Critical Velocity/ Nodal Stability Gas Well Predictions

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Liquid Loading
GAS WELL GRADIENT COMPOSED OF FRICTION AND GRAVITY

\[
\frac{dp}{dl} = \frac{dp}{dl}_{el} + \frac{dp}{dl}_f + \frac{dp}{dl}_{acc}
\]

Holdup (liquid) builds with time and lowers production.
Recognize and Predict Loading by using “Critical Rate” & “Nodal Analysis Concepts”
Critical Velocity
Turner Droplet Model

\[ F_{Gravity} = \frac{g}{g_c} (\rho_L - \rho_G) \times \pi d^3 \]

\[ F_{Drag,UP} = \frac{1}{2 g_c} \rho_G C_D A_d (V_G - V_d)^2 \]

Where
\[ g = \text{gravitational constant} = 32.17 \text{ ft/s}^2 \]
\[ g_c = 32.17 \text{ lbm-ft/lbf-s}^2 \]
\[ d = \text{droplet diameter} \]
\[ \rho_L = \text{liquid density} \]
\[ \rho_G = \text{gas density} \]
\[ C_D = \text{drag coefficient} \]
\[ A_d = \text{droplet projected cross-sectional area} \]
\[ V_G = \text{gas velocity} \]
\[ V_d = \text{droplet velocity} \]
Equate Gravity to Drag Force

\[ F_G = F_D \]

\[ \frac{g}{g_C} \left( \rho_L - \rho_G \right) \frac{\pi d^3}{6} = \frac{1}{2 g_C} \rho_G C_D A_d V_C^2 \]

Substituting \( A_d = \frac{\pi d^2}{4} \) and solving for \( V_C \) gives,

\[ V_C = \sqrt{\frac{4g}{3} \frac{\left( \rho_L - \rho_G \right) d}{\rho_G C_D}} \]
Hinze, AIChE Journal Sept 1955, shows that droplet diameter dependence can be expressed in terms of the dimensionless Weber number

\[ N_{WE} = \frac{V_C^2 \rho_g d}{\sigma g C} = 30 \]

Solving for the droplet diameter gives

\[ d = 30 \frac{\sigma g C}{\rho_g V_C^2} \]

and substituting into Equation A-1 gives

\[ V_C = \sqrt[3]{\frac{4}{3} \left( \frac{\rho_L - \rho_G}{\rho_G} \right) \frac{g}{C_D} \frac{30 \sigma g C}{\rho_g V_C^2}} \]

or

\[ V_C = \left( \frac{40 g g C}{C_D} \right)^{1/4} \left( \frac{\rho_L - \rho_G}{\rho_G^2 \sigma} \right)^{1/4} \]
Turner assumed a drag coefficient of $C_D = .44$ that is valid for fully turbulent conditions. Substituting the turbulent drag coefficient and values for $g$ and $g_C$ gives:

$$V_C = 17.514 \left( \frac{\rho_L - \rho_G}{\rho_G^2} \frac{\sigma}{S} \right)^{1/4} \text{ ft/s}$$

Where

- $r_L = \text{liquid density, lbm/ft}^3$
- $r_G = \text{gas density, lbm/ft}^3$
- $S = \text{surface tension, lbf/ft}$

Equation A-2 can be written for surface tension in dyne/cm units using the conversion

$\text{lbf/ft} = 0.00006852 \text{ dyne/cm}$ to give:

$$V_C = 1.593 \left( \frac{\rho_L - \rho_G}{\rho_G^2} \frac{\sigma}{S} \right)^{1/4} \text{ ft/s}$$

Where

- $r_L = \text{liquid density, lbm/ft}^3$
- $r_G = \text{gas density, lbm/ft}^3$
- $S = \text{surface tension, dyne/cm}$
Evaluating Equation A-4 for typical values of
Gas gravity $\gamma_G = 0.6$
Temperature $T = 120$ F
Gas deviation factor $Z = 0.9$
gives:

$$\rho_G = 2.715 \times 0.6 \frac{P}{(460 + 120) \times 0.9} = 0.0031P \text{ lbm/ft}^3$$

