Stabilizing gas-lift well dynamics with free operating point

A. Plucenio * C. A. Ganzaroli * D. J. Pagano *

* Department of Automation and Systems, Federal University of Santa Catarina, Florianópolis, Brazil (e-mail: {plucenio, cleberag, daniel}@das.ufsc.br)

Abstract: Gas-lift is one of the most used artificial lift methods worldwide. In Brazil it responds for more than 70% of the total oil production. Gas-lift wells are known to present oscillatory behavior associated with phenomena like heading and density wave. This work presents an innovative way to control these oscillations. The approach adopted controls the well dynamics without fixing any operational set point, decoupling the dynamic control from the optimization algorithm.

Keywords: gas-lift simulation, gas-lift control.

1. INTRODUCTION

One dynamic phenomenon observed in gas-lift well operation is heading. Heading is explained as an interaction between the annular and production tubing flow. Typically, gas enters in the production tubing through an orifice type valve working in the non-critical region, Hu (2004), Sinegre et al. (2005). For sufficient low gas mass flow-rate, the gas-lift operating valve is blocked by the weight of the production tubing fluid. The constant top casing gas inflow causes the annular pressure to rise in a ramp form which eventually overcomes the counter-pressure causing a strong gas inflow in the production tubing. This has two consequences: i) forces the production of most of the fluid inside the production tubing lowering the counter pressure in front of the perforations, ii) depletes the annular, lowering its pressure. As a consequence, there is a high liquid inflow from the formation which develops a back pressure that rapidly becomes higher than the annular pressure on the other side of the gas-lift operating valve and the process repeats.

One way to prevent heading is to operate with critical flow in the gas-lift operating valve. For orifice valves this requires using an orifice diameter that would result in a pressure ratio between downstream tubing valve and upstream valve smaller than a critical value (around 0.55). This means too high pressure in the annular and the solution came with the development of Venturi type valves. These valves develop critical flow with a downstream-upstream pressure ratio around 0.9. But wells with Venturi type gas-lift valve also develop oscillations. Apart from the cyclic nature of the behavior, common to the heading case, a new phenomenon called density wave happens with stabilized annular pressure and constant flow in the gas-lift operating valve. Below a certain gas flow-rate the gas accumulates in the proximity of the gas-lift operating valve. As more gas enters in the production tubing the liquid is pushed upwards until it is produced as a slug. The back pressure in front of the perforations is decreased and liquid enters in the production tubing. Gas continues to enter at a low flow-rate and the process repeats. As shown in Sinegre (2006) the gas mass fraction dynamics explains the density wave phenomenon seen in gas-lift wells. These phenomena results in dynamics known as limit cycle and in intermittent production rates. There is a tendency in the oil industry to refer to heading and density wave as completely different phenomenon. What about the oscillations that happen before the development of the sustained oscillations? Although there is a clear difference when the flow in the gas-lift operating valve is critical or not, we believe that the gas mass fraction dynamics is at the center of the problem. We believe that gas mass fraction behavior along the production tubing height is associated with both phenomena. Based on its dynamics, a control technique is developed which suppress the oscillations due to both cases.

The paper is organized as follows. In section 2 the gas-lift well control strategy is introduced. In section 3 a simplified gas-lift well simulator is presented. The control algorithm is detailed and its implementation is discussed in section 4. In section 5 the simulation results are shown. All variables and parameters are defined in table 1.

2. CONTROLLING GAS-LIFT WELL DYNAMICS

Several papers have been published about gas-lift wells modeling and control as in Eikrem et al. (2004), Hu (2004), Imsland et al. (2003) and Plucenio et al. (2009). In Camponogara et al. (2010) an optimization and control strategy was developed to distribute the gas arriving in a gas-lift manifold (GLM) shown in figure 1 following a set of objectives:

\* A. Plucenio and D. J. Pagano are supported by CENPES-Petrobras under project Real Time Optimization and Control of Oil Production Systems, C. A. Ganzaroli is supported by the Brazilian Institute of Petroleum (IBP)

\** Contribution to invited session on Production stabilization
• The incoming gas flow-rate is distributed to the N
  wells in order to maximize an objective function
• The sum of the GLM output gas should be controlled
  in order to have a desired GLM pressure
• The gas flow-rate to each well is constrained to
  minimum and maximum values

\[
V_g = V_i + \frac{V_{\infty}}{1 - \alpha}. \quad (4)
\]

