

The Effect of Development of Two-Phase Flow Regimes on the Stability of Gas Lift Systems

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Abstract—Flow instability during gas lift operation is caused by three major phenomena – the density wave oscillation, the casing heading pressure and the flow perturbation within the two-phase flow region. This paper focuses on the causes and the effect of flow instability during gas lift operation and suggests ways to control it in order to maximise productivity during gas lift operations. A laboratory-scale two-phase flow system to study the effects of flow perturbation was designed and built. The apparatus is comprised of a 2 m long by 66 mm ID transparent PVC pipe with air injection point situated at 0.1 m above the base of the pipe. This is the point where stabilised bubbles were visibly clear after injection. Air is injected into the water filled transparent pipe at different flow rates and pressures. The behavior of the different sizes of the bubbles generated within the two-phase region was captured using a digital camera and the images were analysed using the advanced image processing package. It was observed that the average maximum bubbles sizes increased with the increase in the length of the vertical pipe column from 29.72 to 47 mm. The increase in air injection pressure from 0.5 to 3 bars increased the bubble sizes from 29.72 mm to 44.17 mm and then decreasing when the pressure reaches 4 bars. It was observed that at higher bubble velocity of 6.7 m/s, larger diameter bubbles coalesce and burst due to high agitation and collision with each other. This collapse of the bubbles causes pressure drop and reverse flow within two phase flow and is the main cause of the flow instability phenomena.

Keywords—Gas lift instability, bubble forming, bubble collapsing, image processing.

I. INTRODUCTION

THE petroleum industry has long needed to understand the challenges of two-phase flow behaviours in production tubing in gas lifted wells under different operating conditions (port size, flow rate and injection pressure) and their macroscopic flow instability. This type of instability which is known as systematic instability involves the entire two phase flow system and is dependent on the boundary conditions.

The systematic flow instability can cause serious flow oscillations that require feedback control systems to reduce these flow oscillations. However, these are only partially effective to control these fluctuations. They also increase the backpressure on gas lift systems and this leads to reduce oil production rate. Flow perturbations and density wave type oscillations which occur inside production tubing string are related to the kinematic wave propagation phenomenon of

fluid. These are the main cause of flow instability in production tubing and should not be neglected. This happens when fluids with different densities flow together and create very abnormal fluid behaviors that cause turbulence in the system [1].

Two-phase flow has different patterns. For example, in vertical pipes one of the following flow regimes will be present: Bubbly flow, dispersed flow, annular flow or slug to churn flow [2]. Multiphase flow, in the petroleum industry, has many applications and complications across the entire production system; therefore, engineers face with the necessity to solve and predict flow instability phenomenon by determining the relationships between flow rates, pressure drop and pipe geometry (pipe length, diameter and angle) [3].

The prediction of the overall pressure gradient and pressure profiles for multiphase flow in vertical columns has been developed. However, the effect of casing pressure was neglected [4], [5]. Multi-phase flow patterns and the transitional flow regions during hydrodynamic conditions were investigated using physical model. Hasan and Kabir reported that the difference between flow patterns depended on the depth in the vertical well, which near the bottom hole may only have one phase. Moreover, as fluid flows upward in the vertical pipe, its pressure decreases gradually until it reaches a point that is less than bubble point pressure. When gas starts to vaporize from the fluid mixture it causes the following flow patterns to develop: Bubbly flow, slug flow, churn flow and annular flow [6].

Several experimental works were carried out to investigate flow pattern transitions of two phase flow in a vertical pipe using conductance probes, wire mesh sensor and high speed camera for observations [7]-[9]. Results indicated that void fraction data and flow patterns information gave good agreements with developed flow models. Even though their research data gave consistent agreement with developed models; their investigations did not mention that the bubble break and coalesce process in these transitional regions are the main cause of the disturbance wave. The periodic structure of two phase flow investigated in vertical column with different pipe diameters (0.5 mm – 70 mm) with ring-type conductance probes were used to obtain film thickness, pressure gradient and frequency. It is indicated that as pipe diameter increases some flow transitional regions disappeared [9]. According to Bertuzzi, the performance of the gas lift system can be improved by reducing tubing size and regulated injection pressure but this is depending on the productivity index of the reservoir (PI) and hydrostatic fluid level in the tubing string even if there is not packer between casing and tubing [10].

