Well Performance in Unconventional Reservoirs — State-of-the-art Analysis/Interpretation, and Models

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Production from Unconventional Resources:

● Discussion: *Eagle Ford Well Count from Texas Railroad Commission*
  - Wells completed and permitted in the Eagle Ford Shale.
  - January 2013 ≈ 3,400.
  - March 2014 ≈ 8,400.
Production from Unconventional Resources:

Major challenge in relating basic flow phenomena to reservoir-scale models.

Issues/Comments:
- Fluid storage in the nano-pores, organic matter, adsorbed?
- Flow path can be as small as 10-20 molecular diameters?
- Mineral composition varies widely—Each play is unique.
Production from Unconventional Resources:

- Challenges associated with sampling the reservoir fluid.
- Near critical fluids — composition issues and variations in $p_{\text{crit}}$ and $T_{\text{crit}}$.
- Phase envelope shift and suppression of the bubble point.
- Molecular dynamics work to resolve PVT in nano-pores?

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


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)

From: Brent Thomas (Weatherford) — Schematic on $p_b$ suppressed (undersaturated oil)
Production from Unconventional Resources:

- Microseismic pattern from the Bakken Oil Reservoir:
  - From: Whiting Petroleum Presentation (2010)

- Trilinear flow solution model configuration:
  - From: Ozkan et al. (2010)

- Pressure distributions for a discrete fracture network (DFN) model:
  - From: Kappa Engineering

- Numerical simulation configuration for a multi-frac horizontal well:
  - From: Kappa Engineering
Problem Statement: *Uncertainty on Outcome*

Decline Curve Analysis: *Haynesville Performance Possibilities*

- Significant uncertainty on *EUR* based on the selection of *b*-value.

Schematic for Haynesville Shale Gas Well Performance Possibilities
Production Rate and Time Plot (Semilog Scale)

≈2 years of production data from a Haynesville Shale gas well

Decline Curve Analysis:
- *EUR* = 7.81 Bscf
- *EUR* = 6.15 Bscf
- *EUR* = 5.31 Bscf
- *EUR* = 3.98 Bscf

Production Time, days

Gas Flowrate, *q*<sub>g</sub>, MSCF/D

*EUR* = 3.98 Bscf
*EUR* = 5.31 Bscf
*EUR* = 6.15 Bscf
*EUR* = 7.81 Bscf
Presentation Outline:

- **Decline Curve Analysis**
  - Modified hyperbolic equation
  - Time-rate characteristic behavior
  - Advanced decline curve relations
  - Comparative studies

- **Production Diagnostics**
  - Diagnostic plots
  - Flow regimes and characteristic behavior

- **Analysis and Modeling**
  - Horizontal well with multiple fractures model
  - Analysis and modeling examples
  - Multi-well modeling and well spacing
  - Uncertainty and non-uniqueness

- **Concluding Remarks**
Decline Curve Analysis

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Decline Curve Analysis: *Modified Hyperbolic Equation*

- **Modified Hyperbolic Equation**
  - The schematic represents the most common approach (aka. modified hyperbolic) to estimate ultimate recoveries (EUR).
  - This approach could be "non-unique" in the hands of most users, and often yields widely varying estimates of reserves with time.
Decline Curve Analysis: \textit{Time-Rate Diagnostics}

Basis for decline curve relations:

\[ D = -\frac{1}{q_g} \frac{dq_g}{dt} \]

\[ b = -\frac{d}{dt} \left[ \frac{q_g}{dq_g/dt} \right] \]

\textbf{Flow Regimes: (Time-Rate Data)}

- Identify diagnostic/characteristic behavior exhibited by data.
- Evaluate \( D(t) \) and \( b(t) \) continuously (at all points).
- Power-law exp. relation is based on power-law behavior of \( D \)-parameter.
Decline Curve Analysis: *Eagle Ford Oil Example*

![Decline curve plot](image)

**Advanced decline curve relations** (recently introduced) — (ref. SPE 162910)

2. Stretched Exponential* (2009)
3. Duong (2010)
4. Logistic Growth (2011)
5. Transient-Hyperbolic (2013)
6. ... ???

(*Power-law exponential and stretched exponential relations are almost identical relations, but introduced differently.)*

- Each decline curve model can be described as empirical (no direct link with theory) and generally center on a particular flow regime and/or characteristic behavior.
- Can time-rate analysis truly represent well performance?
Decline Curve Analysis: Continuous EUR

