ANALYSIS OF HORIZONTAL AIR-SILICONE OIL PLUG-TO-SLUG TRANSITION FLOW

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ABSTRACT

The analysis of the experimental data for the air-silicone oil plug-slug transition in a 67mm id and 6m long horizontal pipe was carried out in this work. The superficial gas and liquid velocity ranged from (0.05 – 4.73) m/s and (0.05 – 0.473) m/s respectively. The transition from plug to slug flow was investigated by increasing the superficial gas velocity at fixed superficial liquid velocity. For the investigated experimental data set, the intermittent flow was observed at the superficial liquid velocity of 0.142m/s. The transition from plug to slug flow for the experimental data was observed at the superficial velocity of between 0.7 – 1.2m/s. To characterize the plug – slug transition, the effect of liquid and gas superficial velocity on void fraction, bubble velocity, bubble length and slug frequency were obtained. The drift flux model for the data set was also obtained and compared with existing models for horizontal flow. The results obtained from the analysis agree well with the reports of several literatures for the air – water plug – slug transition in horizontal pipes.

Keywords: Void fraction, drift flux, plug flow, slug flow, flow patterns, flow map.

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DEDICATION

This work is dedicated to Almighty Allah for His infinite mercy, protection and guidance and also to my Late father Alh. AbdulAzeez Asikolaye. May Almighty Allah grant him Aljanat Fridaus.

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CHAPTER ONE

1.1 Introduction

Two-phase flow occurs when two different fluids move concurrently through a pipe. The exact form of two-phase flow is determined according to the phases appearing in the mixture, namely solid-liquid, gas-solid (e.g. particles in a gas or liquid) and gas-liquid (droplets in gas and gas bubbles in a liquid)(Gschnaidtner, 2015).

The study of two-phase flows is of great importance for several technological applications. Particularly, gas-liquid two-phase flows are often encountered in a wide range of industrial applications, such as condensers, evaporators, distillation towers, nuclear power plants, boilers, crude oil transportation and chemical plants among others. Gas-liquid flow is not only the most common of the two-phase flows; it is also the most complex since it combines the characteristics of a deformable interface with those of a compressible phase (Carpintero, 2009). Various difficulties are encountered in the flow of these fluids, some of which are phase velocity differences and the existence of several flow regimes.

1.2 Characterization of two-phase flow

The conventional approach to investigate/characterize two-phase flow is to classify two-phase flow into different flow regimes based on the interfacial structure. In two-phase flow, void fraction and bubble velocity are two of the fundamental parameters. The void fraction describes the gas distribution and is an important parameter for hydrodynamic and thermal design in various two-phase systems, while the bubble velocity determines the transport of the void fraction and interfacial area concentration(Kong & Kim, 2017).

The flow regimes include; bubbly, slug, churn, plug, and stratified, among many others. The existence of these flow regimes in transportation lines poses certain challenges to the industry because they increase the pressure drop, heat and mass transfer and corrosion rate in the pipeline. The complexity of the potential flow regimes has attracted considerable research interest to improve the understanding of two-phase flow behavior in a pipe system under various processing conditions. The understanding of the flow regimes is vital for engineers to improve the configuration of pipelines and downstream processes to attain economic and safe design. Hence the ability to predict the multiphase fluid flow behavior of these processes is central to the efficiency and effectiveness of the processes (Beggs, D. H., & Brill, 1973)

The flow pattern is the result of the mechanical and thermal dynamic equilibrium between the phases that depends on a large number of important parameters such as the phase's superficial velocity, the flow conditions (pressure and temperature), the fluid properties (density, viscosity, and surface tension), the channel geometry and the flow direction (upward, downward, co-current, countercurrent)(Monni, De Salve, & Panella, 2014

1.3 Plug-slug transition in horizontal flow

Plug and slug flows are two of the flow regimes in a horizontal configuration, which are usually classified in general into intermittent flow in previous researches. A large number of small bubbles observed in the liquid slug differentiate slug flow from plug flow. These flow regimes are characterized by alternate appearance of gas that occupies the upper portion of the pipe and liquid slugs that occupy the entire cross-sectional area of the pipe (Kong et al., 2018).

