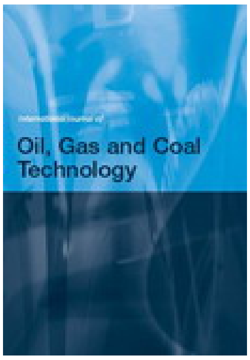

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Impact of surface choking on gas-lift stability and flow behaviour in oil producing wells

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Impact of surface choking on gas-lift stability and flow behaviour in oil producing wells

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Abstract: The effect of surface choking on gaslift stability and flow regime transition in vertical cylindrical pipe during gaslift operation is investigated. Here, a laboratory scale multiphase flow rig was designed, fabricated, and assembled. Gas rates of 0.000113 m^3/s and 0.000187 m^3/s were imposed on a 1 mm single nozzle injector. Surface choking was implemented by setting the system to 15%, 25%, 50% and 100% opening. For each opening condition, transient pressure at four locations; corresponding to length-to-diameter ratios of 0.0, 18.3, 36.7, and 53.3, was recorded. Flow structure and regime transition are characterised by visual, photographic and slow-motion videos, recorded at each location. A transition from random peak-to-peak cyclic and periodic pressure oscillation, accompanied by pressure increase, is observed. Further, bubble size reduction characterised by low vorticity and turbulence is observed at 15% opening. It is concluded that surface choking must be complemented by knowledge of flow behaviour within the system. [Received: June 14, 2022; Accepted: March 20, 2023]

Keywords: gas-lift; multiphase flow; instability; fluid flow structure.

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1 Introduction

Complex multiphase fluids containing oil, gas, water, and sometimes precipitated solids and or formation sands may flow through production tubing to the surface, with several flow regimes recorded. The natural vertical flow performance may be compromised as a result of this complex multiphase flow in the tubing (Brown, 1982; Clegg, 2007). As a result of the decline in vertical flow from natural energy, an artificial lift technique may be used to boost production. One of the approaches hat is often adopted is gas-lift, which involves the injection of gas at high pressure into the tubing at specific spots to elevate the produced fluid from the wellbore to the surface (Rashid et al., 2012).

Bubbly, slug, churn and annular flows have been acknowledged as the main four regimes encountered in two-phases gas-liquid flow in vertically upward cylindrical pipes (Wu et al., 2017; Sharaf et al., 2016; Shaban and Tavoularis, 2014). Although, transitional regimes such as bubbly-slug, slug-churn and churn-annular flows (Shaban and Tavoularis, 2014), wispy annular and dispersed bubble (Sharaf et al., 2016) may exist.This dynamic change of fluid flow structures brings instabilities into the production tubing during gas-lift operations (Guet et al., 2003, 2004; Sami and Turzo, 2020).

A group of authors (e.g., Bertuzzi et al., 1953; Gilbert, 1954; Grupping et al., 1984; Xu and Golan, 1989), described gas-lift instabilities as a phenomenon that periodically stops the oil flow and causes vibrations that damage downhole and surface facilities. This instabilities can occur for a variety of reasons including gas cusping or water coning; the accumulation of water, slugging of oil or condensates in the pipeline; or increased pressure in the well (Chia and Hussain, 1999; Jansen et al., 1999; Al Abdin, 2000; Ranjan et al., 2015).

Nowadays methods used in stabilising wells include wellhead choking; increasing gas injection beyond optimum rate; reducing the injection valve port size and use of feedback control systems (Shao et al., 2016; Faustinelli et al., 1999; Eikrem et al., 2008).

Some authors (e.g., Eikrem et al., 2008; Jahanshahi et al., 2008b, 2008a, 2008c, 2009; Clavijo et al., 2022; Diehl et al., 2018) argue that tubing head choking tends to increase the stability of gas-lifted wells. Others (e.g., Beadle, 1963; Chia and Hussain, 1999) defend that choking a gas-lifted well reduces gas-lift efficiency due to the additional surface back pressure being imposed on the system; consequently resulting in less liquid production rate and higher gas-lift gas injection requirements (Hari et al., 2022). Zhou et al. (2018) advocate the choking technique as a technique that minimises slugging although, this has to be done with care in order to avoid losses in production.

Clift et al. (2005) observed that if the bubbles are smaller, the rising velocity will be reduced, resulting in reduction of gas velocity, increase of void fraction, and reduction of hydrostatic head term of the total pressure drop.To guarantee a reduced bubbles size in the tubing, it is therefore important to find mechanism of reducing bubbles coalescence rates and increase the breakage rates.

Tyagi and Peacock (2022) applied a carbon dioxide tracer in the tubing trough the casing and measured its concentration during gas-lift production well. Fluid flow structure and instabilities due to CO_2 injection were not analised on there study. Artificial neural network as been proposed by some authors as a mean of optimisation gas-lift performance (Salahshoor et al., 2013; Elgibaly et al., 2021). The proposed models, in many cases, do not address influence of gas-lift compressibility factor, significant temperature and pressure variations from bottomhole to the surface, mass transfer effect from one phase to another, presence of third and fourth phases, borehole deviation and, borehole friction effects.

Rodrigues and Almeida (2017) conducted an intrusive experiment by applying bubble-breakages devices inside the tubing. They used different bubble-breakers configurations namely plate, nozzle, and venturi with different inlet and outlet geometries. A 20% reduction in pressure was achieved in some cases, but in other cases, localised pressure losses were generated. They concluded that the bubble-breaker tested were not effective for slug flow and several aspects of the bubble-breaking processes are not well understood. The use of bubble-breakers is limited due to gas-liquid fluid flow structure reconstruction after passing through the bubble-breakers.

The applicability of the techniques such as injecting gas-lift gas at a high flow rate; reduction of surface choke size, controlling the sizes of bubbles, and use of venturi nozzle Guet et al., 2003; Eikrem et al., 2008; Sulaiman et al., 2019; Song et al., 1995; Tollkotter et al., 2016; Chiba and Takahashi, 1998; Kawamura et al., 2004; Santos and Pinheiro, 2014; Mayor et al., 2008; Iguchi et al., 1998; Jansen et al., 1996; Koide et al., 1968; Seim et al., 2011; Samsuri et al., 2019; Tang et al., 1999, may lead to increase in pressure losses due to friction in the tubing, redesign of integral mandrels, and injection at critical gas-lift gas injection flow rate. Additionally, it is impossible to guarantee the size of small bubbles along the production tubing height because of the expansion of bubbles as they rise (Santos and Pinheiro, 2014; Jansen et al., 1996). Chia and Hussain (1999) argued that choking a gas-lift well reduces gas-lift efficiency due to the additional surface backpressure, which results in less produced liquid rate and higher lift gas consumption.