Using the gas mass fraction defined as
\[
x = \frac{\alpha \rho_g}{\alpha \rho_g + (1 - \alpha) \rho_l}, \quad (5)
\]
and the mass conservation equations for the gas and liquid phases, the Riemann invariant is obtained,
\[
\frac{\partial x}{\partial t} + V_g \frac{\partial x}{\partial x} = 0. \quad (6)
\]

This means that for a constant gas velocity \( V_g \) the gas mass fraction at the wellhead, at time \( t \), would be equal to the one that happened at the bottom, at a time \( (t - \tau) \) with \( \tau = \frac{L}{V_g} \), where \( L \) is the distance between wellhead and well bottom. The gas mass fraction travels inside the production tubing and it manifests itself as a changing gas volume fraction at surface. For a sufficient low gas flow-rate entering in the well annular, the heading or density wave phenomenon is established causing intermittent production at surface. We propose stabilizing the gas-lift well by making

\[
\frac{\partial x}{\partial t} = 0, \quad (7)
\]
on the production tubing at the depth of the gas-lift operating valve. By doing so, according to (6), we force \( \frac{\partial x}{\partial x} = 0 \), condition that should stabilize also the gas and liquid volume fractions avoiding slug flow in the wellhead.

Replacing equation (3) in (5),
\[
x = \frac{q_g}{q_g + q_l + V_{\infty} A_{\rho_l}}, \quad (8)
\]
where \( q_g \) and \( q_l \) are respectively the gas and liquid mass flow-rate. The term \( V_{\infty} A_{\rho_l} \) represents a virtual mass flow-rate due to the drift gas velocity, defined here as \( q_d \). The gas mass fraction \( x \) is considered here as the key variable to explain the dynamic of the gas-lift wells. We believe that it is possible to implement \( \frac{\partial q_d}{\partial t} = 0 \), using feedback control to force \( \frac{\partial q_d}{\partial t} = 0 \).

For that purpose we note that
\[
\frac{\partial x}{\partial t} = \dot{x} = \frac{\dot{q}_g (q_l + q_d) - \dot{q}_l q_g - q_d q_q}{(q_g + q_l + q_d)^2}. \quad (9)
\]

An assumption is made that \( \dot{q}_d = 0 \) since \( V_{\infty} \) do not vary too much with time for low void fraction values.

The variable gas mass fraction is not usually measured. On the other hand new gas-lift wells are being equipped with downhole gauges to measure pressure and temperature. To enforce \( \frac{\partial x}{\partial t} = 0 \) in equation (9) means to ensure \( \dot{q}_g = 0 \) and \( \dot{q}_l = 0 \). For critical flow \( \dot{q}_g \) does not depend on \( p_{w,f} \), so, for a constant upstream pressure on the gas-lift operating valve \( \dot{q}_g \) is zero. For subcritical flow \( \dot{q}_g = f(p_{w,f}) \), so \( \dot{q}_g = \frac{\partial q_g}{\partial p_{w,f}} \frac{\partial p_{w,f}}{\partial t} \). Therefore, for \( p_{w,f} = 0 \), \( \dot{q}_g = 0 \). \( q_d \) depends on the inflow performance curve which is written as function of \( p_{w,f} \) and \( \dot{q}_l = \frac{\partial q_l}{\partial p_{w,f}} \frac{\partial p_{w,f}}{\partial t} \). Again, by making \( p_{w,f} = 0 \) we have \( \dot{q}_l = 0 \). We conclude that \( \dot{x} = 0 \) can be warranted by forcing \( p_{w,f} = 0 \).
3. THE GAS-LIFT WELL SIMULATION

In order to test the control approach a simple gas-lift well simulator was developed. Its development was based on the mass and momentum conservation laws in the annular and production tubing. It is assumed that temperature is constant and that there is no mass transfer between the gas and liquid phase. The gas flow from the annular to the production tubing happens through an orifice valve with a check valve. On the surface there is a gas-lift valve connecting the gas-lift manifold to the casing and a production choke between the wellhead and the separator with controlled opening. In order to simplify the model the well is assumed to be vertical and the gas-lift operating valve is considered to be at the same depth as the perforations. The formation fluid inflow is modeled according to a Vögel equation. Two PDEs (Partial Differential Equations) describe the flow in the annular on the variables pressure, $p_A$ and mass flow-rate $q_A$. Three PDEs describe the flow in the production tubing with the variables gas volume fraction, $\alpha$, pressure $p_T$ and total mass flow-rate $q_T$.