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According to Gilbert, two phase flow pressure gradient along the vertical pipe can be obtained by using pressure gradient curves which distinguish between gas-liquid ratios, rate of liquid flow and tubing sizes for flowing fluid in gas lifted wells [11].

The influence of liquid viscosity on pressure gradient in two phase flow in a vertical pipe has been investigated. The results showed that when viscosity is above 12 cp, liquid flow rate is reduced. This is more evident when the liquid flow rate reaches the laminar flow regime. Energy is lost due to friction and then the slippage is raised between the gas and liquid phases [12]. Orkiszewski [13] extended research work of [21] by including the velocity flow range, and then developed a method to predict two phase pressure drops in gas lift wells and flowing wells. This modified method gave more details about the liquid distribution between liquid slugs, the liquid film and entrained liquid in gas bubbles, as well as liquid holdup, especially at high velocities.

Numerical simulation and mathematical models were used to analyse steady and unsteady state flow conditions through vertical column, considering production loss and the effect of optional lift on gas lifted wells [14], [15]. The effects of fluid properties and flow rates on slip velocity in multiphase flow conditions were investigated by [16]. Two gas lift stability criteria, dealing with the sensitivity of the reservoir and its response; the other being pressure depletion response were proposed by [17]. Alhanati et al. [18] investigated the flow stability criteria proposed by Asheim [17] and stated that some assumptions are not valid, due to the facts that some gas lift components were neglected, such as gas injection choke, tubing-casing annulus and subsurface gas lift valves, especially at low flow rates in certain gas liquid ratios (GLR) in the Asheim criteria. Furthermore, the gas liquid ratio of a naturally flowing well has the same GLR of formation but less than a gas lift well because a gas lift well's GLR is equal to the formation plus injected gas ratio. Therefore, formation response to wellbore should not be neglected [19]. These

instabilities caused an undesired situation of producing more injected gas than crude oil from the oil reservoir and reducing total oil production considerably during gas lift operations. It is also harmful to the smoothness, safety and efficiency of gas lift operations. Therefore, this paper will focus on fluid behaviors such as bubbles forming and collapsing due to dispersion and distribution of bubbles while travelling upwards in the vertical column at different operating conditions. The advanced imaging processing software package (Dynamicstudio2015a) will be used to reveal and understand the static and dynamic two phase flow behaviours in production tubing.

II. EXPERIMENTAL SET-UP AND PROCEDURE

A laboratory-scale two-phase vertical flow system was designed and built to study of flow instability during gas lift operation. The schematic of the system is shown in Fig. 1. The experimental set-up consists of a 2 meters transparent Perspex vertical pipe with a 66 mm ID. Air is injected of the bottom of the test column through a range of interchangeable port sizes. The air pressure was varied from 0.5 bar to 5.0 bar corresponding air flowrates of 1litre/min to 9 litre/min, while liquid flowrate was varied from 5 litre/min to 30 litre/min creating liquid structure velocity between 2.4 to 14.6 cm/s in order to attain different fluid behaviours, such as; bubbly and slug flows within the test column when the two flowing fluids are in contact within the column. The operating conditions are summarised in Table I.

TABLE I
EXPERIMENTAL OPERATING CONDITIONS

Parameters	Ranges
Air flow rate l/min	1-9 l/min
Water flow rate l/min	5 -30 L/min
Air inlet size, mm	0.2- 4 mm
Velocity of liquid phase	2.4 -14.6 cm/s