1.1 Criteria for stability in relation to choking

Jansen et al. (1996) applied choke and gas-lift as methods of eliminating severe slugging. This investigation was carried out experimentally and theoretically and the following stability criteria was developed:

$$\frac{P_s + CU_{ls}^2}{P_0} > \frac{\frac{\alpha L}{\alpha'}\left(\Phi - \frac{K}{\rho_l g}\right) - \Phi H}{\frac{P_0}{\rho_l g}} \tag{1}$$

where Φ denotes the average holdup in the riser, ρ_l is the liquid density, C is the choke coefficient, K proportionality constant, H is the riser height, U_{ls} is the liquid superficial velocity, P_0 and P_S denote the atmospheric pressure and pressure inside the separator tank; α and α' stand for gas void fraction and void fraction of gas front entering the liquid column. Equation (1) is a result of the force balance between the gas pressure force induced by the enlargement of the gas phase and the increment hydrostatic head, the pressure at the separator and the pressure drop at the choke (Jansen et al., 1996).

It was observed that both choking and lift gas eliminate slugging by the increment of the back pressure and increasing the amount of lift gas. The degree of stability achieved by increasing the lift gas might be associated with annular flow regime characterised by continuity of the gas phase along the tubing. Annular flow is distinguished by flow of gas and liquid separately (Sharaf et al., 2016; Kaji et al., 2009; Omebere-Iyari and Azzopardi, 2007). This flow regime is undesired in gas-lift operations because it is associated with the slippage and consequent increase in pressure drop due to friction caused by acceleration of the gas phase.

Surface choking is a restriction in a flow line set by decreasing the orifice size of the valve through external adjustment. This technique is commonly applied in gas-lift operations as a strategy for bringing wells to a stable operational condition. However, the consequences of the low-pressure region in the choke can lead to severe problems with cavitation and related flashing (vaporisation). The aforementioned techniques are relevant and in many cases adequate for many engineering calculations. Yet, there are specific cases of gas-lift operations where detailed information about the structure of the flow inside production tubing; particularly the slug characteristics during tubing head choking, is essential (Barnea and Taitel, 1993).

Xie et al. (2017), Diehl et al. (2019) and Diehl et al. (2021) observed devaluation of the slug region while increasing the backpressure during slug flow investigation. Reductions in pressure amplitude as well as the slug frequency, were noticed.

Battino et al. (1984) proposed the equation below equation (2) as a mean of estimation e the solubility of air in water.This equation advocates that the solubility of air in water at fixed temperature, increases with pressure.

$$\begin{aligned} \ln S = {} & -44.031 + \frac{68.471}{\tau} + 19.316 \ln \tau - 0.020613P \\ & + 1.1243 \ln P \end{aligned} \tag{2}$$

where S is the solubility of air in cm^3/g (STP); τ denotes T/1,000, T is the temperature in K and P is absolute pressure in $megaPascal$.

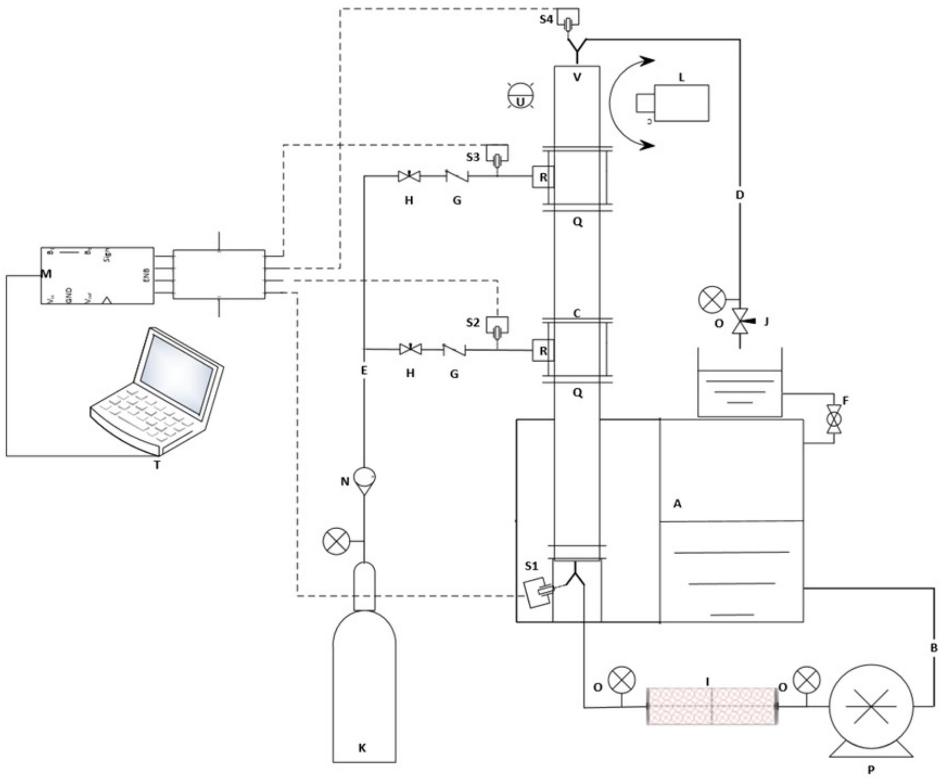
In this work, topside choking is replicated experimentally in order to study its effect on gas-lift stability by:

a Evaluating its impact on bottom hole pressure, operating valve pressure, unloading valve pressure, and tubing head pressure oscillations.

b Investigating its influence on fluid flow structure transition occurring along the production tubing.

c Studying the influence of restricting the outlet flow conditions on spatial and temporal bubbles sizes evolution and devolution including shape, and distribution inside the production tubing.

Figure 1 Process and instrumentation diagram P&ID of the multiphase flowrig, *A* – watertank; *B*, *D*, *E*, *F* – nylon tubing; *C* – perspex riser; *D* – nylon tubing; *G* – check valves; *H* – needle valves; *I* – perspex cylinder; *J* – liquid flow regulator; *K* – compressed air cylinder; *L* – camera; *M* – data acquisition system; *N* – rotameter; *O* – pressure gauges; *P* – pump; *Q* – flanges; *R* – gaslift injection ports; *S* – pressure transducers; *T* – laptop; *U* – light source; *V* – two branches