Analyze All Intervals Using the Hyperbolic Relation

50 days
EUR = 9.42 BSCF

250 days
EUR = 6.08 BSCF

1,930 days
EUR = 4.11 BSCF

Analyze All Intervals Using the Power-Law Exponential Relation

EUR = 4.54 BSCF

EUR = 4.32 BSCF

EUR = 4.06 BSCF

Find Lower Limit Using $q_g$ vs. $G_p$ Straight Line Extrapolation

$G_{p,max} = 0.31$ BSCF

$G_{p,max} = 1.18$ BSCF

$G_{p,max} = 3.57$ BSCF
Decline Curve Analysis: *Continuous EUR*

*Plot $G_p$ Data and EUR Estimates from Models vs. Time for All Intervals*

Identify the Upper Limit for EUR Using the Power Law Exponential Model

Identify the Lower Limit for EUR Using the Straight Line Extrapolation Technique
Production Diagnostics

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**Production Diagnostics: Identifying Flow Regimes**

- **Flow Regimes: (Barnett Shale Example)**
  - Schematic illustrates possible flow regimes exhibited by time-rate-pressure data.
  - Duration/existence of flow regimes is **DIFFERENT** for each play.

![Graph showing Shale Gas Well production data](image)

- **Pressure Drop Normalized Gas Flowrate, \( \frac{q_g}{\Delta P} \), MSCF/D/psi**
- **Time, days**

- **Flow Regimes Diagram**
  - **1.** (1:2 Slope — Linear flow/High fracture conductivity)
  - **2.** (1:4 Slope — Low fracture conductivity)
  - **3.** (1:1 Slope — Fracture interference/Depletion (SRV?))

- **EURLF (VERY OPTIMISTIC)**
- **EURDep (CONSERVATIVE ??)**

Pseudo-elliptical flow regime (flow from matrix to collection of fractures) might exist after fracture interference.
**Discussion:**

- Well clean-up effects (flowback) dominate early time behavior.
- Half-slope indicates linear flow regime is prevailing for Field A.
- Unit slope indicates fracture interference or depletion type signature (decreasing well productivity) for Field B.
- Long time well cleanup effects and operation issues prevent better diagnostics for Field C.
- Field C wells demonstrate linear and/or bilinear flow type signatures.
Production Diagnostics: **Performance Comparison**

- **Field A** (linear flow dominated):
  - \( \Delta p/q \) and \( t^{0.5} \)

- **Field B** (decreasing well productivity):
  - \( \Delta p/q \) and \( t^{0.5} \)

- **Field C** (erratic production):
  - \( \Delta p/q \) and \( t^{0.5} \)

**Graphs**:
- Time-Pressure-Rate Diagnostic Plot for All Wells
- Pressure Drop Normalized Cumulative Gas Production versus Material Balance Time
**Production Diagnostics:** **Grouping Wells**

- **Discussion:**
  - Diagnosis of the performance of 9 wells producing in the same area (plot of productivity index).
  - Performance comparison of multiple wells to identify characteristics.
  - Differences in the productivity can be attributed to completion and operational issues.
Eagle Ford Shale — Production and TVD data from public sources

Contour: TVD (ft)

Bubbles: 6 Month cumulative BOE production (MBOE)

- Wells are grouped by specific characteristics (such as, geology/location, PVT behavior, completion, etc.).
- Representative wells are selected for analysis and modeling.

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Production Diagnostics: **Eagle Ford Example**

![Diagnostic Plot: Rate and Time](image1)

![Diagnostic Plot: Normalized Rate and Material Balance Time](image2)

![Diagnostic Plot: Normalized Pressure and Square Root Time](image3)
Diagnostics:

- **PLOT**: Oil Productivity Index versus Cumulative Oil Production
- **OBJECTIVE**: (Empirically) project recovery for a single well based on flow behavior
Analysis and Modeling

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Analysis and Modeling: **Model Configuration**

1. **Model Parameters:**
   - Permeability \( (k) \)
   - Fracture half-length \( (x_f) \)
   - Fracture conductivity \( (F_c) \)
   - Drainage area \( (A) \)
   - Skin factor \( (s) \)
   - Well length \( (L_w) \)
   - Number of fractures \( (n_f) \)

**Discussion:** *Horizontal Well with Multiple Transverse Fractures*
- This is the simplest model to represent multi-frac horizontal well production.
Analysis and Modeling: **History Matching with Model**

- **Analysis:**
  - **Model**: Horizontal well with multiple fractures, non-linear analysis accounting for multiphase flow and pressure-dependent reservoir properties.
  - **Multiphase Flow**: Rigorous fluid characterization (non-linear solution).
  - **Pressure-dependencies**: Approximate degradations in productivity.
  - Model-based analysis must be guided by production diagnostics.
Forecast:

- Oil and gas rates are extrapolated using the model (80 acres)

- $EUR_{OIL} = 0.23$ MMSTB, $EUR_{GAS} = 1.05$ BSCF
**Analysis and Modeling: Model Forecast**

- **Forecast:**
  - Constant pressure simulation results are imposed on productivity index and cumulative production plots.
  - Forecast is different with respect to drainage area.