$$\frac{\partial p_A}{\partial t} = - \left( \frac{RT}{MA_A p_A} \right) \frac{\partial q_A}{\partial z} + \frac{M A_A g}{RT} p_A - \frac{RT}{2MA_A DA_A p_A} \left( A_A - \frac{RT}{MA_A p_A^2} \right) \frac{\partial p_A}{\partial z}$$

$$\frac{\partial \alpha}{\partial t} = \frac{1}{\rho_l \rho_T (1 - x)} \frac{\partial q_T}{\partial z} - \frac{1}{\rho_i \alpha \rho_T} \frac{\partial q_T}{\partial z}$$

$$\frac{\partial q_T}{\partial t} = - \left( \frac{RT}{MA_T} \right) \frac{\partial q_T}{\partial z} + \left( \frac{q_T^2}{AT \rho_m^2} \right) \frac{\partial \rho_m}{\partial z} - \frac{AUT p_m g - f q_T^2}{2DT \rho_T \rho_m} - \frac{\partial q_T}{\partial z}$$

Apart from the differential equations (10) the following algebraic equations are used,

$$\rho_m = \rho_l \alpha + (1 - \alpha) \rho_i$$

$$q_A^f = q_A^{max} \left( 1 - 2 \left( \frac{P_{oil}}{P_T} \right) - 8 \left( \frac{P_{oil}}{P_T} \right)^2 \right)$$

$$q_A^l = \left( \frac{BSW}{1 - BSW} \right) q_A^{max}$$

$$q_T^f = \frac{GOR q_A^f}{\rho_o}$$

(11)

The equations for the friction factors, orifice and control valves are not presented due to lack of space. The variables used in the model are presented in table 1 while the parameters used in the simulation are shown in table 2.

3.1 Simulation results

The set of PDEs were first solved for steady state to obtain valid initial conditions considering the boundary conditions determined by the gas-lift manifold, reservoir and separator pressures. Next, the annular and production tubing were divided in $N$ sections and the space derivatives were written using a central difference scheme. An ODE solver was used to obtain the solution. The steady state results are shown in figures 2, 3 and 4.

Figures 5 and 6 show the dynamics obtained with the gas-lift simulator developed for manipulations in the gas-lift valve opening. The simulation starts with an injection valve opening of 50%. After one hour the gas-lift valve opening is reduced to 18% and to 11% after four hours. The dynamic of pressure and flow-rates that follow are very similar to what is observed using commercial simulators. With the opening of 11% the well develops a heading behavior characterized by an intermittent flow-rate on the
Regardless of the phenomenon taking place, heading or density wave, there is a gas injection flow-rate, \( \dot{q}_{\text{HB}} \) which takes the system to a Hopf Bifurcation characterized by the development of a stable limit cycle with a fundamental frequency \( \omega_n \). With the well operating on the limit cycle the bottom hole pressure \( P_{wf} \) is written as

\[
P_{wf} = \tilde{P}_{wf} + \Delta P_{wf},
\]

where \( \tilde{P}_{wf} \) is the offset value of the pressure signal which includes \( P_s \), the separator pressure, \( \tilde{P}_{wf} \) represents its zero average oscillatory component and \( u_{PC} \) the pressure drop in the production choke. For the purpose of control design, \( \tilde{P}_{wf} \) is modeled as a sinusoidal wave with the frequency \( \omega_n = 2\pi/T \) and \( T \) is the oscillation period of \( \tilde{P}_{wf} \). Equation (12) shows the discrete model of \( \tilde{P}_{wf} \) with the sampling time \( T_s \) where \( a_1 = 2 - b \), \( a_2 = 1 \) and 

\[
e(k + 1) = \tilde{P}_{wf}(k + 1) - \tilde{P}_{wf}(k).
\]

One approximate expression for \( u_{PC} \) is

\[
u_{PC} = C_{\text{VN}}^2 \frac{q^2}{f(\phi)^2} \rho_m, \quad \text{or} \quad u_{PC} = \frac{B}{f(\phi)^2}
\]

with \( q \) being the mass flow-rate through the choke, \( C_{\text{VN}} \) the valve \( C_v \) for 100% opening, \( \rho_m \) the average fluid density and \( f(\phi) \) representing the valve the type of valve response as function of its opening. Since \( q \) and \( \rho_m \) are not usually measured, a simplified expression is adopted to \( u_{PC} \) considering \( f(\phi) = \phi \),

\[
u_{PC} = \frac{B}{\phi T}.
\]

Obviously the choice of \( B \) must be guided by the expression on equation (15).