2 Methodology

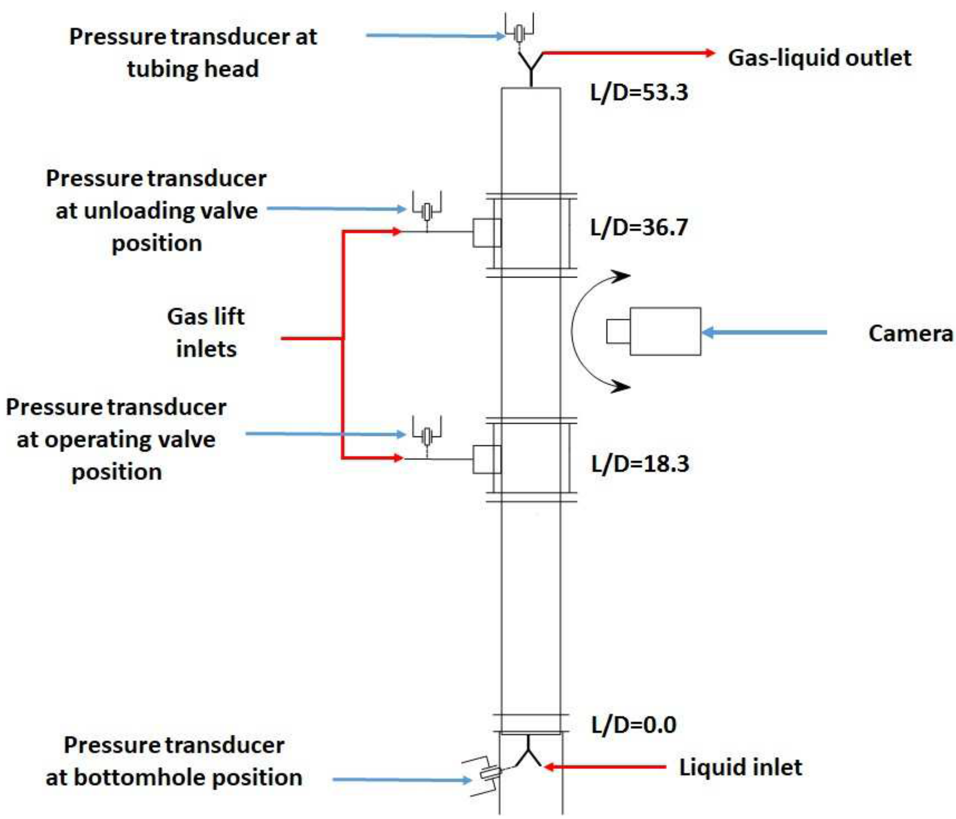
In order to investigate the effect of surface choke on dynamic behaviour associated with gas lift instabilities, a pilot-scale rig was designed, fabricated, and assembled. The design of this facility is such that it allows for a wide range of two-phase flow conditions. Figure 1 is a 2-dimensional schematic of a geometrical representation of a gas-lift production system with an instrumentation diagram (P&ID). The test sections of the production tubing with pressure transducers and high-speed camera are shown in Figure 2.

Four choking configurations were imposed at the tubing head to analyse the flow regime and gas bubble dynamics in the production tubing. This is achieved by mounting a pressure regulator valve inline of the returning pipe connected to the top of the producing tubing. The surface choke is implemented by setting the system to 0% closed (fully opened) to partially closed – 15%, 25% and 50% opened (85%, 75% and 50% choking). For each choking condition, the transient pressure oscillation at four measurement points located at length to diameter ratios of (L/D = 0.0, 18.3, 36.7, 53.3) was recorded as well as the fluid flow structure along the production tubing test sections. Gas-lift injection rates of $1.13e^{-4}$ m^3/s and $1.87e^{-4}$ m^3/s were imposed in a 1 mm internal diameter (ID) single nozzle gas-lift injector connected to a rotameter and a liquid flow rate of $7.7e^{-6}$ m^3/s was set in a speed potentiometer connected to a positive displacement gear pump.

2.1 Instrumentation

Rotameter, pressure regulator, and gas flow regulator are used for monitoring and controlling the gas-lift injection rate, while an inverter frequency regulator with speed potentiometer is used to control the motor shaft rotational speed for setting the liquid flow rate from the water source tank into the test section during the experiments.

Figure 2 2D representation of the test sections of the production tubing with pressure transducers and high speed camera locations (see online version for colours)



In order to measure and record the transient pressure oscillation due to gas-lift at the bottomhole, operating valve, unloading valve, and production tubing head, four pressure transducers reference $PXM319-010G10V$, with a pressure range of 0–10 bar were used to acquire transient pressure measurements. The first one is installed at the bottom of the tubing for acquiring the bottom hole pressure p_{wf} at (L/D = 0.0), the second pressured transducer is installed at operating gas-lift valve (L/D = 18.3), the third one is located at the unloading gas-lift valve (L/D = 36.7) and the fourth one is at the top of the producing tubing for reading and recording the tubing head pressure p_{th} (L/D = 53.3) as shown in Figure 2 respectively.

The pressure transducers are connected to a data acquisition system reference OM-USB108FS. Transient behaviour of pressure at bottomhole; operating valve, unloading valve, and at tubing head is recorded in real-time during gas-lift operation. The pressure transducers require a supply voltage of 24 V to operate. For this, a electronic circuit device that converts a source of direct current (DC) from 5 voltage from the USB DAQ unit level to 24 voltage was installed.

2.2 Assumptions, boundary and initial conditions

The fluids physical properties are listed in Table 1. At operational conditions of the test rig, the fluids are assumed to be incompressible and mass transfer between the phases may occur at production tubing head. The inlet flow rate of the liquid phase is placed at the bottom of the tubing (see Figure 2), while the gas-lift gas flow rate is set at lower side of the tubing (operating valve), see Figure 2.

Table 1 Fluid physical properties and initial conditions

	Flow rate v, [m^3/s]	*Density ρ, [kg/m^3]*	*Viscosity μ, [Pa.s]*	*Tension σ, [N/m]*
Water	$7.7e^{-6}$ m^3/s	998	$1.03e^{-3}$	0.07226
Air	$1.13e^{-4}$; $1.87e^{-4}$	1.19	$1.79e^{-5}$	

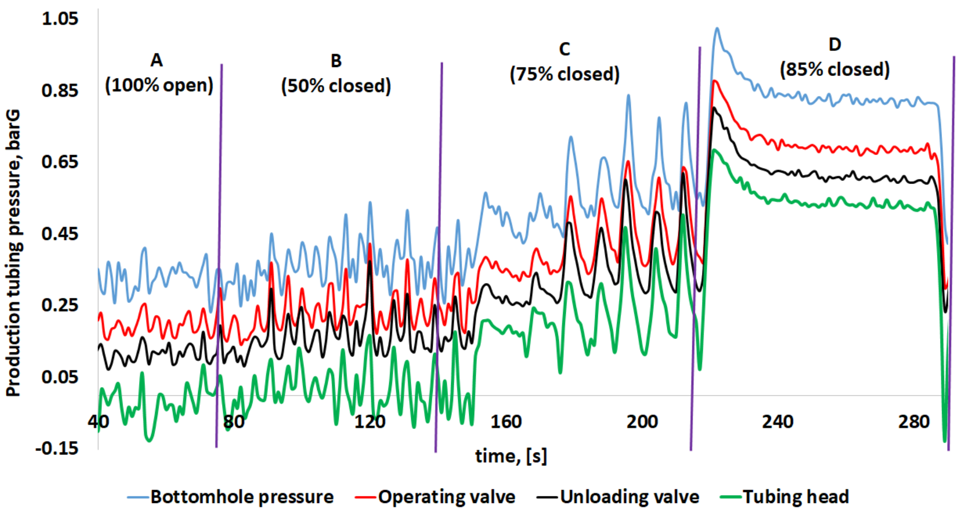
Source: Shao et al. (2008)