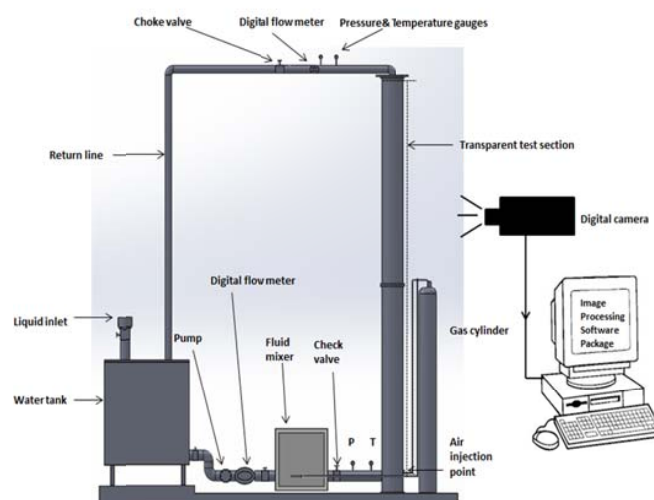


Fig. 1 Experimental Set-up

The vertical test column was divided into five segments from the bottom of the test rig to the top. The first segment was measured from the injection point of 0.1 m upward to the end of the transparent column at two meters length. This distance was determined experimentally as the best position where the generated bubbles were visibly stable to be captured by digital camera. Each segment is 0.38 m in length and operated under different operating conditions and the bubble images generated within the each segment is recorded by a digital camera in front of the column at different levels. Digital camera videos were recorded for 30 seconds for each operating scenario and then these videos were converted to single frames by a special converter (Free Video to JPG converter V.5) and frame rate was 0.016s.

The image processing steps to analyse the frames using the advanced image processing technique (DynamicStudio 2015a) involve a six-step operation. The first is model calibration which involves measuring scale factor of each frame located two point (A and B) to measure the velocity of bubbles, followed by image min/max, where the image is processed to compute power mean greyscale values from a series of images, arithmetic image method is for enable arithmetic on pixel values and can be performed on any type of images (for example 8-, 10- or 12-bit images), image masking involves defining a mask for regions or area of specific interest on frame and masking images by assigning specific grey-values in regions defined, also images processed by filters featured in the image processing library (IPL) module to smooth images (Low-pass), detect the bubbles edges (High pass), and enhance image contrast (Low-pass & Morphology) and finally shadow processing and sizing is used to detect the edges of the bubbles then extract measurements such as the bubble sizes, the positions of bubbles, the shape of bubbles, the velocity of each bubble as shown in Fig. 2 [20].

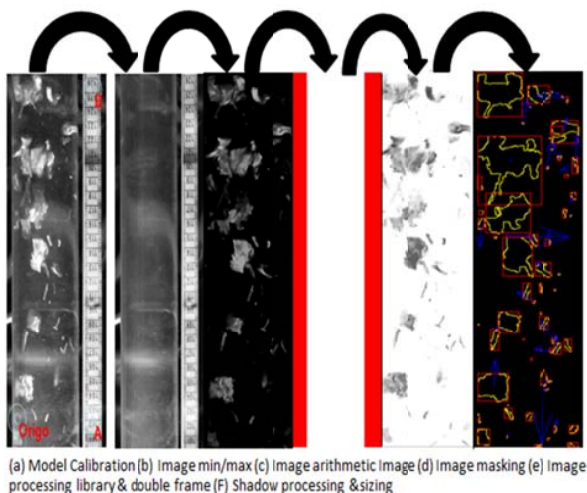


Fig. 2 Advanced Image Processing Procedure [20]

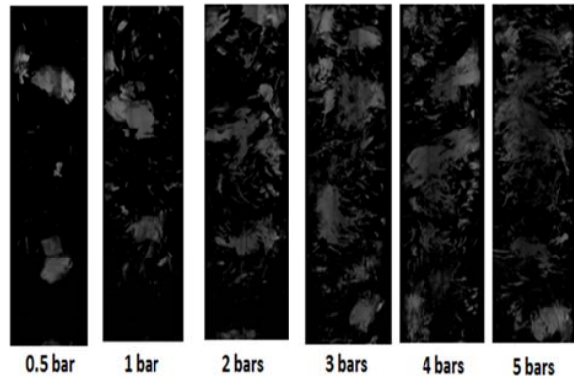


Fig. 3 Arithmetic images of the effect of injection pressure

Test conditions to generate bubble sizes within the two-phase flow that can cause flow instability in vertical pipe were carried out by varying the air pressure as shown in Fig. 3, rate and liquid flowrate and the following conditions were studied:

- Effect of liquid structure velocity on average maximum bubble sizes at constant pressure
- This experiment was conducted by varying the liquid velocity from 2.4 cm/s to 14.6 cm/s at air injection pressure of 0.5 bar and the generated bubble sizes were recorded. The experiment was repeated for air injection pressure of 1 bar – 5 bars.
- Effect of injection pressure on bubble sizes behaviors.
- Effect of bubble velocities on bubble sizes at constant pressure.
- Effect of port sizes on bubble sizes at constant injection pressure of 1 bar and liquid flow rate 5 l/min.
- Effect average maximum bubble sizes on outlet flow rate (production rate).

