Pseudo Steady-State
Plunger Lift Model

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Reasons

• Selection and justification of (high cost) deliquification measures based on comparison of incremental production and cost profiles

• Outflow models for production forecasting “easily” constructed for steady-state techniques such as velocity string, foam, gas lift and downhole pump

• More complicated for transient techniques such as plunger lift and intermittent production (plunger-less lift)
Production Forecast

- Need to calculate average capacity ($Q_{\text{cap}}$) as function of reservoir pressure ($P_{\text{res}}$), and minimum achievable reservoir pressure ($P_{\text{min}}$) to compare plunger lift against alternatives
  - $P_{\text{min}}$ dictates incremental reserves
  - $Q_{\text{cap}}$ governs time to recover those reserves
  - Combination determines discounted incremental reserves and costs for economics

- To date plunger modeling has focused mostly on understanding and optimizing plunger cycle, rather than capturing associated production performance
Production Performance – Prolific

Production Performance

- \( P_{\text{min}} \) dictates incremental reserves
- \( Q_{\text{cap}} \) governs time to recover reserves
- Combi determines discounted reserves

1 bara = 14.5 psia, 1e3 m³/d = 35.31 Mscf/d
Production Performance – Poor

Production forecast follows when combined with reservoir model

1 bara = 14.5 psia, $1 \text{e}^3 \text{m}^3/\text{d} = 35.31 \text{Mscf/d}$
Well Model – Three Curves

Inflow – Forchheimer
\[ P_{\text{res}}^2 - FBHP^2 = A \cdot Q + F \cdot Q^2 \]

Back Pressure Curve
\[ (P_{\text{res}}^2 - FBHP^2)^n = \frac{Q}{C_{\text{res}}} \]
\[ C_{\text{res}} = \frac{1}{A} \quad @ \quad n=1 \]

Outflow – Cullender and Smith
\[ FBHP^2 = B \cdot FTHP^2 + C \cdot Q^2 \]

Liquid Loading Rate – Turner
\[ Q_{\text{min}} = TC \cdot FTHP^{0.5} \cdot ID^2 / [(\text{FTHT} + 273) \cdot Z] \]

\[ Q_{\text{cap}} = \left[ (A^2 + 4CC + F) \cdot (P_{\text{res}}^2 - B \cdot FTHP^2) \right]^{0.5} \cdot A / 2(C + F) \]

\[ P_{\min}^2 = B \cdot FTHP^2 + A \cdot Q_{\min} + (C + F) \cdot Q_{\min}^2 \]

1 bara = 14.5 psia, 1e3 m³/d = 35.31 Mscf/d
Outflow Model – Approximation OK

Transition from “dry” gas well to “wet” gas well takes time
E.g. Q=100e3 m³/d, LGR=100 m³/e6m³, 4” ID ↔ 4 bar/hr
Compression: $Q_{\text{cap}}$ Benefit, $P_{\text{min}}$ Benefit

1 bara = 14.5 psia, $1 \text{e}^3 \text{ m}^3/\text{d} = 35.31 \text{Mscf/d}$
Velocity String: $Q_{\text{cap}}$, Penalty, $P_{\text{min}}$, Benefit

1 bara = 14.5 psia, $1 \times 10^3$ m$^3$/d = 35.31 Mscf/d
Nomenclature

- $P_{res} =$ reservoir pressure
- $P_{min} =$ minimum achievable $P_{res}$
- $Q_{cap} =$ average well capacity
- $Q =$ gas rate
- $Q_{min} =$ minimum stable gas rate
- $\text{FTHP} =$ flowing wellhead press.
- $\text{FBHP} =$ flowing bottom hole pr.
- $A =$ Darcy inflow resistance
- $F =$ non-Darcy inflow resistance
- $B =$ hydrostatic outflow parameter
- $C =$ friction outflow parameter
- $\text{TC} =$ liquid loading parameter
- $\text{LGR} =$ liquid to gas ratio
- $V_{up} =$ average upward plunger velocity
- $V_{down} =$ average downward plunger velocity
- $T_{off} =$ shut-in period
- $\Delta P =$ liquid load + plunger friction
- $V_t =$ tubing volume
- $V_a =$ annulus volume
- $F =$ plunger frequency
Plunger Lift Cycle

- Cartoon depicts Fekete Virtuewell plunger model

Plunger moves up and down tubing at given velocities $V_{up}$ and $V_{down}$:

\[ Q_{min} \sim FTHP.ID^2.V_{up}, T_{off} > T_{down} \]

On = Up

After Flow

Off = Plunger Down + Buildup Period

Legend:
- Csg Press
- Tbg Press
- Line Press
- WH Gas Rate
- BH Gas Rate
Plunger Lift Cycle

- **ON (UP) – AFTER FLOW – OFF (BUILDUP)**

\[ Q_{min} \text{ is delivered by reservoir inflow } Q \text{ plus blow down of annulus volume if } Q < Q_{min} \]

**Up & Start Buildup**

\[ Q = \frac{[A^2 + 4(C+F)(P_{res}^2 - (B^{0.5}THP + DP)^2)]^{0.5} - A}{2(C+F)} \]

**After Flow**

\[ Q = \frac{[A^2 + 4(C+F)(P_{res}^2 - (B^{0.5}THP + DP/2)^2)]^{0.5} - A}{2(C+F)} \]
Plunger Lift Cycle

- **ON (UP) – AFTER FLOW – OFF (BUILDUP)**

Pressure buildup $\Delta P$ during Off period is just sufficient to generate required annulus decompression volume.