3 Results and discussion

3.1 Influence of choking at tubing head-on pressure instability

Gas-lift stability is evaluated on bottom hole pressure; operating valve pressure; unloading valve pressure and tubing head pressure. The range of tubing head choke is set in % of valve opening. The experiments were performed by closing the production choke from 0% closed (fully opened) to 85% closed (15% opened) and for each set of the tubing head choke, the transient pressure at four measurement points were recorded. For this set of runs, 1 mm ID single nozzle gas-lift injector was used in the experiments and a lift gas injection rate of $1.87e^{-4}$ m^3/s was set in a rotameter while the liquid flow rate was set at $7.7e^{-6}$ m^3/s in a speed potentiometer connected to a positive displacement gear pump. Transient pressure profile recorded simultaneously with the four pressure transducers located in L/D = 0.0 (bottomhole), L/D = 18.3 (operating valve), L/D = 36.7 (unloading valve) and L/D = 53.3 (tubing head) along the production tubing is shown in Figure 3, where four distinguishable patterns are observed as a consequence of gradually choking at tubing head. In region A (production choke fully opened) the pressure profile shows peak-to-peak oscillatory behaviour (maximum and minimum) with no periodicity and no similarity in the profiles at the four measurement points along with the production tubing These oscillations are induced by the expansion, breakage, and coalescence of the gas-lift flowing inside the tubing. Similar trend of dynamic pressure oscillation was observed by Tang et al. (1999) when investigated the transient dynamic characteristics of the gas-lift unloading process. Huff (1988) tested the pressure transient dynamic in gas lift wells and the behaviour observed is characterised by high-pressure spikes caused by the injection lift gas into the borehole separated by relatively low pressure periods. The finding of the authors above are in agreement with our experimental measurements.

Figure 3 Impact of production choke on tubing pressure behaviour in the test section between L/D = 36.7 to L/D = 53.3, the choke was gradually closed during the operation from, (A) 100% opened (B) 50% closed (C) 75% closed (D) 85% closed and the GLGIR was set to $1.87e^{-4}$ m^3/s while the liquid flow rate was set at $7.7e^{-6}$ m^3/s (see online version for colours)

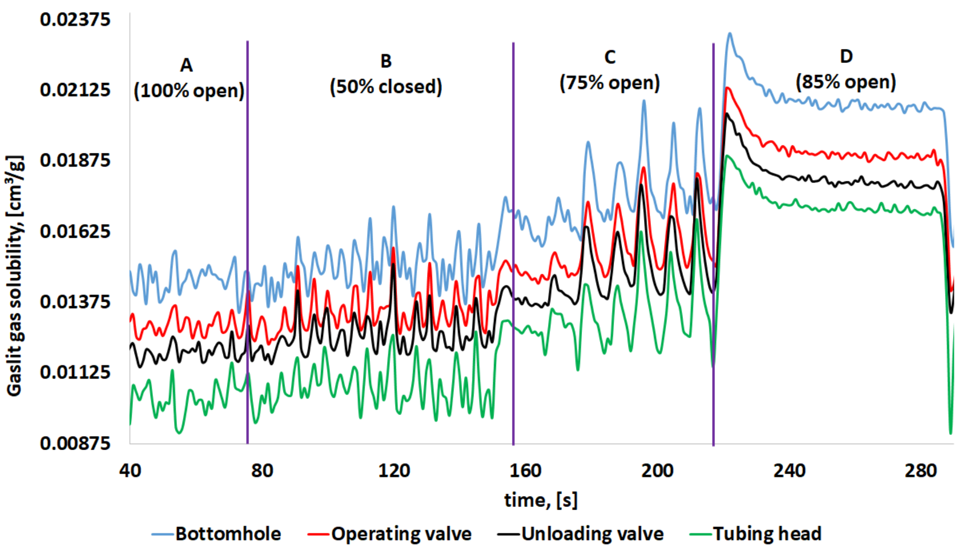


By closing the production choke in 50% (region B), the pressure continues to fluctuate in the four measurement points with higher amplitude than in region A and the profile tend to be similar in the four measurement points characterised by a coincidence of the occurrence (periodicity) of the peaks. For 75% closed choke (region C), there is an increase in pressure oscillatory amplitude with a periodicity of the occurrence of peaks in the four measurement points. The measured pressure in the four measurements points shows a similar trend. Further, increment in the choke up to 85% (region D) shows fluctuations of pressure with very low amplitudes compared to the rest conditions observed in regions A, B, and C. An increase in pressure in the four measurement points along the production tubing height is observed during the gradual choking of the system. Additionally, there is a change in pressure behaviour at the four measurements from random peak-to-peak fluctuations to periodic fluctuations of higher amplitudes in regions B and C and an almost stable pressure profile with very low fluctuation in region D, see Figure 3.

3.2 Estimation of transient solubility of lift gas in liquid along the tubing height

The influence of tubing head choking on lift gas solubility along the production tubing is estimated based on equation (2). The trend noticed in Figure 4 reflects the equation (2) for a constant temperature, a solubility of the gas is directly propositional to pressure. This is proved by comparing Figure 3 with Figure 4. The two figures, show similar profiles during tubing head choking.

Figure 4 Impact of production choking on gas-lift solubility in the test sections L/D = 0.0, L/D = 18.3, L/D = 36.7 and L/D = 53.3, the choke was gradually closed during the operation from, (A) 100% opened (B) 50% closed (C) 75% closed (D) 85% closed and the GLGIR was set to $1.87e^{-4}$ m^3/s while the liquid flow rate was set at $7.7e^{-6}$ m^3/s (see online version for colours)



3.3 Impact of surface choking on bubbles size and fluid flow structure

We examine the effect of restricting the outlet flow conditions on flow patterns occurring in the last test section in-between length to diameter ratio L/D = 36.7 to L/D = 53.3 of the production tubing. The experiments were performed by varying (closing) gradually the production choke at the outlet from fully opened 100%, to partially closed 85%. For this set of run, 1 mm ID single nozzle gas-lift injector was used for this experiments andthe $GLGIR$ of $1.87e^{-4}$ m^3/s was set at gas regulator valve connected to a rotameter for constant liquid flow rate of $7.7e^{-6}$ m^3/s.

Videos in slow motion were obtained and analysed using a CASIO Exilim 200 high speed camera with resolution of 640 $\times$ 480 at 120 frames per second (fps). The sequence of JPEG format images of the two phases flowing vertically upward were obtained by converting the slow motion MOV videos files to JPEG format images using a conversion utility software DVDVideoSoft Free studio available online (https://www.dvdvideosoft.com/) and downloaded as open source from the internet. The sequence of images were processed in ImageJ software for estimating the equivalent size of the bubbles along the test sections. Image sequence of flow regimes observed in the test section in-between $L/D = 36.7$ to $L/D = 53.3$ are presented in Figures 5 for fully opened production choke and Figure 6 for partially closed choke 85% respectively.