Plug flow exists at relatively low gas flow rate region (j_g < 0.5 m/s) at 0.1 m/s < j_f < 3.00 m/s. (Kong et al., 2018). Transition of plug to slug flow is associated with bubble detachment from elongated bubble tail or bubble entrainment inside the liquid slug. The plug-to-slug transition flow can be observed by increasing superficial gas velocity holding superficial liquid velocity constant (Kong & Kim, 2017).

1.4 Problem Statement

The existence of several flow regimes in transportation lines poses certain challenges to the industry. This is because they increase the pressure drop, heat and mass transfer and corrosion rate in the pipeline. Hence, there is a need to study what happens as the fluids flow through the pipe. Several studies have been carried out to investigate the transition from plug to slug flow in horizontal pipes. They were however restricted to the use of air-water systems. This work investigates the transition of plug-to-slug with model fluid air and silicone-oil.

1.5 Aim and Objectives of the Research

The aim of this research is to investigate the transition between plug-to-slug flow of a horizontal air–silicone oil 67mm diameter and 6m long pipe.

The objectives include;

- Processing, analyzing and interpreting of raw experimental data
- Characterize plug and slug flow regimes using time series analysis, a MACRO and a matlab program;
- Predict the transition between the plug–slug transition boundary
- Investigate the effect of liquid and gas superficial velocities on void fraction, bubble velocity, bubble length and slug frequency
- Compare the results with others reported for air-water two phase flows.

1.6 Organization of the Research

The report is structured in this format;

- Chapter one contains the introduction of the topic, defining the problem, the aim and the objectives of the research.
- Chapter two is the review of previous researches on two-phase flow, horizontal and vertical flow regimes; identification of flow regime using flow pattern map, PDF and time series analysis, and Characterizing plug-slug transition in horizontal pipe.
- Chapter three describes the methodology to achieve the set objectives for this work consisting of data acquisition, data processing, flow regime identification and data analysis.
- Chapter four; the results and detailed discussion of the results obtained for the analysis of the experimental data.
- Chapter five concludes the research work.

CHAPTER TWO

2.0 LITERATURE REVIEW

Multiphase flow is the simultaneous flow of several phases. The study of multiphase flow is very important in energy-related industries and applications. The simplest case of multiphase flow is two-phase flow(Paridah et al., 2016). Two-phase flow can be solid-liquid flow, liquid-liquid flow, gas-solid flow, and gas-liquid flow.

2.1 Flow regimes classification in two-phase flow

Flow patterns in two-phase flow depend on different flow parameters, including the physical properties of fluids (the density of the gas and liquid phases (ρg and ρl), the viscosity of the gas and liquid phases (μ_g and μ_l), and the surface tension (σ)), the flow rate of the gas and liquid phases (Q_g and Q_l), as well as the geometrical dimensions of the flow system.

The flow regimes can be divided into three main classes:

1. Regimes for horizontal flow in pipes, where the heavier phase (water) tends to be located close to the bottom, because of gravity. In most cases the gas phase pushes the liquid phase along the flow direction.
2. Regimes for vertical flow in pipes. The liquid phase tends to be on the pipe walls, forming a stable or an unstable film. Flow velocity can be different and flow regimes form differently for upward and downward flows.
3. Regimes for sloped pipes, which are not as well known. Here the slope angle is important as well as the direction of the flow (upwards or downwards).

2.2 Horizontal flow regime

According to (Monni, De Salve, & Panella, 2014), the horizontal gas–liquid flow can be classified in four general flow structures: stratified flow, bubbly flow, slug/plug flow and annular flow. Each flow pattern can also be divided in sub-categories: stratified flow in smooth and wavy flow, intermittent flow in slug and plug flow and annular flow in smooth, wavy and mist flow.

2.2.1 Bubbly flow: Small bubbles are present in the flow, and are dispersed everywhere in the cross section. Bubbles gather in the top of the pipe for low velocities and become foam like at high velocities.

2.2.2 Plug Flow: These are liquid plugs separated by elongated gas bubbles. These bubbles are smaller than the tube diameter such that the liquid phase is separated and found below them. This particular flow regime is also known as the elongated bubble flow(Kwatia, 2016) Bubbles join and form larger gas plugs. The plugs flow in the upper part of the pipe because of gravity effects.