The original 2 m pipe was analysed segment by segment at lengths of 0.11 m, 0.49 m, 0.87 m and 1.25 m with the same 66 mm ID. The injected air pressure was maintained at 0.5 bar while the water flowrate was 5 litre/min. The various bubble sizes for different pipe length were recorded.

The images of bubble sizes generated during the experiment were analysed and the bubble sizes were determined by using advanced image processing technique.

A. Effect of Liquid Structure Velocity on Average and Maximum Bubble Sizes

Fig. 4 shows the relationship between the liquid velocities on the average maximum bubble sizes at 0.5 bar air injection pressure. At lower liquid velocities of 2.4 cm/s, the bubble size increases with increase in injected air pressure. The bubble sizes however will reduce as the liquid velocities increase due to increase in agitation and collision within the confined space as shown in the graph. Fig. 5 shows another evidence of this positive effect of velocity of liquid phase on average bubble sizes. Therefore, increasing liquid phase velocity stabilizes two phase flow behaviors in the vertical column as shown in the graph. Furthermore, this reduces the average bubble sizes and minimizing and optimizing the

development and turbulences within two phase flow in production tubing and increase oil production rate.

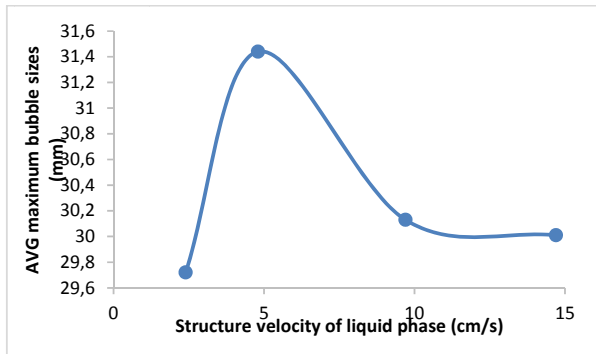


Fig. 4 Effect of structure liquid structure velocity on maximum bubbles sizes at constant pressure 0.5 bar (standard deviation 0.77)

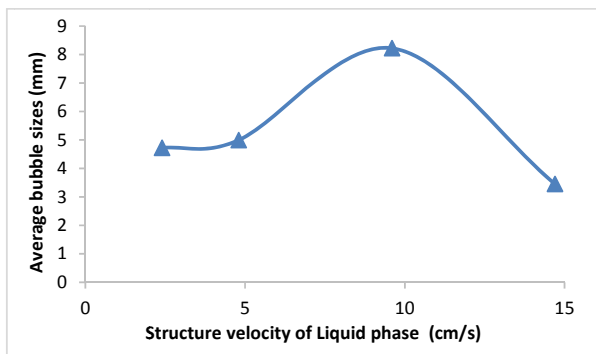


Fig. 5 Effect of structure liquid structure velocity on average bubble sizes at constant pressure 0.5 bar (standard deviation 0.66)

B. Effect of Air Injection Pressures on Bubble Sizes

The increase in injection pressure has a considerable effect on the two phase flow behaviours. Fig. 6 shows the relationship between air injection pressure at the bottom of the vertical test column and bubble sizes' growth at middle length of pipe. This effect was investigated for water velocity of 2.4 cm/s and different air injection pressures from 0.5 bar to 5.0 bar. The average maximum bubble sizes were 38 mm at 0.5 bar; and after the injection pressure was increased to 2 bars at the same water velocity, the diameters of bubbles grew and were measured to be 43 mm. However average maximum bubble sizes declined after increasing pressure to 3 bars. This decline in bubble sizes is due to increasing in the backpressure when the pressure increased in restricting the development of flow. This provides evidence that the injection pressure has a big an effect on the development and behaviours of two phase flow in the gas lifted systems as shown in Fig. 7, because the diameters of bubbles have a very large impact on the flow patterns, behaviours and stability of the two-phase flow. Consequently, injection pressure could increase and decrease bubbles sizes gradually. Fig. 8 shows this effect on average bubbles sizes and how pressure stabilizes the upward flow by reducing average bubble sizes and restricting the flow developments.

