer Distinguished Service Medal (2013)

- **Current Research Activities:**
  - Nano-Scale Flow Phenomena
  - Reservoir Engineering of Near-Critical, "Liquids-Rich" Shale Systems
  - Evaluation of Well Performance Data for Shale/Liquids-Rich Systems
  - Numerical Modeling of Ultra-Low Permeability Reservoir Systems
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A Brief Introduction

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Start-Up: Conventional Versus Unconventional

Conventional Reservoirs
- Localized structural trap
- External HC sourcing
- Hydrodynamic influence
- Porosity important
- Permeability > 0.1 md
- Permeability ≠ f(p)
- Traditional phase behavior (PVT)
- Minimal extraction effort
- Significant production history
- Often late development life-cycle
- Few wells for commerciality
- Base reserves on volumetrics
- Assess entire prospect before drilling
- Boundary-dominated flow (months)

Unconventional Reservoirs (Shale)
- "Continuous-type" deposit
- Self-sourced HC
- Minimal hydrodynamic influence
- Porosity may not be important
- Permeability << 0.1 md
- Permeability = f(p)
- Complex (HP/HT) PVT
- Significant extraction effort
- Limited production history
- Early development life-cycle
- Many wells for commerciality
- Base reserves on analogs
- Prospect driven by drilling
- No boundary-dominated flow

Attributed to Brad Berg
(Anadarko Petroleum Corporation)
Pore-Scale: Petrophysics/Permeability


Time-Rate Analysis: Schematics and Basic Concepts

Schematic Production Performance Plot

- Estimated Ultimate Recovery (EUR) [The area under the hybrid (hyperbolic-exponential rate curves]
- Economic Limit (in rate — q\text{lim})
- Hyperbolic Rate
- Exponential Rate

Logarithm of Rate

Production Time

Logarithm of Production Rate

Flow Regimes — Multi-Fracture Horizontal Well

- 1:3 Slope (high F\text{a})
- Formation Linear Flow Regime
- Compound Linear Flow Regime
- Elliptical Flow Regime
- Transition Regime

Early-Time Regimes are HYPERBOLIC?

\[ q(t) = q_i \left[1 + b D t^{(1/b)} \right] \]

Logarithm of Production Time

Flow Regimes in a Multi-Fracture Horizontal Well

a. Schematic of hyperbolic-exponential DCA approach.

b. Schematic of "fracture stages" in a multi-fracture horizontal well.

c. Schematic of flow regimes which occur in a multi-fracture horizontal well (note linear and bilinear flow regimes).

d. Example of modern decline curve diagnostics (q\text{Db}-functions) used for production forecasting and estimation of EUR.

Modern Decline Analysis — Power-Law Exponential Rate

PLE Rate Relation:

\[ q(t) = q_i \exp\left[-D_\approx t - \hat{D}_\approx t^n\right] \]

Decline Function: \( D(t) \)

\[ D(t) = \frac{1}{q} \frac{dq}{dt} \approx D_\approx + n\hat{D}_\approx t^{(1-n)} \]

Hyperbolic Function: \( b(t) \)

\[ b(t) = \frac{d}{dt} \left[ \frac{1}{D(t)} \right] \approx \frac{n\hat{D}_\approx (1-n)}{[n\hat{D}_\approx + D_\approx t^{(1-n)}]^2} t^{-n} \]

Notes:

- \( b(t) \) and \( D(t) \) are evaluated continuously.
- \( D(t) \) trend indicates "power-law" behavior.

Example of modern decline curve diagnostics (q\text{Db}-functions) used for production forecasting and estimation of EUR.
Phase Behavior: ... PVT at the Nano-Scale

PVT: (Issues/Challenges/Solutions?)
- Undersaturated oil, $p_b$ suppression (nano-pore volumes/distributions).
- Volatile oil/critical fluid, nano-volume effects less an issue ($IFT/p_c$).
- Gas condensates — composition issues/ variations in $p_{Crit}$ and $T_{Crit}$.
- Need molecular dynamics work to resolve/validate PVT in nano-pores.

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Critical Temperature as a Function of Pore Size

a. Critical point suppression due to pore size (various gases).

b. Phase diagrams of confined and unconfined heavy gas condensate mixture (Pedersen et al, 1989). (vertical (red) line is the reservoir temperature).

c. The percentage of liquid drop out (% by volume) of a heavy gas condensate mixture (Pedersen et al, 1989) at 400°F. (400°F is reservoir temperature — see plot at left).

Reservoir Modeling: Concepts

Modeling Approach for a Horizontal Multi-Fracture Well

Modeling: (Grand Challenges)
- Fully integrated (not coupled) geomechanical/flow simulation model.
- Models may not be properly "parameterized" — no data to validate.
- Statistical versus deterministic models (system is "too complex")?
- Use models to establish/validate/bound drainage volumes.
- Use models to constrain assumptions about geomechanics/fluid flow.


b. Typical transient response where PSS is seen in the SRV (Note times for different regimes, this is a relatively high permeability shale analog case).