### 4.1 Developing the control law

The development of the control law is based in the Lyapunov approach. The following Lyapunov function is proposed

\[
L(e(t)) = \frac{1}{2} e(t)^2,
\]

\[|e(t)| < \epsilon,
\]

\[
\epsilon = 0.1
\]

\[
\Delta P_{wf} \text{ is the difference between the measured and calculated pressure at the bottom of the tubing.}
\]

\[
\Delta P_{hf} = \Delta P_{wf} + \Delta P_{hf}
\]

\[
P_{wf} = \tilde{P}_{wf} + \Delta P_{wf},
\]

\[
u_{PC} = C_{\text{VN}}^2 \frac{q^2}{f(\phi)^2} \rho_m, \quad \text{or} \quad u_{PC} = \frac{B}{f(\phi)^2}
\]

\[
u_{PC} = \frac{B}{\phi T}
\]

\[
\Delta P_{wf} \text{ is the difference between the measured and calculated pressure at the bottom of the tubing.}
\]

\[
P_{wf} = \tilde{P}_{wf} + \Delta P_{wf},
\]

\[
u_{PC} = C_{\text{VN}}^2 \frac{q^2}{f(\phi)^2} \rho_m, \quad \text{or} \quad u_{PC} = \frac{B}{f(\phi)^2}
\]

\[
u_{PC} = \frac{B}{\phi T}
\]
which is positive definite since, \( L(0) = 0 \) and \( L(e(t)) > 0 \) \( \forall e(t) \neq 0 \). For the closed loop to be stable, 
\[
\frac{dL(e(t))}{dt} \leq 0, 
\]
(18)
which is equivalent to the discrete representation, 
\[
\frac{\Delta L(e(k))}{\Delta(kT_s)} \leq 0, \quad \text{but} 
\]
(19)
\[
\frac{\Delta L(e(k))}{\Delta(kT_s)} = e(k)\left(\frac{e(k) - e(k - 1)}{b}\right). 
\]
(20)
The control action must ensure that 
\[
\Delta L(e(k)) \leq 0, \quad \text{or} 
\]
(21)
e(k)(e(k) - e(k - 1)) \leq 0. \quad \text{(22)}
If the control algorithm ensures that for any sample time \( k \), \( e(k + 1) = Ge(k) \) with \( 0 < G < 1 \), then 
\[
\Delta L(e(k)) = Ge(k - 1) (Ge(k - 1) - e(k - 1)) 
\]
\[
\Delta L(e(k)) = e(k)^2(G^2 - G) 
\]
(23)
Since \( e(k - 1)^2 > 0 \) and \( (G^2 - G) < 0, \Delta L(e(k)) \leq 0 \). If the control action ensures that for any \( k, e(k) = Ge(k - 1) \) for \( 0 < G < 1 \), then \( \Delta L(e(k)) \leq 0 \) and \( e(k) \) tends to zero. Substituting the requirement that \( e(k + 1) = Ge(k) \) in equation (14),
\[
Ge(k) = a_1e(k) - a_2e(k - 1) + b\Delta u_{PC(k)}, \quad \text{(24)}
\]
which can be arranged to represent a Proportional Integral control algorithm,
\[
u_{PC(k)} = u_{PC(k - 1)} + \left(\frac{G - a_1}{b}\right)(e(k) + 1) e(k - 1), \quad \text{with} \quad K_c^0 = -1/b \quad \text{and} \quad T_i = \frac{T_s}{1 - G - b}.
\]
It is well known that the production choke has to be kept as much opened as possible since closing it causes the bottom hole pressure \( P_{e,f} \) to increase resulting in decreased formation fluid inflow. In order to achieve this secondary objective, the control algorithm is modified to include a term which forces the choke opening to a desired opening. This is accomplished with the following modified PI control,
\[
u_{PC(k)} = u_{PC(k - 1)} + \gamma_o e(k) + \gamma_1 e(k - 1) + \beta_1 \left(u_{PC(k)} - u_{PC(k - 1)}\right), \quad \text{with} \quad u_{PC} = \frac{B}{\phi_d}.
\]
(25)
with \( \phi_d \) representing the desired choke opening in steady state and \( \beta_1 \) being a factor to adjust the speed response of this term. The desired opening \( \phi_d^{HB} < 1 \) is assigned for \( q_g \leq q_g^{HB} \). For higher surface gas flow-rates \( \phi_d = 1 \). In order to have a smooth transition the following rule is proposed for \( \phi_d \) which is used to compute \( u_{PC} \).
\[
\text{if} \quad q_g \leq q_g^{HB} \quad \text{then} \quad \phi_d = \phi_d^{HB} \quad \text{(26)}
\]
\[
\text{else} \quad \phi_d = \phi_d + (1 - \phi_d) e^{-\beta_2(t_e - t_e^{HB})}. \quad \text{(27)}
\]
A final consideration has to be done as for the application of control for flow-rates higher than \( q_g^{HB} \). Manipulating the production choke should be done only in extreme situations as for the case of heading and density wave. Obviously for \( q_g \) close to \( q_g^{HB} \) a level of control may be desired. Instead of turning the control off for higher gas flow-rate the control gain \( K_c \) can be weighted,
\[
\text{if} \quad q_g \leq q_g^{HB} \quad K_c = K_c^0, \quad \text{(27)}
\]
\[
\text{else} \quad K_c = \frac{K_c^0}{(\beta_3 q_g)^n}, \quad \text{with} \quad \beta_3 q_g^{HB} = 1.
\]
The value of \( n \) can be adjusted to make \( K_c = \frac{K_c^0}{10} \) or smaller for the well nominal operating \( q_g \).