2.2.3 Stratified Flow: The two phases are completely separated; with gas in the upper part and liquid in the lower part of the pipe. Surface is relatively smooth and variations are small. This type of flow can only occur at low velocity.

2.2.4 Wavy Flow: This flow appears at higher velocities, compared to the stratified flow. Waves form on the phase boundaries, resulting in more friction between the two phases. If the gas velocity is considerable higher that of liquid, waves travel in the direction of flow,

2.2.5 Slug flow: Slug flow occurs in plug flow at higher gas flow rates. In this case, the gas velocities increase as the flow rate increases. This causes the elongated bubbles to increase in size to fill almost the entire diameter of the tube.

2.2.6 Annular Flow: The liquid forms a coat all around the pipe walls. Gas flows in the middle, possibly with liquid droplets traveling along it. Coat tends to be thicker at the bottom than at the top, because of gravity effects.

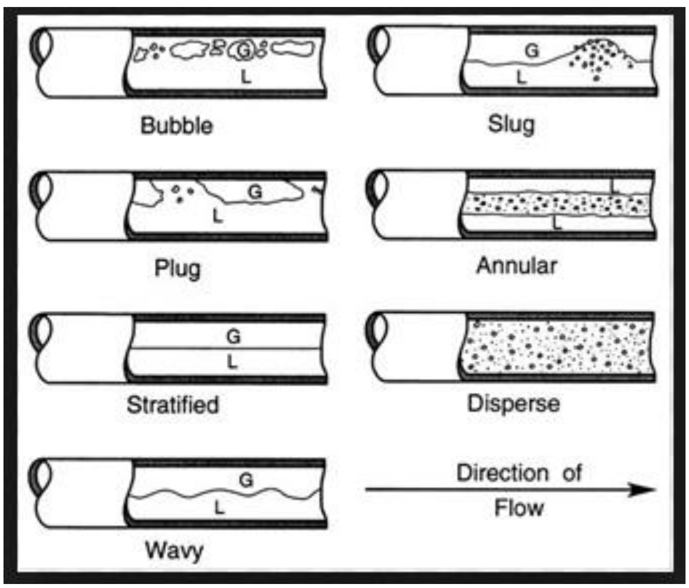

Figure2. 1Flow patterns in Horizontal gas-liquid pipe (Abdulmouti, 2014)

2.3 Vertical Flow Regimes

The major flow patterns encountered in vertical co-current flow of gas and liquid include bubbly, slug, churn, and annular flow.

2.3.1 Bubbly Flow: Gas bubbles are present in a liquid dominated flow. Bubbles are mostly evenly distributed, but tend to gather near the pipe center with increased speed. Velocity is similar for both phases, $S \approx 1$.

2.3.2 Slug Flow: Gas bubbles gather and form bullet shaped voids in the pipe center. The flow is unstable, resulting in pressure shocks and vibrations in the pipe.

2.3.3 Churn Flow: Gas bubbles gather and form a gas path in the center of the pipe. The flow is foam like and very unstable, resulting in high pressure variations. The gas velocity is high, pushing the liquid upwards.

2.3.4 Annular Flow: The liquid forms a uniform layer on the pipe walls. The layer can be unstable, with a wavy surface, but is much more stable than in the churn flow. Annular flow develops from churn flow when the gas flow rate is increased, such that there is a coalescence of bubbles into larger ones that fill the entire diameter of the pipe with liquid film along the walls of the pipe. Under certain conditions, gas bubbles can be entrained within the film. At high liquid flow rates, the liquid droplets become concentrations and coalesce into wisps. This is identified as a wispy annular flow in some flow pattern maps.