From: KAPPA Consortium on Unconventional Resources (Draft project document) 7th February 2011 (www.kappaeng.com).

b. Pressure gradient after 8 months (top) and 10 years (bottom) of production (Note times for different regimes, this is a relatively high permeability shale analog case).
Reservoir Modeling: Well Performance Example

- **a. Time match of oil (green) and gas (red) rate performance.** Note that the match substantially degrades after the shut-in (reservoir effect?).

- **b. Time match of (calculated) bottomhole pressures.**

- **c. Cumulative oil match of oil rate using 80- and 800-acre spacings.**

- **d. Plot of EUR versus well spacing (drainage area) for example case.**

Modern Decline Analysis: Statistical Analysis

[all data obtained from publicly available sources — Dry Horizontal Shale Gas Wells ONLY]

Comment:
- Left plot yields time required to estimate EUR (~12-32 months).
- The "hyperbolic" (or "constant b") flow regime is required to estimate EUR.
Modern Decline Analysis: Statistical Analysis

Results vary when segregated by geological area, completions, spacing, etc.
Analyses represent an attempt to quantify the RANGE of values.

Comment:

- Results vary when segregated by geological area, completions, spacing, etc.
- Analyses represent an attempt to quantify the RANGE of values.

The "it-rhymes-with-itch" list:

● Fractures:
  ■ How do we model the SRV (or enhanced permeability region, etc.)?
  ■ Most appropriate approach for modeling hydraulic fractures.
  ■ Does fracture modeling (really) matter?
  ■ What is the holy grail for creation, propagation, transport in fractures?

● Matching Performance:
  ■ What do pressure-dependent properties mean in a physical sense?
  ■ Is a simple numerical model match meaningful?
  ■ Is an analytical model match meaningful?
  ■ Can we do something different? (e.g., use some sort of surrogate?).

● Phase Behavior:
  ■ Enormous investment in theory, computing, validation — is it worth it?
  ■ Will we (ever) be able to correctly model EOR processes in shales?
  ■ Are there reasonable surrogates for this complex PVT?

● Wish List:
  ■ See "genetic" behavior in well performance — use as empirical model?
  ■ Phase behavior — molecular modeling is fine, but not (ever?) practical.
  ■ Correctly modeling fracture creation and function (i.e., flow behavior).
  ■ Connecting a well model to the reservoir (for artificial lift).
  ■ Understanding when we can use Darcy's law — and when we cannot.
What Keeps Us (Reservoir Engineers) Up at Night:

● Stimulation/Fracture Geometry:
  ■ Well spacing, reservoir model type (dual vs. single porosity), etc.?
  ■ Does the SRV change with time (specifically, does it shrink)?

● Reservoir Model:
  ■ Validity of dual $\phi/k$ models, enhanced $k$ pods, fracture networks?
  ■ Model selection has a significant impact on POTENTIAL well spacing.
  ■ Can we predict/incorporate influence of natural fractures?
  ■ Is effort on geomechanics (really) going to lead to better understanding?

● Data Collection:
  ■ Taking data to validate model, or using model to guide development?
  ■ Downhole data — expensive — but are there any viable alternatives?
  ■ Poor data $\rightarrow$ poor engineering and poor modeling.
  ■ Petrophysical data ($\phi$, $k$, $p_c$) — scale, validity, integration?
  ■ Role of "distributed" data? (temperature, pressure, rates, etc.)

● Process:
  ■ No "cowboy-ing" the choke — develop a choke plan and stick to it!
  ■ Incorporating artificial lift from inception! (including modeling)
  ■ Use modeling to interpret performance and constrain parameters.
  ■ Focus on what we can measure; use that as a basis for modeling.
  ■ Start to consider statistics in addition to mechanics.
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Random Thoughts

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Discussion:

- Process of "shifting" is the same as old-style type curve matching.
- Selection of the best case to serve as reference is important.
Diagnostic Plots: log(rate) vs. SQRT(cumulative)

Discussion:
- Each trend can be extrapolated — will be TOO HIGH (NOT EUR!).
- BUT, extrapolation may be a good proxy for EUR.
- Some (Dilhan?) have correlated rate intercepts and $SQRT(G_{p,ext})$ values.
Diagnostic Plots: Application of "Shifted Data"

Discussion:
- Extrapolation/correlation of trends.
- Somewhat empirical, what does it mean.
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End of Presentation

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Questions?
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Quiz

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Quiz: *How much water/day does an average golf course use?*

**Answers:**
- 75 Bbl
- 750 Bbl
- 7500 Bbl
- 75,000 Bbl

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Quiz: How much **total water** does an average frac job use?

Answers:
- 72 Bbl
- 720 Bbl
- 7200 Bbl
- 72,000 Bbl

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