Difference between $Q_{\text{cap}}$ and $Q_{\text{min}}$ is delivered by annulus decompression volume $V_a \times \Delta P$.

$$
\Delta P = (P_{\text{res}} - B^{0.5} \cdot \text{FTHP} - \text{DP}) \cdot [1 - \exp(-c \cdot T_{\text{off}} - 0.3 \cdot c^2 \cdot T_{\text{off}}^2)]
$$

where

$$
c = 1 \times 10^3 \frac{Q}{(V_a + V_t) \cdot (P_{\text{res}} - B^{0.5} \cdot \text{FTHP} - \text{DP})}
$$

and

$$
Q = \frac{\{A^2 + 4 \cdot (C + F) \cdot (P_{\text{res}}^2 - (B^{0.5} \cdot \text{THP} + \text{DP})^2)\}^{0.5} - A}{2 \cdot (C + F)}
$$
Plunger Lift – No Annulus Support

1 bara = 14.5 psia, 1e3 m³/d = 35.31 Mscf/d
Plunger Lift – Annulus Support

1 bara = 14.5 psia, 1e3 m³/d = 35.31 Mscf/d
Plunger Modeling

• Liquid load x plunger frequency $F$ equals produced liquid volume $LGR \times Q_{cap}$

• Calculate maximum $Q_{cap}$, $F$, $T_{off}$ and $\Delta P$ by varying $DP$

• Calculate maximum $Q_{cap}$, $F$, $\Delta P$ and $DP$ as function of reservoir pressure $P_{res}$

• Show impact of inflow performance, annulus volume, liquid production, inflow performance and wellhead pressure

• Ignore complexity and transient nature of plunger cycle, including plunger friction, plunger by-pass, annulus friction and varying plunger velocity!
Vary Liquid Load DP to Maximize $Q_{\text{cap}}$

1 bara = 14.5 psia, $1 \text{e3 m}^3/\text{d} = 35.31 \text{Mscf/d}$
Small Annulus Volume – $V_a = 4 \ m^3$

1 bara = 14.5 psia, $1 \times 10^3 \ m^3/d = 35.31 \ Mscf/d$
Large Annulus Volume – $V_a = 100 \text{ m}^3$
Medium Annulus Volume – $V_a = 20 \text{ m}^3$

1 bar = 14.5 psia, $1\text{e}3 \text{ m}^3/\text{d} = 35.31 \text{Mscf/d}$
Vary LGR @ $P_{\text{res}} = 62$ bara

Frequency, liquid load and associated capacity loss increase as LGR increases.

1 bara = 14.5 psia, $1 \times 10^3$ m$^3$/d = 35.31 Mscf/d
Vary LGR @ $P_{res}=40$ bara

$1$ bara = $14.5$ psia, $1e3$ m$^3$/d = $35.31$ Mscf/d

$P_{min}$ increases as LGR increases
Plunger causes deferment in prolific wells

Before $Q_{\text{min}} = 46.9 \times 10^3 \text{m}^3/\text{d}$
After $Q_{\text{min}} = 31.7 \times 10^3 \text{m}^3/\text{d}$ (68%)
Vary A @ FTHP=5 bara

Before $Q_{\text{min}} = 19.2 \times 10^3 \text{m}^3/\text{d}$
After $Q_{\text{min}} = 6.3 \times 10^3 \text{m}^3/\text{d}$ (33%)

1 bara = 14.5 psia, $1 \times 10^3 \text{m}^3/\text{d} = 35.31 \text{Mscf/d}$

Plunger most effective at low FTHP
**Observations**

- Gas rate shows broad maximum Vs liquid load
- Suggests that plunger settings are quite forgiving

<table>
<thead>
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<th>Parameter</th>
<th>$P_{\text{min}}$ Benefit</th>
<th>$Q_{\text{cap}}$ Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annulus Volume</td>
<td>Increases</td>
<td>(Decreases)</td>
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<tr>
<td>LGR</td>
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<td>Inflow Resistance</td>
<td>Increases</td>
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<td>FTHP</td>
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<td>(Increases)</td>
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<tr>
<td>$V_{\text{up}}$</td>
<td>Decreases @ low $V_a$</td>
<td></td>
</tr>
<tr>
<td>$V_{\text{down}}$</td>
<td></td>
<td>Decreases</td>
</tr>
</tbody>
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Conclusions

• Need pseudo steady-state plunger model to rank plunger against alternative techniques
• Capture plunger performance by using simplest of inflow and outflow models
• Make crude assumptions in the process
• Need to validate model against field results
• Plunger best suited for poor inflow and low liquid-gas ratio
• Plunger performance benefits from significant annulus volume and low wellhead pressure
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