5. SIMULATION RESULTS

5.1 Application to Heading

Table 3 presents the parameters used in the control for a well described in section 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_s )</td>
<td>60 s</td>
</tr>
<tr>
<td>( w_m )</td>
<td>0.0015</td>
</tr>
<tr>
<td>( K_w )</td>
<td>-124.8</td>
</tr>
<tr>
<td>( T_i )</td>
<td>121 s (G = 0.5)</td>
</tr>
<tr>
<td>( B )</td>
<td>2/3000 ( Pa )</td>
</tr>
<tr>
<td>( \beta_1 )</td>
<td>0.75</td>
</tr>
<tr>
<td>( \beta_2 )</td>
<td>12</td>
</tr>
<tr>
<td>( \beta_3 )</td>
<td>1</td>
</tr>
<tr>
<td>( n )</td>
<td>3</td>
</tr>
<tr>
<td>( q_g^{HB} )</td>
<td>0.7 kg/s</td>
</tr>
<tr>
<td>( u_{PC} )</td>
<td>0.8</td>
</tr>
</tbody>
</table>

![Fig. 7. Results I- Production tubing with control off at \( t = 24 \) h](image).](image)

In figure 7 and 8 the results obtained with the control technique are shown. The same sequence of gas injection valve opening shown in figure 5 is implemented with control applied. The oscillations are suppressed but return when the control is turned off and the choke opening is kept fixed at 80%. As planned, the choke opening, shown on figure 8, keeps the desired opening in steady state. Which is 100% for high gas injection flow-rate and 80% for flow-rates around the value \( q_g^{HB} \). At the moment of changing the gas injection, the choke opening reacts in order to suppress the oscillations. The control action \( u_{PC} \)
added with the separator pressure is presented in figure 7-b. It is very close to the pressure on the wellhead in steady state showing that B value was well chosen.

5.2 Application to density wave

On figure 9 the same control technique was applied to a well using a Venturi valve. This was simulated with a fixed gas mass flow-rate entering the production tubing at the depth of the gas-lift valve. The oscillations are again suppressed with the desired choke opening of 80% in steady state. It must be noticed that the gas mass fraction shown in 9-f at top and bottom of the production tubing are stabilized with the control action. On the same figure it is observed that, indeed, the gas mass fraction at top is very similar to the one at bottom with a delay as pointed out by Sinegre et al. (2005).

5.3 Choke opening characteristic

The control algorithm proposed does not compute the choke opening but a value expressed by equation (15). Would the control action value be required to be linear with the choke opening, then \( u_{PC} = \frac{B}{f(\phi)} = C(1 - \phi) \), or

\[
f(\phi) = \left( \frac{B}{C(1 - \phi)} \right)^{1/2}.
\]  

(28)

Plotting \( f(\phi) \) as in equation (28) shows that an equal-percentage valve type would be appropriate for the choke.

6. CONCLUSIONS

The control technique proposed and applied to the simulated wells achieved the objective of suppressing the oscillations due to heading and density wave. The main advantage of this technique is its ability to stabilize the well without forcing an operational set-point. This allows for decoupling the optimization strategy from the dynamic control. The controlled steady state value of an unstable downhole pressure is hard to determine and setting an infeasible value as a set-point does not help stabilization. The expected benefits of the proposed approach are

- to enlarge the gas injection flow-rate range of each well, improving optimization results,
- to keep a larger number of wells working for a limited availability of gas for injection,
- to simplify the optimization algorithm.

The same technique has been applied with success on the control of severe slug in risers and the results will be presented in another publication. One approach drawback is the utilization of the bottom hole pressure derivative. Noise measurement is always present and may create difficulties for the application of the technique. Fortunately the downhole pressure is sampled at a rate much higher than the used for control application and there are several possible resampling and filtering techniques that can recover the derivative.

REFERENCES