Typical values for density and surface tension are
Water density $= 67$ lbm/ft$^3$
Condensate density $= 45$ lbm/ft$^3$
Water surface tension $= 60$ dyne/cm
Condensate surface tension $= 20$ dyne/cm
Field Equations

Coleman, et al., (Exxon)

\[
V_{C,\text{water}} = 1.593 \left( \frac{67 - .0031P}{(0.0031P)^2} \cdot 60 \right)^{1/4} = 4.434 \left( \frac{67 - .0031P}{0.0031P} \right)^{1/4} \text{ ft/s}
\]

\[
V_{C,\text{cond}} = 1.593 \left( \frac{45 - .0031P}{(0.0031P)^2} \cdot 20 \right)^{1/4} = 3.369 \left( \frac{45 - .0031P}{0.0031P} \right)^{1/4} \text{ ft/s}
\]

Turner et al., (with 20% adjustment)

\[
V_{C,\text{water}} = 5.321 \left( \frac{67 - .0031P}{0.0031P} \right)^{1/4} \text{ ft/s}
\]

\[
V_{C,\text{cond}} = 4.043 \left( \frac{45 - .0031P}{0.0031P} \right)^{1/4} \text{ ft/s}
\]
Field Equations: Critical Rate

\[ V_{C,\text{water}} = 5.321 \frac{(67 - 0.0031P)^{1/4}}{(0.0031P)^{1/2}} \text{ ft/s} \]

\[ V_{C,\text{cond}} = 4.043 \frac{(45 - 0.0031P)^{1/4}}{(0.0031P)^{1/2}} \text{ ft/s} \]

\[ q_{t,\text{condensate}} \left(\frac{\text{MMscf}}{D}\right) = \frac{0.0676P d_{ti}^2}{(T + 460)Z} \frac{(45 - 0.0031P)^{1/4}}{(0.0031P)^{1/2}} \]

\[ q_{t,\text{water}} \left(\frac{\text{MMscf}}{D}\right) = \frac{0.0890P d_{ti}^2}{(T + 460)Z} \frac{(67 - 0.0031P)^{1/4}}{(0.0031P)^{1/2}} \]
### Well Data

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<tr>
<th>Test</th>
<th>Gas Specific Gravity (air = 1)</th>
<th>Depth (ft)</th>
<th>Tubing ID (in.)</th>
<th>Condensate (bbl/MMscf)</th>
<th>Water (bbl/MMscf)</th>
<th>WHFP (psia)</th>
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Example: Using Turner, 2 3/8’s, 100 psi, read~320 Mscf/D
Other References Related to Critical Velocity or Rate


Conclusions

1. Case studies show that Turner’s method with 20%-adjustment still under-estimates the minimum gas velocity for liquid removal (Fig. 1).

2. The kinetic energy theory indicates that the controlling conditions for liquid drop removal in gas wells are bottom hole conditions rather than top-hole conditions (Eq. 11).

3. The new method developed on the basis of the minimum kinetic energy criterion and a 4-phase flow model is more accurate than Turner’s method (Fig. 2).

Fig. 3 – The critical gas production rates for water removal in a 3.5-inch tubing at wellhead pressure 900 psia.
Critical Rate: Summary