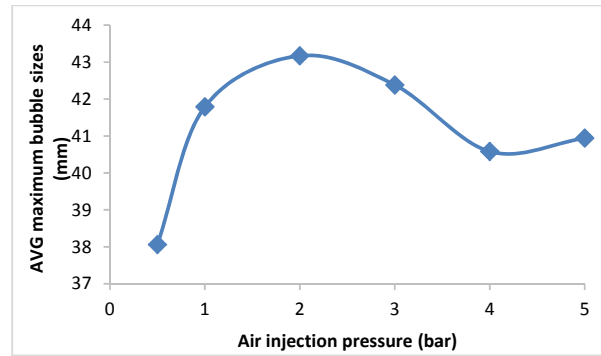


Fig. 6 Effect of injection pressure on average maximum bubble sizes (standard deviation 6.36)

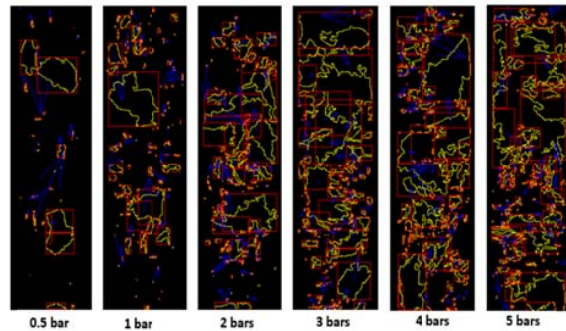


Fig. 7 Shapes of bubbles at different pressures using shadow sizing technique

Fig. 9 shows relationship between velocities of average maximum bubble sizes. The graph indicated that there is a drop in the velocity of bubbles and fluctuations especially when pressure was 3 bars. This point has been observed in two phase flow behavior. This region is where bubbles with large diameters reach certain sizes, depending on the pipe diameter and operating conditions then they burst as shown in Fig. 10, causing a collision with other neighbouring bubbles and turbulences. Therefore, this collision leads to agitation and a decrease in pressure (pressure drop) due to burst bubbles. Furthermore, they explode into small bubbles causing small scale ripple reverse flow. This phenomenon causes unstable flow rate and a shortage in the amount of liquid flowing from the vertical tube. This behaviour is a major cause of the instability of the two-phase flow in a vertical column, especially when increasing the velocity of the bubbles, which leads to an increase in the diameters of bubbles. This cyclic process will be repeated simultaneously depending on the increase of bubbles' velocities flowing upward in the pipe. To avoid this phenomena bubbles sizes must be reduced.

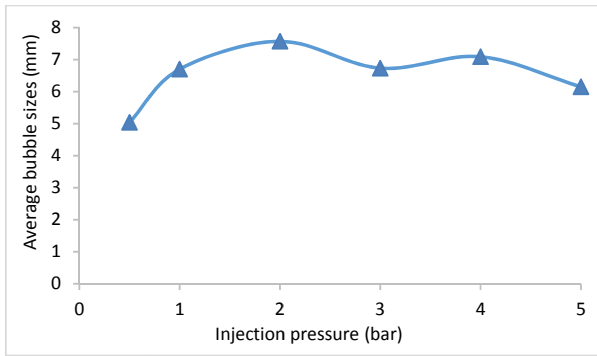


Fig. 8 Effect of injection pressure on average bubble sizes (standard deviation 0.54)

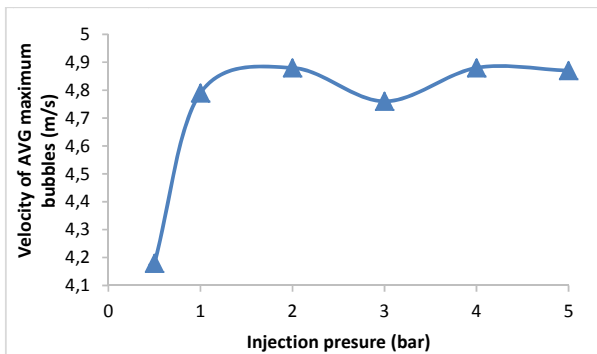


Fig. 9 Effect of injection pressure on velocity of bubbles at constant liquid flow rate 5 l/min (standard deviation 0.96)