Figure 5 Effect of choking on bubble size and fluid flow structure in the test section in between $L/D = 36.7$ to $L/D = 53.3$, the choke was fully opened and the GLGIR was set to $1.87e^{-4}$ m^3/s while the liquid flow rate was set at $7.7e^{-6}$ m^3/s (see online version for colours)

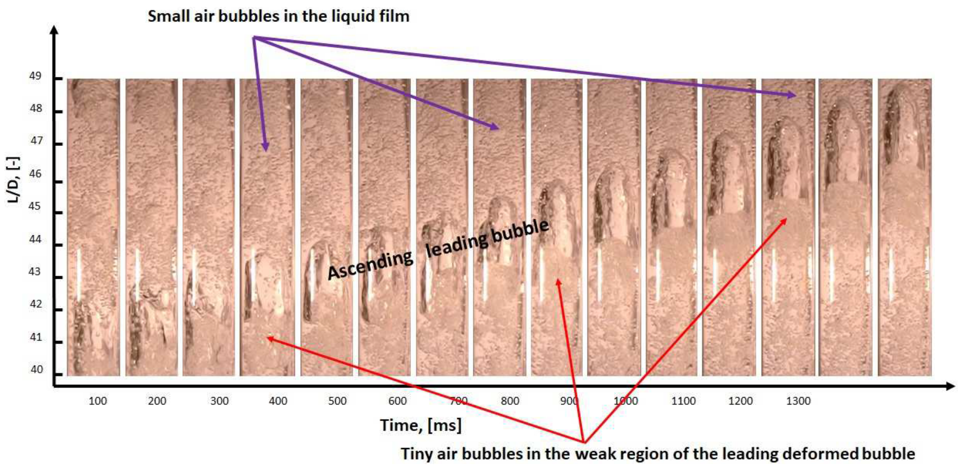
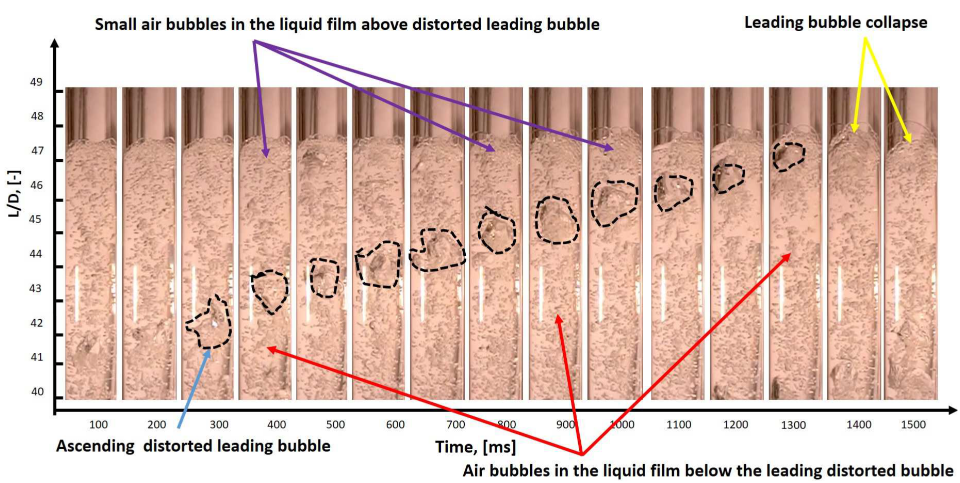


Figure 6 Effect of choking on bubbles size and fluid flow structure in the test section in between $L/D = 36.7$ to $L/D = 53.3$, the choke was 85% closed and the GLGIR was set to $1.87e^{-4}$ m^3/s while the liquid flow rate was set at $7.7e^{-6}$ m^3/s (see online version for colours)



As presented in Figure 5, large coalescence cap bubbles with characteristic distorted bullet-like shape at the nose and occupying most of the cross-section of the production tubing end is observed. The bubble is separated by liquid slugs as it flows upward along the tubing and high breakage into tiny bubbles at wake region of the formed Taylor bubble is noticed. In-between L/D = 36.7 to L/D = 53.3, the maximum perimeter of the Taylor bubble observed is 70.98 mm. In the case of 85% closed choke the fluid flow structure is illustrated in Figure 6. The upwardly ascending leading bubble is characterised by irregular shape and deformation along the production tubing and maximum bubble size of 35.65 mm was observed.

The slow motion videos examined show a drastic reduction of the bubble rise velocity as it approaches the production tubing head and consequent collapse at top of the tubing and surrounding the flowing bubble small bubbles are observed and the vorticity of the liquid film is less perceived. The back pressure effect caused by the choke forces the gas to be dissolved in the liquid film. Surrounding the flowing bubble small bubbles are observed at the vorticity of the liquid film is less perceived. Deceleration of the two-phases flow as the choke closes was also observed by Alves et al. (2017) in their investigation on transient churn-annular flows in a long vertical tube. Zhou et al. (2018) observed reduction in acceleration of intruding bubble due to existence of riser-top choking.

3.4 Influence of lift gas injection point in pressure instability

The mechanism of wave propagation in the production tubing is investigated taking into account the coupled motion of the two-phase medium (air-water). The liquid flow rate was set to LFR = 7.7e^{-6} m^3/s while the gas-lift were injected instantly for three seconds by manipulating the flow regulator valve located at

a L/D = 18.3 (operating valve)

b L/D = 36.7 (unloading valve) along the production tubing.

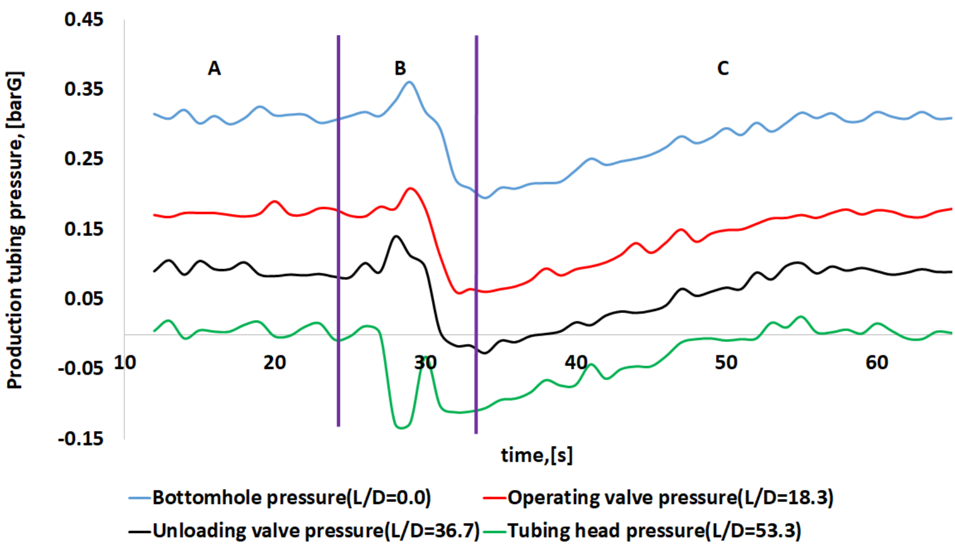
Pressure transducers located at L/D = 0.0, L/D = 18.3, L/D = 36.7 and L/D = 53.3 were used to record the pressure transient at the bottomhole; operating valve; unloading valve and tubing head respectively. The amplitude of the time sequence pressure fluctuation is analised by plotting the standard deviation of the measured pressure fluctuation (Bhowmick et al., 2014; Johnsson et al., 2000), in L/D = 0.0, L/D = 18.3, L/D = 36.7 and L/D = 53.3. The test sections are indicated in Figure 2.