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**Oil productivity index and cumulative oil production plot**

**Gas productivity index and cumulative gas production plot**
Modeling: *Multi-well Modeling (Well Interference)*

- Used model parameters obtained from the analyzed well(s).
- Assumed development wells have the same well configuration
- Assumed development wells have the same reservoir and fluid properties.
- Vary distance between two wells to investigate the effect of spacing on EUR (Distance between wells corresponds to drainage area).
Analysis and Modeling: **Multi-well Simulation**

- **Pressure Distribution — 1 Year**
- **Pressure Distribution — 3 Years**
- **Pressure Distribution — 5 Years**
- **Pressure Distribution — 8 Years**

- 80 acres well spacing is assumed for the multi-well simulation run.
Analysis and Modeling: Multi-well Simulation

200 acres well spacing is assumed for the multi-well simulation run.
Discussion:

- EUR is a function of well spacing for less than 100 acres drainage area assumption (not affected over 100 acres).
- EUR values are estimated at 30 years of production.
- In our simulation runs, 100 acres drainage area corresponds to 738 ft distance between two wells.
### Analysis and Modeling: Uncertainty/Non-uniqueness

16 acres is the minimum "contacted" drainage area

- Different permeability values are utilized for history match and almost identical matches are obtained for each case. It is possible to obtain probabilistic forecasts.

\[
\text{EUR} \approx f(k, x_f, k(p), ...) 
\]

Less uncertainty in EUR if minimum contacted drainage area is imposed -- conservative???
Analysis and Modeling: *Time-Rate Profile*

\[ q_g = \frac{q_{gi}}{(1 + b D_i t)^{(1/b)}} \]

- \( q_{gi} \) = initial gas production rate
- \( D_i \) = initial decline rate, percent per year
- \( b \) = hyperbolic decline exponent (controls the shape of the curve)
- \( T_d \) = terminal decline (exponential)

**Discussion:**
- Model-based analysis results can be converted into a time-rate (decline) profile.
Concluding Remarks

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Concluding Remarks: **Well Performance Analysis Procedure**

- **Analysis**
- **Validation**
- **Forecast**

**Diagnostics**

- **SPE 144276** — All Wells Data Diagnostics Plot (Pressure Drop Normalized Flowrate versus Production Time)
- **SPE 144274** — All Wells Data Diagnostics Plot (Rate Normalized Pressure Drop versus Square Root of Production Time)
- **SPE 144275** — All Wells Data Diagnostics Plot (Computed D-parameter versus Production Time)
- **SPE 144276** — Well D Data Diagnostics Plot (Flowrate and Calculated Bottomhole Pressure versus Time)
- **SPE 144277** — All Wells Data Diagnostics Plot with Characteristic Decline Model (Pressure Drop Normalized Flowrate versus Production Time)
- **SPE 144275** — Effect of Horizontal Well Length and Number of Fracture Stages Production Forecast Plot for Various Horizontal Well Lengths (L_w) (80 Years) Cumulative Gas Production versus Production Time

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**SPEE Denver Chapter Luncheon Meeting**
Denver, COLORADO | 15 May 2014

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Concluding Remarks: *Proved Reserves Categories*

- **Proved reserves (1P):** "... *reasonable certainty* — to be recovered much more likely than not"
- "Reasonably certain* EUR is much more likely to increase or remain constant with time
- **Proved plus Probable reserves (2P):** "... as likely as not to be recovered" (50% prob.)
- **Proved plus Probable plus Possible reserves (3P):** "... possibly but not likely to be recovered" (10% probability)
Concluding Remarks: *Well Performance in Unconventionals*

- Decline curve analysis is currently the primary tool for forecasting, *although it may not be fully representative*.
- Time-rate-pressure data analyses need to become the dominant tool for evaluating completions and forecasting production.
- Diagnostic interpretation of production data is the key to understanding well performance behavior of a given well.
- Diagnostic analyses should be performed prior to model-based analyses to identify flow regimes and to assess the consistency of the data.
- We need to incorporate the fundamentals of flow mechanisms (e.g., near critical fluid behavior, geomechanics, formation characterization, hydraulic fracture growth, etc.) into analysis and modeling for improved analysis and forecasting.
- Numerical simulation gives insight into the evaluation of well spacing for future development.
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END OF PRESENTATION

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Major References:


