

Effects of Gas/Oil Ratio (GOR), Lift Gas Injection Rate and Percentage Choke Opening on Casing-Heading Instability in a Gas-Lifted System

Ojonugwa Adukwu

ABSTRACT

This research investigated the effects of gas/oil ratio, lift gas injection rate and percentage choke opening on casing-heading instability in gas lift system. The gas lift models and parameters used were first presented and injection valve flow rate at no oscillation was shown. The severity was monitored on the flow rate of gas through the injection valve. As the GOR decreases, chances of casing heading instability increases from damped oscillation to mild oscillation till severe oscillation takes place. On the other hand, increasing the flow of lift gas into the annulus reduces the chance of oscillation. The percent valve opening increase leads to increase in chances of instability. This knowledge helps in providing information needed to reduce or eliminate casing-heading instability. The study is important as casing heading instability leads to reduced average oil production which means the gas lift system is operated suboptimally.

Keywords: Gas lift, Casing-Heading Instability, Gas Oil Ratio, Gas Lift Valve, Optimisation

INTRODUCTION

Hydrocarbons are usually located deep down beneath the earth surface. Naturally, the reservoir pressure provides the energy required to lift the crude oil from the reservoir into the tubing for onward delivery to the downstream facilities. But as production increases, this reservoir pressure declines to the point where it can no longer lift the crude oil as desired. Artificial lift methods is then require to augment the natural reservoir pressure [1]. These artificial means include sucker-rod pump [2], electric submersible pump [3], and gas lift [4] among others. Gas lift is used mostly in oil fields with dense oil well and the cost of running the gas lift is extremely high hence there is the need to run it optimally. Many problems affect the optimal operation of the gas lift. These problems include faults, weather and casing-heading instability among others.

Figure (1) is a gas lift system. It is made up of two concentric cylinder-like structure with the outer one called the annulus and the inner one, the tubing. The lift gas is delivered into the system from the compressor station (not shown) through the gas lift choke. The annulus holds the lift gas and delivers it to the tubing through the injection valve. There are many injection valves in a typical gas lift system and they are located at different heights of the well. The tubing contains the oil and the gas from the annulus and the reservoir respectively. Produced mixture is sent to the platform through the production choke. Produced mixtures from other wells in the field are gathered at the platforms for delivery to the separator through a common riser [5].

Casing-heading instability is described here briefly. As production increases, reservoir pressure becomes insufficient for lifting the oil out of the reservoir due to the hydrostatic pressure of the oil being too high for the reservoir pressure. Gas from the annulus then mixes with the oil in the tubing reducing the density of the mixture hence the bottom hole pressure to the point where the reservoir pressure can then lift the mixture. Production increases and the pressure decreases further encouraging the flow of more gas into the well from the annulus. This leads to a decrease in annulus pressure until the annulus pressure becomes lower than the well pressure. Gas no longer flows from annulus into the tubing. Oil begins to accumulate in the tubing while gas begins to accumulate in the annulus. This continues until the annulus pressure becomes larger than the tubing pressure again and flow from annulus to tubing starts again. This behavior causes the variation of the states and variables of the gas lift system, a situation called casing-heading instability [6,7].