3.4.1 Lift gas injected from operating valve located at L/D = 18.3

The transient pressure profile in the four remeasuring points were plotted against time and the profile is presented in Figure 7. As shown in Figure 7 three regions are observable: region A before the opening of the regulator valve where there is single phase (water) flowing in the production tubing characterised by natural pressure fluctuations of low amplitude ranging from maximum of 0.323 barG to a minimum of 0.299 barG in L/D = 0.0 (bottomhole); 0.186 barG to 0.161 barG in L/D = 18.3 (operating valve), 0.0991 barG to 0.0786 barG in L/D = 36.7 (unloading valve) and from 0.0142 barG to –0.0103 barG at L/D = 53.3 (tubing head) accordingly.

High oscillations of transient pressure with larger amplitude compared to the ones in region A are observed in region B (pressure profile in this region B is refereed to immediately after opening the valve and the gas-lift gets in contact with flowing water). Step-up pressure change was observed in L/D = 0.0 at bottomhole from 0.304 barG to 0.385 barG. Similar trend is noticed in operating valve were a step-up from 0.161 barG to 0.185 barG, while a step-down pressure change is noticed in L/D = 36.6 from 0.0894 barG to 0.0269 barG and from –0.0288 barG to –0.045 barG for L/D = 53.3 respectively.

Figure 7 Time sequence of the pressure fluctuation due to instantly injection of gas-lift for three seconds by manipulating the flow regulator valve located at, (A) L/D = 18.3 (operating valve) (B) L/D = 36.7 (unloading valve) along the production tubing (see online version for colours)



Notes: The LFR was set to $LFR = 7.7e^{-6}$ m^3/s while the gas-lift was injected from L/D = 18.3 (operating valve) instantaneously for three seconds and closed afterward. The pressure profile were recorded in the four measurement points along the production tubing.

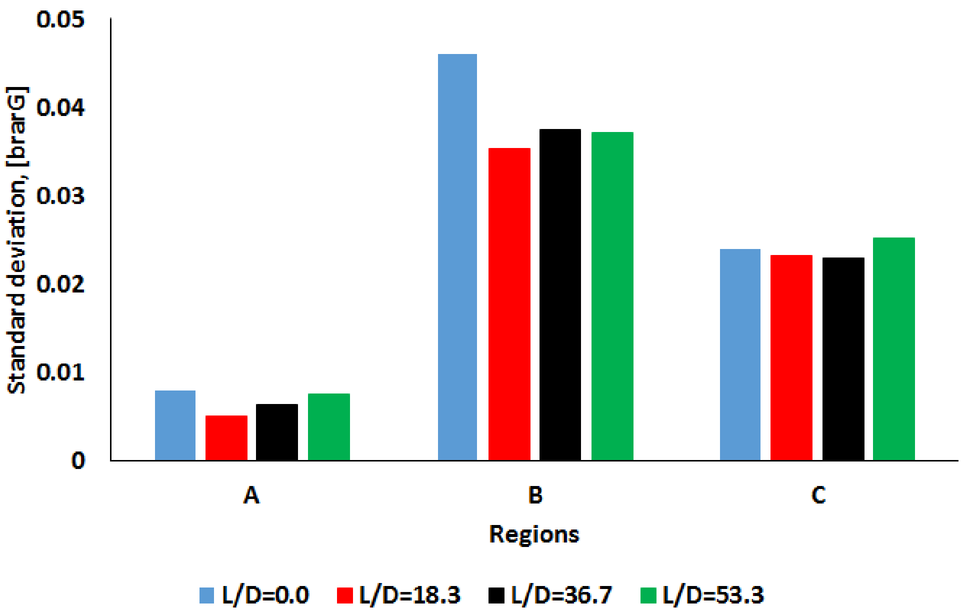
Region C is characterised by relaxation period of pressure oscillations as a result of close of flow regulator valve where there is a decay in pressure disturbance amplitude and a linear increase of pressure on time in the four measurement points to the level of region A.

As can be scrutinised from Figure 7, there is delay of three seconds in pressure fluctuation as a result of gas injection in L/D = 0.0 (bottomhole), two second delay in pressure oscillation in L/D = 36.7 and four seconds delay in pressure fluctuation in L/D = 53.3 respectively. The perturbation of pressure as a result of gas-lift injection into the production tubing is delayed in the four measurement points away from the injection point and has immediate effect at injection point. The time delay might e associated to the wave propagation effect from the point of injection to up and downward direction along the tubing. As can be noticed when the fluid flowing from the bottomohole contacts with the gas at injection point L/D = 18.3 the force of impact of the lift gas brings about pressure fluctuation.

The amplitude of the time sequence pressure fluctuation is analised by plotting the standard deviation of the measured pressure fluctuation in L/D = 0.0, L/D = 18.3, L/D

= 36.7 and L/D = 53.3. A comparison is made in the three regions A (before opening the valve), B (flow regulator valve opened for three seconds) and C (after closing the valve) as illustrated in Figure 8. As observed, the influence of gas volume fraction is noticed along the production tubing and this affects the wave velocity. Miyazaki et al. (1971) observed step-up pressure disturbance during transient response on propagation of pressure wave in air-water two phases system. This investigation has shown similar trend of pressure response as a result of variation of gas volume fraction inside the tubing.