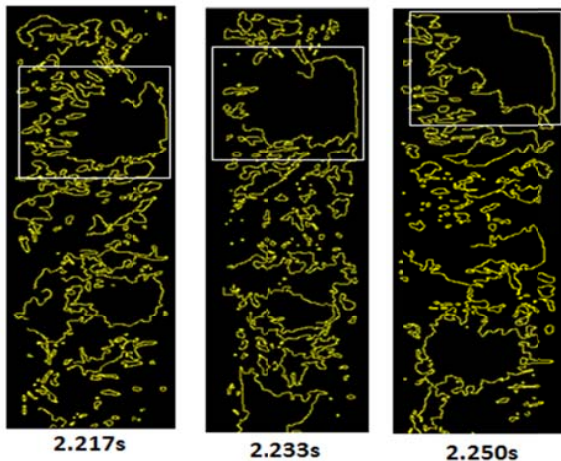


Fig. 10 Bubble rupture and collision using shadow sizing imaging at 3bars

C. Effect of Velocity of Bubbles on Bubble Sizes at Different Air Injection Pressures

Fig. 11 shows the relationship between the velocities of bubbles and bubble sizes at constant liquid velocity 2.4 cm/s. It is very clear through the graph that as velocity of bubbles increases the bubble sizes increase with accretion of injection pressure. The velocity profiles were strongly influenced by the

bubble size. Also it is found that initial bubble sizes have considerable and sensitive effect on two phase flow structure and development. This behavior was very clear especially when liquid velocity and injection pressure reduced to minimum operating conditions, shows very clear evident of the effect of initial small bubbles entering the column through the injection point and then coalesce to together forming bigger bubbles and this is the starting point of the development of flow. Fig 12 shows how initial bubbles coalesce together and forming bigger bubbles.

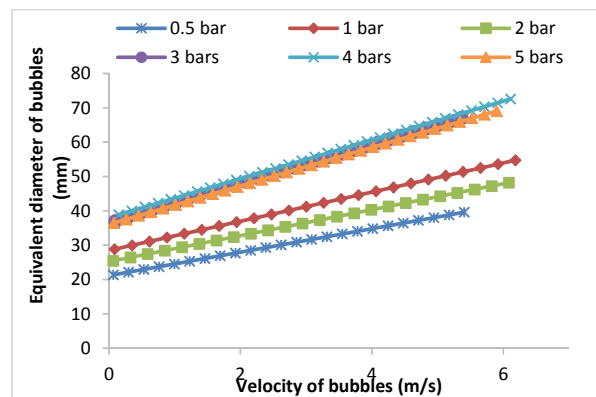


Fig. 11 Effect of bubble velocities on bubble sizes at different pressures (Standard deviation 11.6)

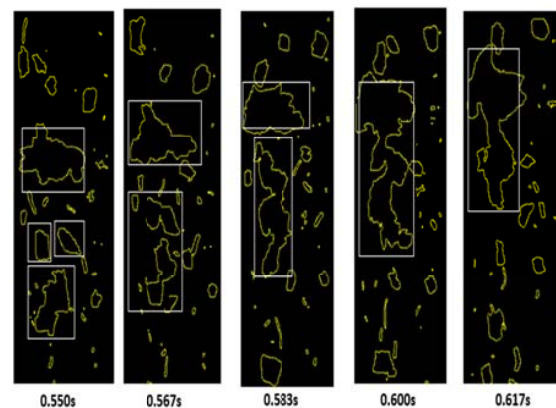


Fig. 12 Bubble coalesce rate at low liquid phase velocity 2.4 cm/s

D. Effect of Port Sizes on Maximum Bubble Sizes at Constant Injection Pressure 1 Bar and Liquid Flow Rate 5 l/min

Fig. 13 shows the effect of port sizes (gas lift valve) on bubble sizes at different small range (0.2 mm - 1 mm) at constant liquid flowrate and injection pressure 1 bar. The results showed that as port size increases the bubbles increase. However, there was drop on equivalent maximum bubble size when port size was 0.7 mm, and bigger fluctuations observed when port size increases. In addition, it was found that higher jet velocity produced from smaller diameter nozzle shows higher breakup frequency of the bubbles at 6.6 m/s in the plunging zone and consequently, smaller bubbles are observed

throughout the column with smaller diameter nozzle. Therefore, increasing port size has destabilizing effect because it increases bubble sizes and also leads instability on two phase flow.