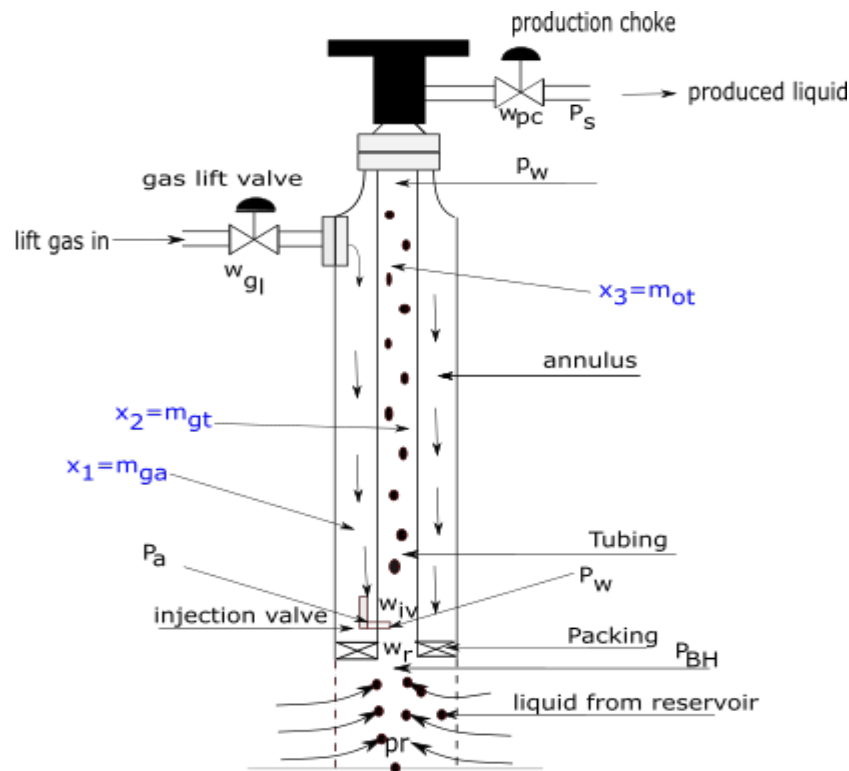


Figure (1) A single well gas lift system

Casing-heading instability is a phenomenon that makes the variables and states of the gas lift system exhibit oscillatory behavior. This oscillation reduces average oil production hence must be minimized or removed [8]. Various factors affect the casing-heading instability including natural, design and lift gas usage, control among others. In this paper we simulate a gas lift system using field scale gas lift data to investigate how the GOR, w_{gl} and input valve opening affect the casing heading instability.

This paper is organized as follows; Chapter 2 discusses various factors that affect the casing heading instability. Chapter 3 presents the gas lift models that is commonly used in oil industry

while chapter 4 simulates the gas lift system showing how the factors affect the instability. Chapter 5 concludes the paper.

CONTROL OF CASING-HEADING INSTABILITY

As noted earlier, gas lift is used because the bottom hole pressure in the tubing is too large for the reservoir pressure to lift the oil in the tubing. Mixing the oil with gas reduces the density hence the bottom hole pressure. The more gas in the tubing, the lower the bottom hole pressure and the more chance there is a continuous production of oil through the choke. But as the gas in the well increases, the mass of the gas can be significant enough in the well leading to increase in bottom hole pressure again. Many natural means therefore affect the gas lift system. The Gas/oil ratio describes the ratio of the mass of oil to the mass of gas from the reservoir. This implies that higher GOR increases gas supply naturally to the tubing hence reducing casing heading instability [8]. Reservoir pressure is the natural source of energy for lifting oil from the reservoir. The higher the reservoir pressure, the more the flow hence the lower the chances of casing heading instability.

Casing heading instability can be examined during design too. The pressure in the annulus at the injection point of the gas into the tubing is called annulus pressure here while the pressure at the same point in the tubing side is called well pressure. If annulus pressure is held higher than the well pressure in the tubing, there will be continuous flow of gas from annulus into the tubing and casing-heading instability will be eliminated. The annulus volume increases the annulus pressure while the tubing pressure increases the bottom hole pressure. Higher annulus pressure therefore reduces chances of casing-heading instability while higher tubing pressure increases the chances.

The amount of gas in the annulus determines the annulus pressure. The mass of gas in the annulus is determined by flow rate of the gas into the annulus and the flow rate of the gas through the injection valve into the tubing. Higher flow rate of the injection gas reduces the chances of casing heading instability. But increasing this gas increases oil production until a point at which further increase leads to decrease in production as shown in figure 2.

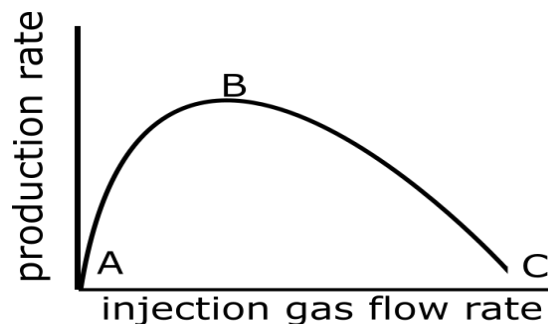


Figure 2 - Oil production variation with injection gas flow rate

In figure 2, the rate of oil production increases with flow rate of the injection gas from Point A. At point B, the oil production reaches its maximum and further increase in injection gas leads to a decrease in oil production. Point B therefore is the optimum gas supply beyond which the

gas lift system will be operated sub-optimally till point C. Hence casing heading reduction can only continue with gas supply up to point B.

Another factor that affects the chance of casing-heading instability is controller. Gas lift system is very unpredictable as the reservoir condition is constantly changing. This in addition to the environmental factors such as temperature changes, water around the system makes the gas lift system to be constantly varying. Using controller that has set point for the annulus pressure and well pressure ensures continuous flow from annulus to tubing hence removing casing heading instability. Since the pressure of annulus gas depends on the mass of gas in the annulus, the mass of gas in the annulus can also be used as set point for the controller.