Figure 8 Standard deviation plot of the pressure fluctuation in four points along the production tubing (see online version for colours)

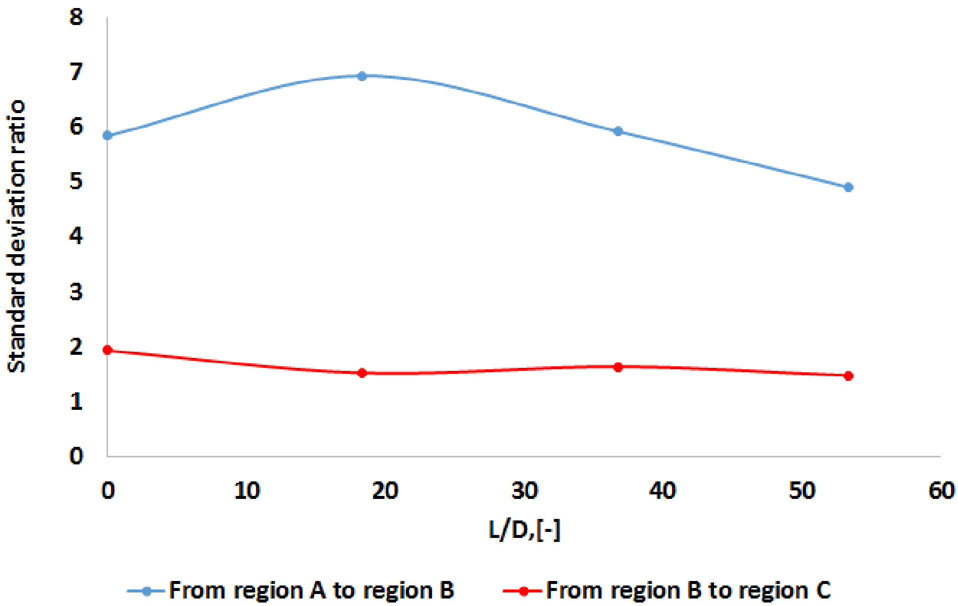


Huang et al. (2005) investigated experimentally the characteristic of pressure wave propagation in bubbly and slug flow and noticed that the pressure wave intensity decreases exponentially with distance. This observation agrees with our investigation presented in Figures 7 and 10 respectively.

Low standard deviation is observed in region A ranging from a maximum of 0.00789 barG to a minimum of 0.005095 barG while in region B there is high standard deviation ranging from 0.04418 barG to 0.04052 barG and in region C a decay of standard deviation is noticed. The standard deviation increases six times from region A to region B and decreases two times from region B to region C in L/D = 0.0 (bottomhole), while in L/D = 18.3 the standard deviation is increased seven times from region A to region B and decreases two times from region B to region C, in L/D = 36.7 the standard deviation increases seven times from region A to region B and has reduction ratio of 2 from region B to region C. In L/D = 53.3 the standard deviation increases five times from region A to region B and decreases two times from region B to region.

Costigan and Whalley (1997) observed a rarefaction wave from the bottom of the cylindrical pipe to the top when studying the speed of sound in air-water flow in vertical upward flows. They argued that amplitude of successive reflections decayed rapidly as the energy of wave was dissipated.

Figure 9 Standard deviation ratios of the amplitudes oscillation as function of L/D from region A to region B and from region B to region C (see online version for colours)



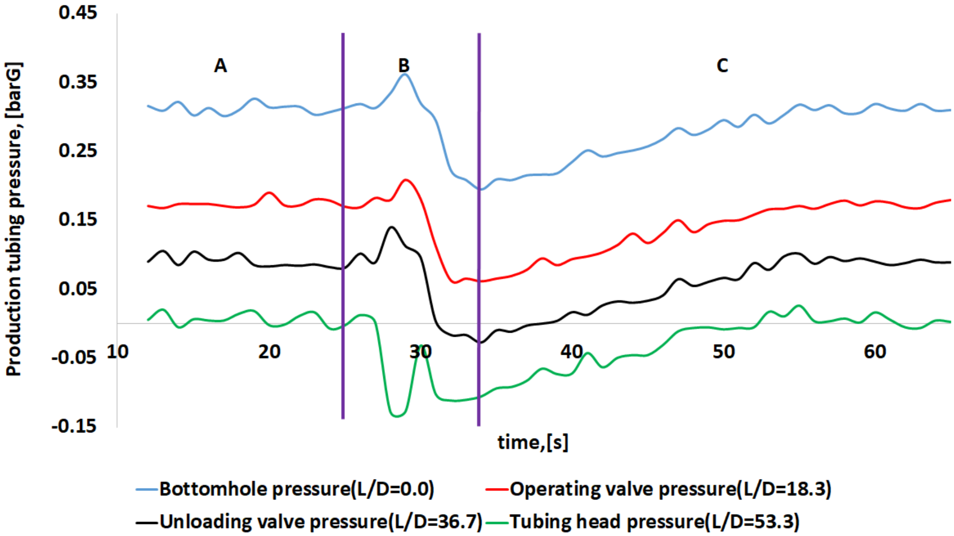
Notes: Blue solid line represents the increase ratio of the amplitude of pressure oscillation from region region A to region B and the red solid line shown the reduction ratio of the amplitude of pressure oscillation from region B to region C.

The fluctuation ratios of the amplitude oscillations from region A to C is shown in Figure 9 where the standard deviation increases six times from region A to region B and decreases two times from region B to region C in $L/D = 0.0$ (bottomhole), while in $L/D = 18.3$ the standard deviation is increased seven times from region A to region B and decreases two times from region B to region C, in $L/D = 36.7$ the standard deviation increases 7 times from region A to region B and has reduction ratio of 2 from region B to region C. In $L/D = 53.3$ the standard deviation increases five times from region A to region B and decreases two times from region B to region.

3.4.2 *Lift gas injected from unloading valve located at L/D = 36.7*

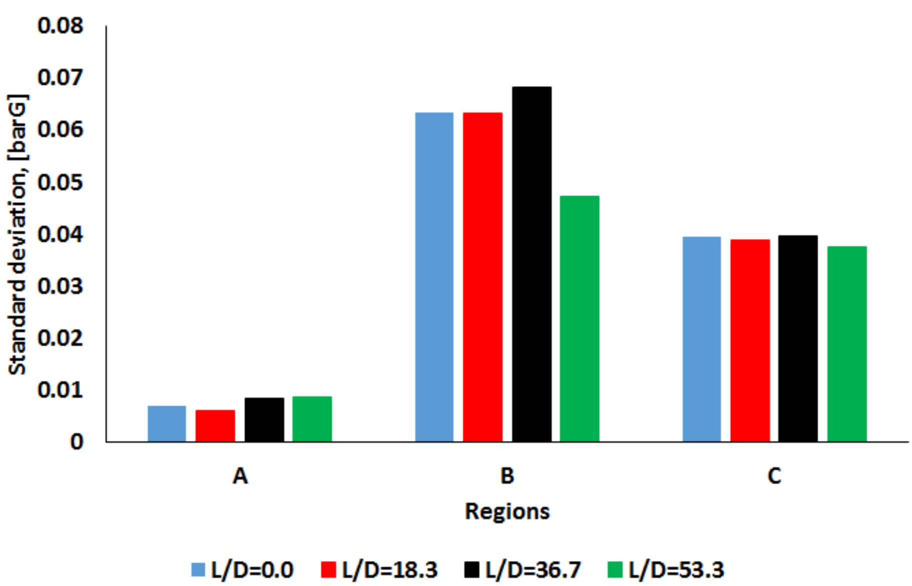
Plots of time series fluctuation of pressure in the four measurement points $L/D = 0.0$, $L/D = 18.3$, $L/D = 36.7$ and $L/D = 53.3$ are illustrated in Figure 10. As observed in Figure 10 three regions are distinguishable: region A corresponding to the period before opening the valve, region B which corresponds to the period in which the injection valve was opened instantaneously for three seconds and region C which corresponds to the period in which the valve is closed.