• Turner, Coleman and other models do not agree
• Most except Guo et al. are in dependent of liquid rate
• It is theoretically better to use at pressure downhole but seldom done
• Most critical models are fairly simplistic models
• Must be considered approximate but widely used with fair success
• New model with critical as fn of bwpd seems logical but untested by industry as far as is known
Nodal Analysis
Nodal Analysis™: 
A Model of the Well

\[
\begin{align*}
\Delta P_1 &= P_i - P_{wfp} = \text{Loss in Porous Medium} \\
\Delta P_2 &= P_{wfp} - P_{wfp} = \text{Loss across completion} \\
\Delta P_3 &= P_{LFR} - P_{DBR} = \text{Loss across restriction} \\
\Delta P_4 &= P_{SUBV} - P_{DSV} = \text{Loss across safety valve} \\
\Delta P_5 &= P_{wsh} - P_{wsc} = \text{Loss across surface choke} \\
\Delta P_6 &= P_{DBC} - P_{top} = \text{Loss in flowline} \\
\Delta P_7 &= P_{wpt} - P_{wpt} = \text{Total loss in tubing} \\
\Delta P_8 &= P_{wpt} - P_{wpt} = \text{Total loss in flowline}
\end{align*}
\]
**Nodal Analysis™ (SLB)**

**Inflow to the node**

\[ PR - \Delta P \text{ (upstream components press drop's) } = P_{\text{node}} \]

**Outflow from the node**

\[ P_{\text{sep}} + \Delta P \text{ (downstream components press drop's) } = P_{\text{node}} \]
Inflow Curves
Inflow or Reservoir Curve

Reservoir Inflow curve often represented by:

\[ Q = C \left( P_r^2 - P_{wf}^2 \right)^n \] .... (back pressure equation)
Outflow Curves
At low rates, liquid builds up in the tubing and requires more pressure to flow

(Tubing J-Curve)

(Use various correlations, Gray, etc.)
Liquid Loading J-Curve with Tubing to Perfs

**Liquid Loading J-Curve with Gray**

- **Flowing BHP (psig)**
- **Tbg - Critical Rate (Min BHP) = 547 mscf/d**
  - Pfwh = 125 psig
  - Cond = 0.0 bbl/MMscf
  - Water = 15.0 bbl/MMscf

- **2.375" at 10000 ft**

Liquid loading occurs when gas rate is too low to efficiently remove the produced liquids. This results in unstable flow behavior and potential logging off of the well.

- **Unstable flow**
  - High liquid buildup

- **Stable flow**
  - High friction
  - May have some liquid buildup

**Optimal Operation**

Mar. 5 - 7, 2007
2007 Gas Well De-Liquification Workshop
Denver, Colorado
Flowpoint: Greene, SWPSC
Liquid Loading

- Liquid loading occurs when gas rate is too low to efficiently remove the produced liquids.
- This results in unstable flow behavior and potential logging off of the well.
Liquid Loading
Effect of Tubing String

**Nodal Plot**

- **S1 - Tubing Flow - Pbg = 500 psig**
- **S2 - Tubing Flow - Pbg = 500 psig**
- **S3 - Tubing Flow - Pbg = 500 psig**
- **Stable Flow**

- **Pbar = 1450 psia**
- **Pbar = 1250 psia**
- **Pbar = 1050 psia**

- Cond .6 bbl/MMscf
- Water 15.0 bbl/MMscf

- S1 - 2.375" at 10000 ft
- S2 - 1.9" at 10000 ft
- S3 - 1.66" at 10000 ft

Gray Correlation
Nodal Analysis: Effects such as Size of the Tubing Diameter vs. Flow Rate can be studied.
Nodal “Turn-Up” Point is **BIGGEST ERROR** in Multiphase Flow Predictions

**Figure 6.12** Comparison of Some Vertical Flow Pressure-Drop Models
Nodal Stability
Nodal Analysis Well Situations

- Inflow or rsrv curve
- Tubing crv, no flow
- Tubing crv, flow
- Tubing crv, more flow
- Tubing crv, flow but unstable

Intersections are flow pts

Psi on perfs vs BPD
Nodal Analysis: Stability

Flow around A & B is unstable
Flow around C and D is stable
What About Flow Below the Critical???

- Exxon said on average with their data, production was 40% less.
- Sutton, et al., Marathon, SPE 80887 modeled flow with gas bubbling through static liquid column.