In this work, we examined the effects of gas/oil ratio (GOR), flow into the annulus (w_{gl}) and fraction of valve opening (u) on the severity of casing-heading instability. The values of the factors that kept the system in stable, damped oscillation, mild oscillation and severe oscillation were investigated.

GAS LIFT MODELS

Various gas lift models exist depending on the need for the models. The most accurate models are the ones represented by partial differential equation like [9]. For control applications, this model can be difficult to use. Accurate models are more complex to use hence tradeoffs are usually done between model accuracy and ease of use.

The models used here are a mixture of that present in [8] and [10] with slight modifications for our simulations here. The gas lift system is a DAE of the form:

$$\dot{x} = f(x, z, u) \quad (1a)$$

$$0 = g(x, z, u) \quad (1b)$$

Where (1a) is the differential part and (1b) is the algebraic part discussed below:

The differential equations relates to mass balance in the system and given in (2) to (4) below.

$$\frac{dm_{ga}}{dt} = w_{gl} - w_{iv} \quad (2)$$

$$\frac{dm_{gt}}{dt} = w_{iv} + w_{rg} - w_{pg} \quad (3)$$

$$\frac{dm_{ot}}{dt} = w_{ro} - w_{po} \quad (4)$$

The state variables are m_{ga} , m_{gt} and m_{ot} which are mass of gas in annulus, in tubing and mass of oil in tubing respectively. While w_{gl} , w_{iv} , w_{rg} , w_{pg} , w_{po} and w_{ro} are flow rates of injection gas, flow rate of gas from annulus into the tubing, flow rate of reservoir gas, flow rate of produced gas, flow rate of reservoir oil and flow rate of produced oil respectively.

The algebraic equations regarding the pressures are given by equations (5) – (7)

$$P_a = \left(\frac{T_a R}{V_a M} + \frac{g}{A_a} \right) g_a \quad (5)$$

$$P_{wh} = \frac{T_a R}{M} \left(\frac{m_{gt}}{V_t + V_{bh} - \frac{m_{ot}}{\rho_l}} \right) \quad (6)$$

$$P_w = P_{wh} + \frac{(m_{gt} + m_{ot} - \rho_m V_{bh}) g H_t}{V_t} \quad (7)$$

$$P_{bh} = P_w + \rho_m g H_{bh} \quad (8)$$

P_a , P_{wh} , P_w and P_{bh} are the annulus pressure, wellhead pressure, well pressure at the point of injection and bottom hole pressure respectively. T_a , R , V_a , M , g , A_a , T_t , V_t , V_{bh} , ρ_m and H_t are the annulus temperature, gas constant, annulus volume, molar mass of gas, acceleration due to gravity, area of annulus, temperature of tubing, volume of tubing, volume of bottom hole, density of mixture in the tubing and height of tubing respectively.

The algebraic equations relating the flows and their constraints are given by equations (9) to (14)

$$w_{iv} = C_{iv} \sqrt{\max(0, \rho_a (P_a - P_w))} \quad (9)$$

$$w_{pc} = C_{pc} \sqrt{\max(0, \rho_w (P_{wh} - P_s))} f(u) \quad (10)$$

$$w_{pg} = \frac{\lambda}{\lambda + 1} w_{pc} \quad (11)$$

$$w_{po} = \frac{1}{\lambda + 1} w_{pc} \quad (12)$$

$$w_{ro} = C_r \sqrt{\rho_o (P_r - P_{bh})} \quad (13)$$

$$w_{rg} = GOR. w_{ro} \quad (14)$$

w_{pc} , C_{iv} , C_{pc} , C_{gl} , λ , P_s , ρ_a , ρ_o , GOR are flow rate through production choke, injection valve characteristics, production choke characteristics, reservoir flow characteristics, ratio of gas to oil in the tubing mixture, separator pressure, density of annulus gas, density of oil, and gas /oil ratio in the reservoir respectively.

The densities are given in equations (15) and (16)

$$\rho_a = \frac{m_{ga} P_a}{T_a R} \quad (15)$$

$$\rho_m = \frac{m_{gt} + m_{ot}}{L_w A_w} \quad (16)$$

$f(u)$, where $0 < u < 1$ in equation (10) is the valve characteristics that controls the oscillatory behavior of the gas-lifted system. Here $f(u)$ is given by equation (17).

$$f(u) = 50^{u-1} \quad (17)$$

Equations (1a) and (1b) are solved using Euler method, ODE15s, ODE23t among others to produce the evolution of the states. We solve this problem here using ODE15s.