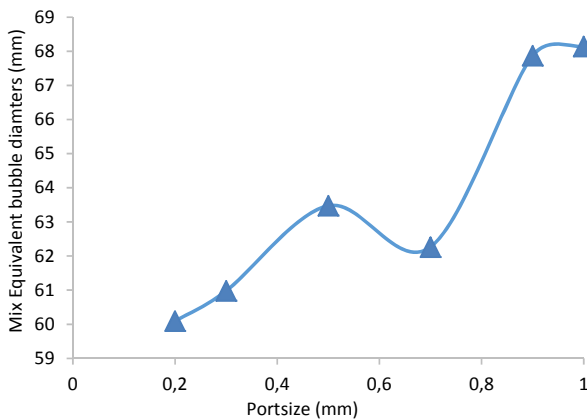


Fig. 13 Effect of port sizes on maximum equivalent bubble diameters at constant injection pressure 1 bar and liquid flow rate 5 l/min (standard deviation 3.4)

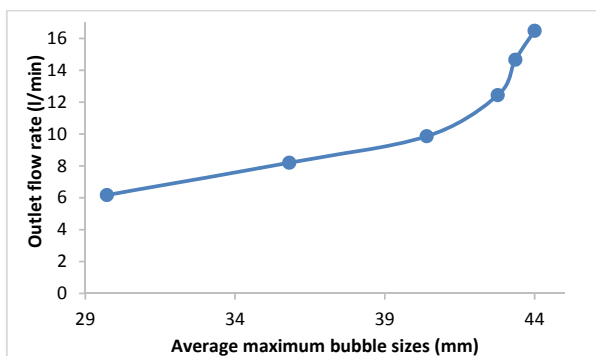


Fig. 14 Effect Average maximum bubble sizes on outlet flow rate at constant liquid flow rate 5 l/min and different injection pressure (standard deviation 0.97)

E. Effect of Average Maximum Bubble Sizes Outlet Flow Rate (Production Rate) at Constant Inlet Liquid Flow Rate 5 l/min

Fig. 14 shows relationship between average bubble sizes and outlet flow rate in the vertical column. The effect of stable average bubble sizes on outlet flow rate is very clear. The results showed that stable bubble sizes increases as outlet flow rate increases (production rate). This increase in the bubble sizes is recommended to certain extent and must not reach to critical maximum bubble sizes where bubbles start collapsing and causing flow instability. This is because the bubble sizes can change the flow pattern and radial distribution of bubbles in the column. In addition, maintaining small bubble sizes can enhance the efficiency of the gas-lift method. Furthermore, the initial bubble size significantly affected the flow pattern transition from bubbly flow to slug flow. This effect was clear from making the relationship between bubble size dependent and critical void fraction, especially in the transitional region

from bubbly flow to slug flow. Therefore, decreasing bubble size can shift larger values of the void fraction in the transitional regions and stabilize the gas lifted system.

IV. CONCLUSION

The flow structure and behaviours of two phase flow have been investigated experimentally in a vertical transparent pipe (ID: 66 mm, Length: 2 m) using image processing package (Dynamic studio 2015a). The following concluding remarks are derived from this study:

- Bubbly and slug flow patterns were observed in the test section, the axial distribution of bubbles at different operating conditions showed very interesting observations about air bubbles' coalescence and collision mechanisms statically and dynamically.
- It has been found that bubble sizes had a significant effect on the stability of the axial structure of two phase flow, especially when bubbles reached a critical size (maturation) and then collapsed. This behaviour causes small pressure drop and vacuum and back flow in that particular region of collapsed bubbles which lead to collision with some bubbles nearby. Furthermore, this collision causes disturbances and small waves within the system. This process will be repeated simultaneously depending on velocities of bubbles flowing upward in the pipe.
- The velocity of air bubbles had considerable impact on fluctuations, structure and development of two phase flow. It has been noticed that bubbles under the same operating conditions have different velocities depending on their sizes. Therefore as air bubble velocity increases the bubble sizes increases.
- The velocity and flowrate of liquid phase has positive and stabilizing effect on stability of two phase flow. Because it reduces the bubble sizes and acting like reservoir respond (productivity index) to the well bore when it is increases.
- Injection pressure has two effects on bubble sizes, at low pressure increases the bubble sizes but at high pressure it has negative effect on bubble size and stabilizes the column.
- Port size diameter has great effect on bubble sizes as higher breakup frequency was anticipated at smaller diameter of the injection point result in lower bubble sizes were observed.

REFERENCES

- [1] Hu, B., *Characterization of gas-lift instabilities*. 2005.
- [2] Eikrem, G.O., *Stabilization of Gas-Lift Wells by Feedback Control*. 2006.
- [3] Brill, J.P., *Multiphase Flow in Wells*. 1987.
- [4] Poettman, F.H. and P.G. Carpenter, *The Multiphase Flow of Gas, Oil, and Water Through Vertical Flow Strings with Application to the Design of Gas-lift Installations*. 1952, American Petroleum Institute.
- [5] Zabaras, G.J., *Physical Modelling Of Vertical Multiphase Flow: Prediction Of Pressure Gradients In Oil And Gas Wells*. 1994, Offshore Technology Conference.
- [6] Hasan, A.R. and C.S. Kabir, *A Study of Multiphase Flow Behavior in Vertical Wells*. 1988.

- [7] Kaji, R., B.J. Azzopardi, and D. Lucas, *Investigation of flow development of co-current gas-liquid vertical slug flow*. International Journal of Multiphase Flow, 2009. 35(4): p. 335-348.
- [8] Omebere-Iyari, N.K. and B.J. Azzopardi, *A Study of Flow Patterns for Gas/Liquid Flow in Small Diameter Tubes*. Chemical Engineering Research and Design, 2007. 85(2): p. 180-192.
- [9] Kaji, R. and B.J. Azzopardi, *The effect of pipe diameter on the structure of gas/liquid flow in vertical pipes*. International Journal of Multiphase Flow, 2010. 36(4): p. 303-313.
- [10] Bertuzzi, A.F., J.K. Welchon, and F.H. Poettman, *Description and Analysis of an Efficient Continuous-Flow Gas-Lift Installation*. 1953.
- [11] Gilbert, W.E., *Flowing and Gas-lift well Performance*. 1954, American Petroleum Institute.
- [12] Hagedorn, A.R. and K.E. Brown, *The Effect of Liquid Viscosity in Two-Phase Vertical Flow*. 1964.
- [13] Orkiszewski, J., *Predicting Two-Phase Pressure Drops in Vertical Pipe*. 1967.
- [14] Gould, T.L. and M.R. Tek, *Steady and Unsteady State Two-Phase Flow through Vertical Flow Strings*. 1970, Society of Petroleum Engineers.
- [15] Bin, H. and M. Golan, *Gas-lift Instability Resulted Production Loss and Its Remedy by Feedback Control: Dynamical Simulation Results*. 2003, Society of Petroleum Engineers.
- [16] Nicolas, Y. and E.J. Witterholt, *Measurements Of Multiphase Fluid Flow*. 1972, Society of Petroleum Engineers.
- [17] Asheim, H., *Criteria for Gas-Lift Stability*. 1988.
- [18] Alhanati, F.J.S., et al., *Continuous Gas-Lift Instability: Diagnosis, Criteria, and Solutions*. 1993, Society of Petroleum Engineers.
- [19] Faustinelli, J., A. Cuauero, and G. Bermúdez, *A Solution to Instability Problems in Continuous Gas-Lift Wells Offshore Lake Maracaibo*. 1999, Society of Petroleum Engineers.
- [20] Dentec, C.D., *Dynamicstudio2015 manual*. 2015.
- [21] Peter Griffith, G.B.W., *Two-Phase Slug Flow*. Journal of Heat Transfer, 1961. Volume 83 (3): p. 307-318.