![Graph](image.png)  

**Fig. 4 – Example of Well Performance with Liquid Loading**
Model Gas Well
Example Gas Well

- Data:
- Reservoir:
  - C = .0001414 Mscf/D
  - n = 1.0
  - Pr = 1500 psi
- Tubing: 2 3/8’s to 10,000’
- Liquids: 50 bbl/MMscf

- Pressures/Temps/Fluid Properties
  - Pwh: 100 psi
  - Twh: 100 F
  - BHT: 200 F
  - GG: .7
  - WG: 1.03
  - WOR: 1.

SNAP: Ryder Scott
Example Output
Well Unstable and Also Flowing Below Critical for Water

This well unstable according to shape of outflow curve at point of intersection with IPR
Effects of Tubing Size
Smaller tubing such as 1.61 or 1.38 (or smaller) ID stabilizes flow.

Critical rate for 1.61 is 245 mscfd

Critical rate for 1.38 is 152 mscfd

So 1.61” or smaller stabilizes and flows above critical rate
Effects of Surface Pressure
Adding constant surface pressure such as higher separator pressure does not stabilize or tend to flow above critical rate.
Lower Surface Pressure:

Flowing at 12 psig stabilizes and flows above critical of 157 mscfd

Flowing at 50 psig flows above critical rate of 241 mscfd but is “just stable”?
Effects of Restrictions at Bottom of Tubing
Adding a choke restriction at bottom hole of .15” diameter or .14” diameter stabilizes flow. It is still below critical flow however.
Effects of Restrictions at Surface
Adding a choke of .21” diameter or .18” diameter at surface stabilizes flow. It is still below critical rate however.
Effects of Flowline
A flowline of more and more pressure drop has a stabilizing effect but flow is still below critical rate.
Summary & Conclusions
Summary & Conclusions

• Smaller tubing has stabilizing effect but if too small will add too much friction (well known)

• Adding constant pressure to the surface of the well reduces rate and does not stabilize the well or tend to flow below critical

• Adding lower constant pressure to the surface of the well stabilizes the well and tends to flow above critical rate (compression)

• Adding a rate dependent pressure drop (choke) to bottom or top of well has stabilizing effect but flow remains below critical rate if below critical to begin with
Summary & Conclusions
Continued

• The effects of a flowline (rate dependent pressure drop) has a stabilizing effect on the flow but flow continues below critical if below to start with as FL pressure drop is added.

• Never add rate dependent pressure drop (choke) to a well that is flowing above critical rate. It will only reduce flowrate

• Adding too much of a rate dependent pressure drop (choke) will/can reduce flowrate to zero
• In general never add a rate dependent pressure drop to plunger lift, or pumping wells or gaslift wells. There are some exceptions where back pressure may help beam handle gas better and choking gaslift well can sometimes reduce heading and cycling.
Questions Remaining

• Since Nodal Analysis shows a stabilizing effect on a loaded gas well only, (but still flows below critical rate), does this explain the anecdotal cases where adding chokes to wells in the field gets them to flow continuously where they would not before?

• Cases are reported where wells that require stop clocking will flow continuously if a choke is added to the surface. It may serve as intermediate solution to loading before AL is needed.

• Is critical rate alone good enough to evaluate loading wells or is Nodal Analysis also to evaluate stability?
Problems

• Multiphase correlations have poor agreement to evaluate stability in loaded/unloaded gas wells

• Critical velocity correlations also disagree and have problems previously discussed
Better?

Numerical and Analytical Modeling of the Gas-Well Liquid-Loading Process


November 2006 SPE Production & Operations
Possible Uses of Analysis

• If a well is loaded and it must be intermitted to continue production, consider using a choke to get the well to flow continuously once again. The cost is low to try this.

• DO NOT add chokes across the field indiscriminately or you will have problems.

• Thanks to Mohan Kelkar, Tulsa University, for pointing out the stabilizing effects of adding chokes to loaded gas wells. At least stabilizing as far as Nodal Analysis predictions are concerned. He also has reported success stories with this technique.
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