SIMULATIONS RESULTS

The gas lift DAE in (1) is solved using ODE15s in MATLAB using the data in table (1). The solution provides the states and other variables discussed above but were are concerned about the states and the flow rate through the injection valve that delivers gas from the annulus to the

tubing. We simulate when the GOR, the injection gas flow rate (w_{gl}) and the choke valve opening (u) steer the gas lift system into stable, damped oscillation, mild oscillation and severe oscillations. We monitor this from the flow rate of the injection gas. Figure (3) shows the flow rate through the injection valve (w_{iv}) before casing heading and figure (4) shows the oscillating states of the system while figure (5) shows flow rate through the injection valve when casing – heading sets in.

In figure (3), the flow rate through the injection valve remains above zero except at the beginning where there was no flow. Production still continues at this point despite no flow through the injection valve. This is because the tubing initially contains enough gas that makes the mixture density to reduce the bottom hole pressure to the point where the reservoir pressure can lift the mixture. There after flow from annulus to tubing continues hence there is no casing heading instability.

Table 4.1: Gas lift parameters for field scale data

Parameters	Values	Units	Definition
Lw	1500	m	Length of well
Hw	1500	m	Height of well
Dw	0.121	m	Diameter of well
Lbh	500	m	Length of Bottom hole
Dbh	0.121	m	Diameter of bottom hole
La	1500	m	Length of annulus
Ha	1500	m	Height of annulus
Da	0.189	m	Diameter of annulus
Cr	2 E-4	m^2	Reservoir flow
Civ	1E-4	m^2	Injection valve
Cpc	2E-3	m^2	Production Choke
Rho_o	800	Kg/ m^3	Density of oil
GOR	0.001		Gas/Oil ratio
Pr	150E5	Pascal	Reservoir pressure
Ps	20E5	Pascal	Separator Pressure
Ta	300	K	Annulus Temperature
Tw	305	K	Well Temperature
Mw	0.028	kg	Molar mass of gas
R	8.314	J/(m*K)	Gas constant

In figure (4), the states of the gas lift system oscillate due to the system in the casing–heading instability region. The states are the mass of gas in the annulus, the mass of gas in the tubing and the mass of oil in tubing respectively. This is due to the flow through the injection valve oscillating as seen in figure (5). When the annulus pressure is less than the well pressure at the point of injection, there is no flow from the annulus to the tubing through the injection valve. This point corresponds to the point in figure (5) where the flow rate is zero. The flow rate remains zero while the oil accumulates in the well and the gas accumulates in the annulus until the mass in the annulus is such that the annulus pressure is greater than the tubing pressure and flow starts again.