Figure 10 Time sequence of the pressure fluctuation due to injection of gas-lift along the production tubing (see online version for colours)



Notes: The LFR was set to $LFR = 7.7e^{-6}$ m^3/s while the gas-lift was injected from $L/D = 36.7$ (unloading valve) instantaneously for three seconds and closed afterward. The pressure profile were recorded in the four measurement points along the production tubing.

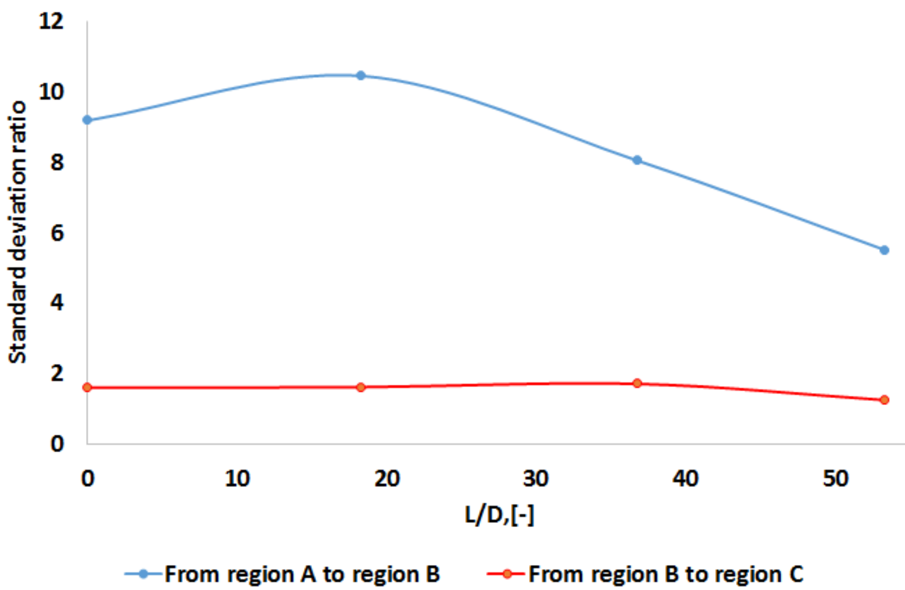
Figure 11 Standard deviation plot of the pressure fluctuation in four points along the production tubing for gas-lift injected at $L/D = 36.7$ (see online version for colours)



Region A is typified by natural pressure fluctuations of low amplitudes ranging from maximum of 0.326 barG to a minimum of 0.301 barG in L/D = 0.0 (bottomhole); 0.191 barG to 0.168 barG in L/D = 18.3 (operating valve), 0.106 barG to 0.0816 barG in L/D = 36.7 (unloading valve) and from 0.02 barG to –0.0073 barG at L/D = 53.3 (tubing head) respectively. The low oscillation in pressure is confirmed by low standard deviation of the amplitude that range from 0.0069 barG in L/D = 0.0, 0.0060 barG in L/D = 18.3, 0.0085 in L/D = 36.7 and 0.0086 barG in L/D = 53.3. The standard deviation plot of the pressure fluctuation in four points (L/D = 0.0, L/D = 18.3, L/D = 36.7 and L/D = 53.3) along the production tubing is presented in Figure 11.

Region B is characterised by high oscillations of the time series pressure with larger amplitude compared to the ones in region A. Step-up pressure change was observed at measurement points L/D = 0.0, L/D = 18.3 and in L/D = 36.7. The increase in pressure amplitude reaches a maximum values of 0.3615 barG in L/D = 0.0, 0.2092 in L/D = 18.3 and 0.1402 in L/D = 36.7 while a step-down pressure change is noticed in L/D = 53.3 with a minimum value of –0.1275 barG.

Figure 12 Standard deviation ratios as function of L/D from region A to region B and from region B to region C (see online version for colours)



Notes: Blue solid line represents the increase ratio of the amplitude of pressure oscillation from region region A to region B and the red solid line shown the reduction ratio of the amplitude of pressure oscillation from region B to region C.

Region C is characterised by relaxation period of pressure oscillations as a result of close of flow regulator valve where there is a decay in pressure disturbance amplitude and a linear increase of pressure on time in the four measurement points to the level of region A. The restoring time (time required to restore the pressure to the level of pressure in region A) is about 32 seconds.

The time response to the disturbance imposed by the addition of gas into the production tubing is different in the four measurement points as can be seen in Figure 10. At injection point L/D = 36.7 the effect is immediately, whereas at points L/D = 0.0, L/D = 18.3 and L/D = 53.3 here is a delay of two seconds.The same happens after the closing of the valve where the recovery of pressure is delayed in two seconds at points L/D = 53.3 far away the point where the gas-lift has been injected (L/D = 36.7).

As can be observed in Figure 11 the standard deviation is lower in A ranging from a maximum of 0.0086 barG to a minimum of 0.0060 barG while in region B there is high standard deviation ranging from 0.0474 barG to 0.0682 barG and in region C a decay of standard deviation is noticed. The fluctuation ratios of the amplitude oscillations from region A to C is presented in Figure 12 where the standard deviation increases nine times from region A to region B and decreases two times from region B to region C in L/D = 0.0 (bottomhole), while in L/D = 18.3 the standard deviation is increased ten times from region A to region B and decreases two times from region B to region C, in L/D = 36.7 the standard deviation increases 8 times from region A to region B and has reduction ratio of 2 from region B to region C. In L/D = 53.3 the standard deviation increases 5 times from region A to region B and decreases two times from region B to region.

4 Conclusions

The following conclusions can be drawn from this investigation:

- By increasing the choke, a transition from random peak-to-peak oscillation of pressure between an average value to a cyclic periodic oscillation is observed. This behaviour is accompanied by increase in pressure along the production tubing.
- The momentary stability observed in the production tubing associated with increasing the tubing head choke is strongly related to bubbles size evolution and increase in lift gas solubility along the production tubing height. Tubing head choke acts as a pressure stabiliser capable of bringing about delay in fluid flow regime transition change.
- The use of tubing-head choke in stabilising flow in gas-lift wells has to be conjugated with knowledge and understanding of fluid flow behaviour along the production tubing during gas-lift operations.
- The experimental data obtained in this study provides a direct means of characterising flow regime and deriving relationship between topside choking and well stability in gas-lifted wells.
- The influence of surface choking and fluid flow regime transition on liquid production rate will be investigated as part of future research.

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