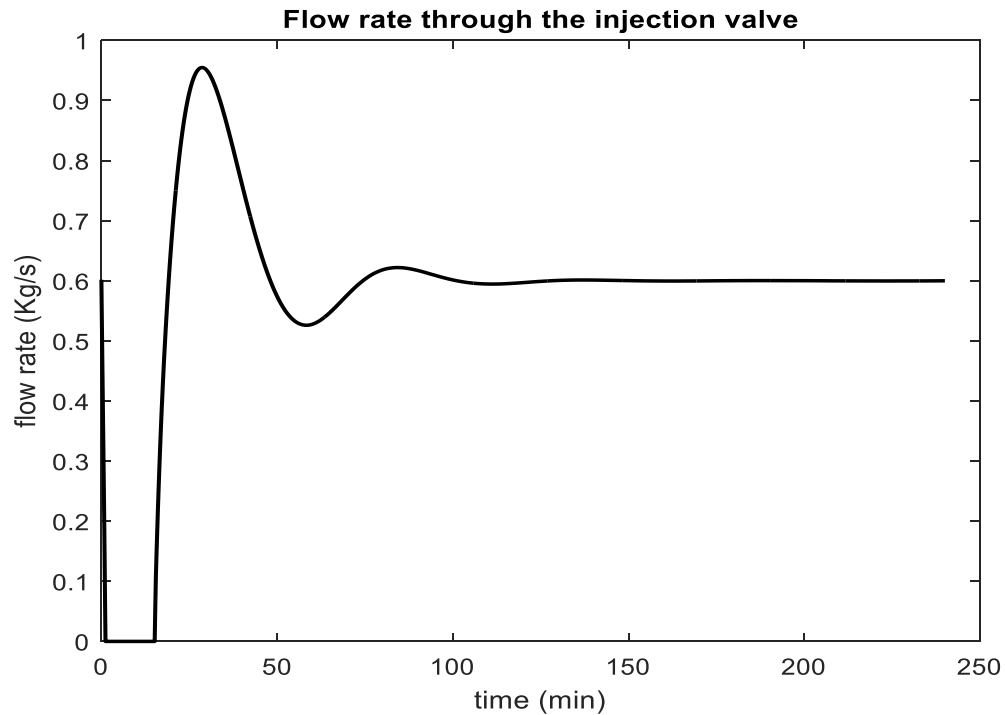


Figure 3 - Flow rate through the injection valve without oscillation

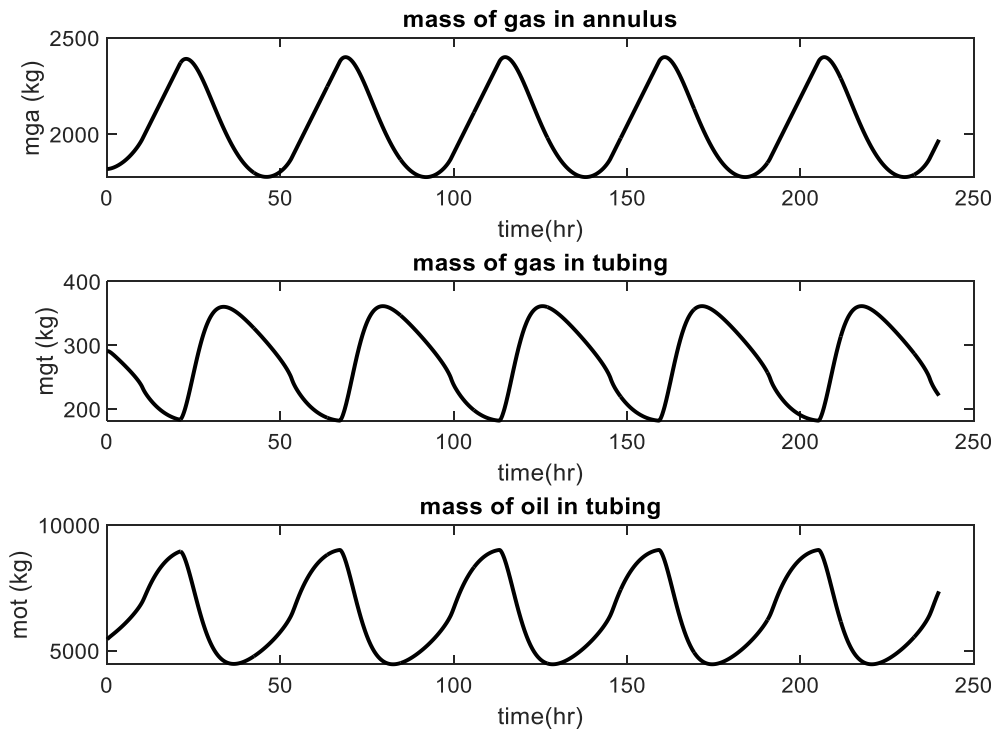


Figure 4 - Oscillatory state of gas lift system

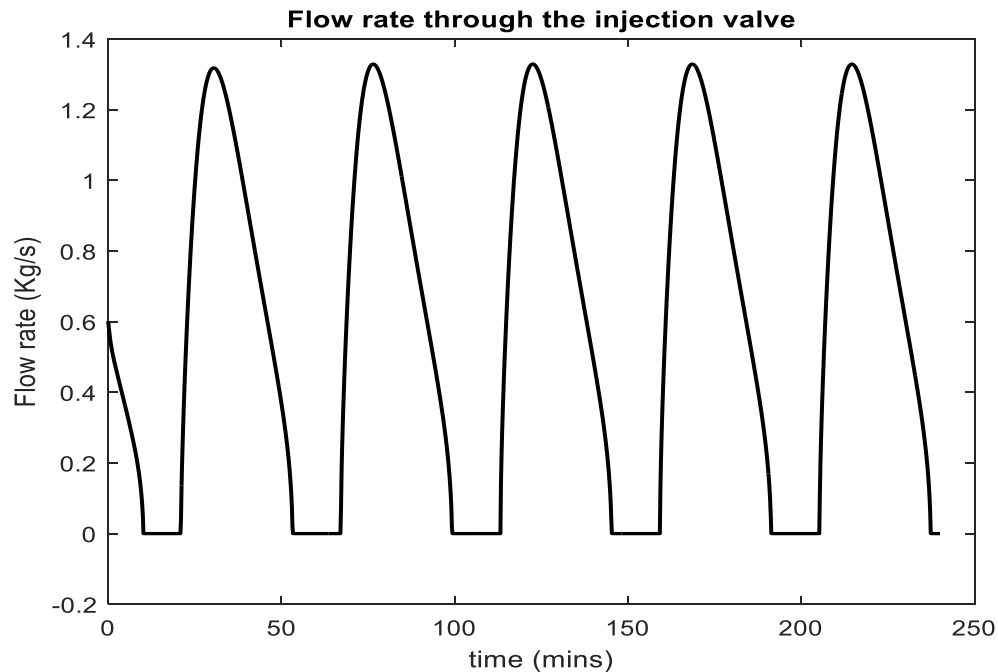


Figure 5 - Flow rate through the injection valve during oscillation

We now simulate how the various factors affect severity of casing-heading instability.

Gas/Oil Ratio (GOR)

In this part we simulate the gas lift system to show the values of the GOR when the system is stable, damped, mild oscillation and severe oscillations. Figure (6) shows the four cases where the stable corresponds to the GOR of 0.04, the damped correspond to GOR of 0.0022, the mild oscillations corresponds to GOR of 0.00216 and the severe oscillation corresponds to GOR of 0.0001.

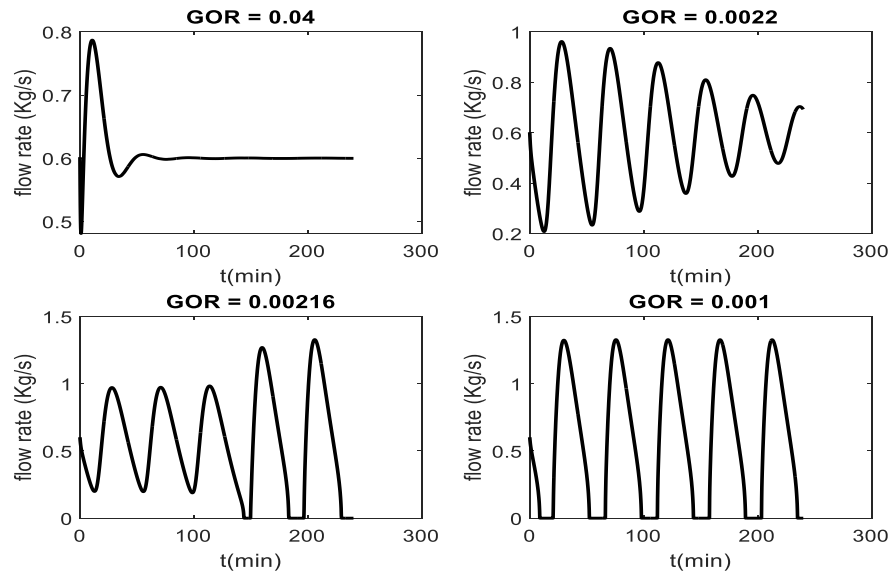


Figure 6 - Flow rate through the injection valve for different values of GOR

One thing that is obvious from figure (6) is that a GOR of 0.04 is able to remove casing-heading instability completely. A GOR of 0.04 implies a 4% gas in the liquid from the reservoir. The result from this simulation therefore meant if we can ensure the gas/oil mixture from the reservoir is in the ratio 4:100, there will be no oscillation provided other factors (including gas supply into annulus) are kept intact. But GOR is a property of the reservoir and we have no control over it. It is also not deterministic as it changes. Since the GOR forms part of the model of the gas lift system, it is treated as a parameter hence must be estimated every sample time.

Lowering the GOR further down to 0.0022 implying 0.2% of gas in the liquid mixture from the reservoir, there is oscillation which is damped as shown in figure (6). In this case there is always flow through the injection valve but not adequate enough to maintain nearly constant production rate. This too is not healthy for the gas lift components and it makes the gas lift system to be operated suboptimally. Decreasing the GOR further to 0.00216, full oscillation sets in and at GOR of 0.001, the gas lift system goes into severe oscillation where during most cycles, there are times where there are no flow through the injection valve.

Flow Rate of Gas Lift Gas into the Annulus (w_{gl})

Similar search is done for the flow of gas into the annulus and figure (7) shows the behavior of the gas lift system. For the given data in table (1), 0.8 kg/s flow rate of injection gas can stabilize the gas lift system. Note that the gas supply higher than this can also stabilize it. If the gas supply rate is reduced, oscillation begins to set as seen at w_{gl} of 0.6275 kg/s, damped oscillation is observed as shown in figure (7). Lowering the gas supply rate to 0.6271, full oscillation sets in with the flow rate through the injection valve becoming zero at some points.

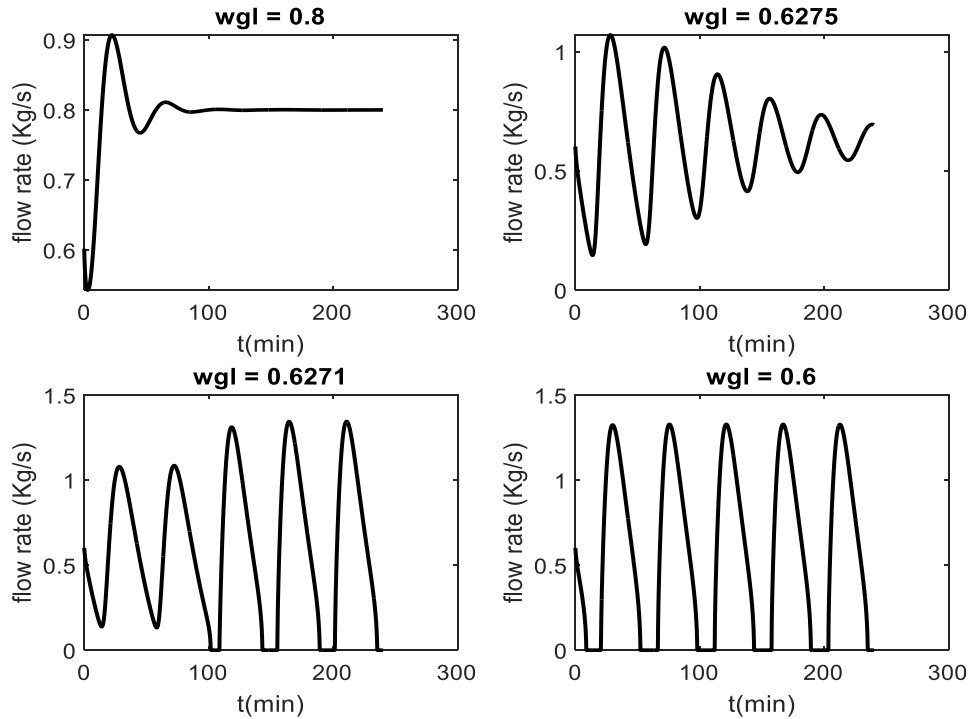


Figure (7) - Flow rate through the injection valve for different values of wgl

A further decrease of the flow rate to 0.6 kg/s leads to the gas lift system entering severe oscillation where every cycle experiences a time where there is no flow through the injection valve. At this point, the average oil production is lower than the theoretical production.

Percentage Valve Opening (u)

The percentage valve opening effect on the casing heading instability was conducted in similar manner to the GOR above. Figure (8) shows the flow rate of the injection valve during the four conditions above. The percentage valve opening that stabilizes the system is $u = 0.6$ (or 60% of valve opened). As the valve is opened further, chances of instability increases till at $u = 0.82$, damped oscillation occurs. The damping decreases with increased opening till at $u = 0.857$ when fully undamped oscillation starts but later damped. At $u = 0.9$, severe oscillations sets in where sometimes there is no flow through the injection valve.

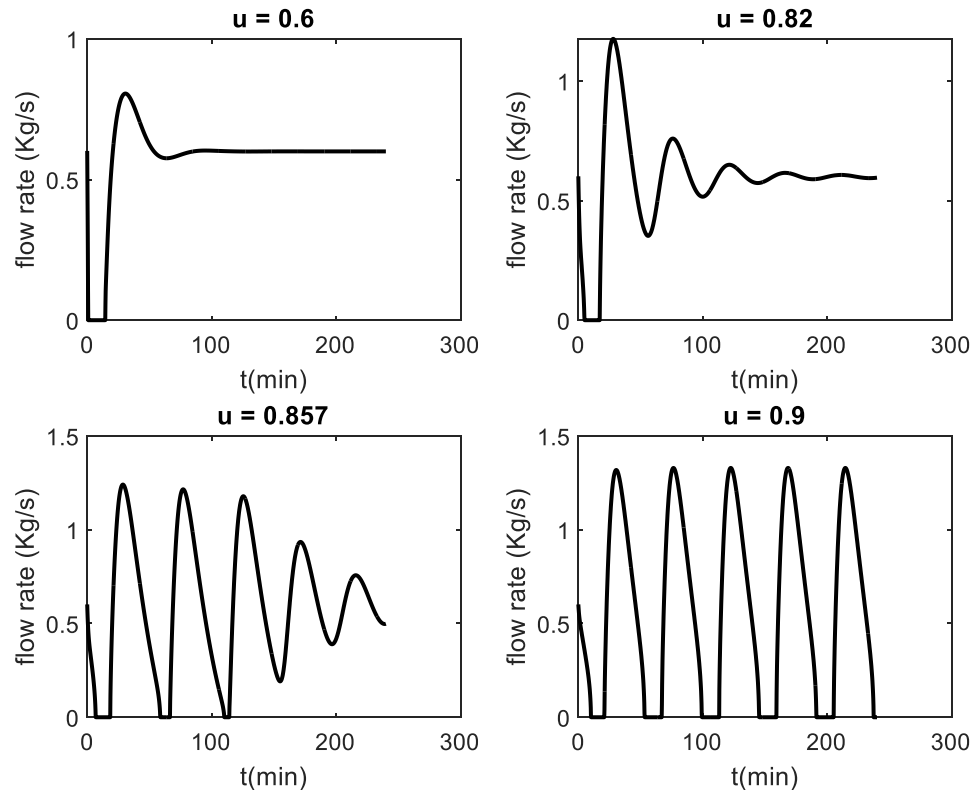


Figure (8) - Flow rate through the injection valve for different values of u

CONCLUSION

We examined the effects of gas/oil ratio (GOR), injection gas supply rate (w_{gl}) and percentage gas lift choke opening (u) on the severity of casing heading instability. The gas lift models and parameters used were first presented and injection valve flow rate at no oscillation was shown. The severity was monitored on the flow rate of gas through the injection valve. As the GOR decreases, chances of casing heading instability increases from damped oscillation to mild oscillation till severe oscillation takes place. On the other hand, increasing the flow of lift gas into the annulus reduces the chance of oscillation. The percentage valve opening increase leads to increase in chances of instability. This knowledge helps in providing information needed to reduce or eliminate casing-heading instability. The study is important as casing heading instability leads to reduced average oil production which means the gas lift system is operated suboptimally. This work can be extended to other parameters and variables in the gas system for comprehensive knowledge about the behavior hence control of casing-heading instability.

References

- [1] Kolawole, O., Gamadi, T. and Bullard, D., 2019. SPE-196592-MS.
- [2] Clarke, F. and Malone, L., 2016, October. Sucker rod pumping in the eagle ford shale field study. In *SPE North America Artificial Lift Conference and Exhibition*. OnePetro.
- [3] Freet, T.G. and McCaslin, K.P., 1992, October. Successful Submersible Lift Operations in Gassy Horizontal Wells, Pearsall Field, Texas. In *SPE Annual Technical Conference and Exhibition*. OnePetro.

-
- [4] Hardegree, C.N., Gerrard, B.A., Wildman, S.L. and McKenzie, K.S., 2020. Chamber Gas Lift in Horizontals. *SPE Production & Operations*, 35(01), pp.018-025.
- [5] Wu, J., Cao, W. and Cong, T., 2022. Numerical investigation on the performance of gas-lift pump with large density ratio of liquid to gas. *International Journal of Multiphase Flow*, 148, p.103936.
- [6] Eikrem, G.O., Foss, B., Imsland, L., Hu, B. and Golan, M., 2002. Stabilization of gas lifted wells. *IFAC Proceedings Volumes*, 35(1), pp.139-144.
- [7] Eikrem, G.O., Imsland, L. and Foss, B., 2004. Stabilization of gas lifted wells based on state estimation. *IFAC Proceedings Volumes*, 37(1), pp.323-328.
- [8] Krishnamoorthy, D., Foss, B. and Skogestad, S., 2018. Steady-state real-time optimization using transient measurements. *Computers & Chemical Engineering*, 115, pp.34-45.
- [9] Aliev, F.A., Dzhamalbekov, M.A. and Il'yasov, M.K., 2011. Mathematical simulation and control of gas lift. *Journal of Computer and Systems Sciences International*, 50(5), pp.805-814.
- [10] Jahanshahi, E., 2013. Control Solutions for Multiphase Flow: Linear and nonlinear approaches to anti-slug control.