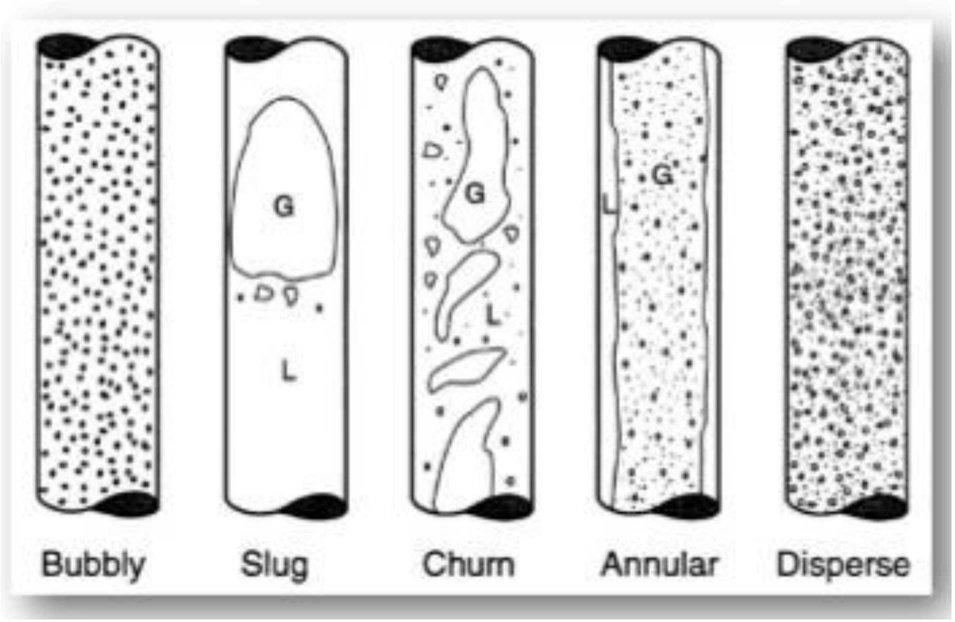

Figure2. 2Flow patterns in Vertical gas-liquid pipe (Weisman & Pei, 1983)

2.4 Parameters to characterize flow regimes

In two-phase flow, void fraction and bubble velocity are two of the fundamental parameters. The void fraction describes the gas distribution and is an important parameter for hydrodynamic and thermal design in various two-phase systems, while the bubble velocity determines the transport of the void fraction and interfacial area concentration.

2.4.1 Void Fraction

Void fraction is the fraction of pipe volume occupied by the gas phase. This parameter is one of the important parameters used to characterize a flow pattern in two phase flows. It is used for determining other parameters like two-phase flow viscosity, density, the relative average velocity of two-phases and for predicting flow pattern transitions, heat transfer, interfacial area calculation and determination of pressure drop. It can be measured using wire mesh sensors, quick-close valves, γ rays, x-rays, and microwave, among many others(Oteng Bismak, 2014). In considering void fraction, the time average value (taken over a long period) is used, but it should be noted that the void fraction fluctuates with time, and instantaneous values are also of interest (Hewitt, Shires, & Bott, 1994)

2.5 Flow Pattern Map

Generally, the flow recognition is performed by visual observation or by using flow pattern maps. To easily identify the aforementioned flow regimes, several maps and correlations have been developed by different researchers. The easiest and simplest being the maps. To predict a particular flow pattern, the boundaries in which the flow pattern dominates is drawn and located knowing the mass, flux, liquid and gas superficial velocities. Flow pattern maps can be graphically categorized for both vertical and horizontal multiphase flows. Once all pattern boundaries observed are mapped, a clear overview of the behavior can be observed as a function of flow conditions. There are two main types, which are theoretical and experimental flow pattern maps.

2.5.1 Flow pattern map for Horizontal flow

A flow pattern map is a representation of the existence of flow patterns in a two dimensional domain in terms of system variables. They consist of flow regimes separated by transition lines. The flow pattern that can be observed is dependent on-the fluid properties, flow rates, pipe diameter, pipe inclination angle, and operating conditions at ends of the pipe. The accurate prediction of the flow pattern existing under a given conditions is required, since every flow pattern has a unique hydrodynamic characteristics

Baker (1954) published the earliest flow pattern map for horizontal flow for air-water system. The map uses the superficial mass flux terms for the gas and liquid phases. For systems other than air-water, Baker used the following gas-liquid property correction factors:

$$\psi = \frac{\sigma W}{\sigma L}\left(\frac{\mu L}{\mu W}\left(\frac{\rho W}{\rho L}\right)^2\right)^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

$$\lambda = \left(\frac{\rho G}{\rho A} \cdot \frac{\rho L}{\rho W}\right)^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

Subscripts G and L refer to the gas and liquid phases respectively, while subscripts W and A refer to physical properties of water and air respectively at 68^{o}F and 14.7 psia (20^{o}C and 1 atm).

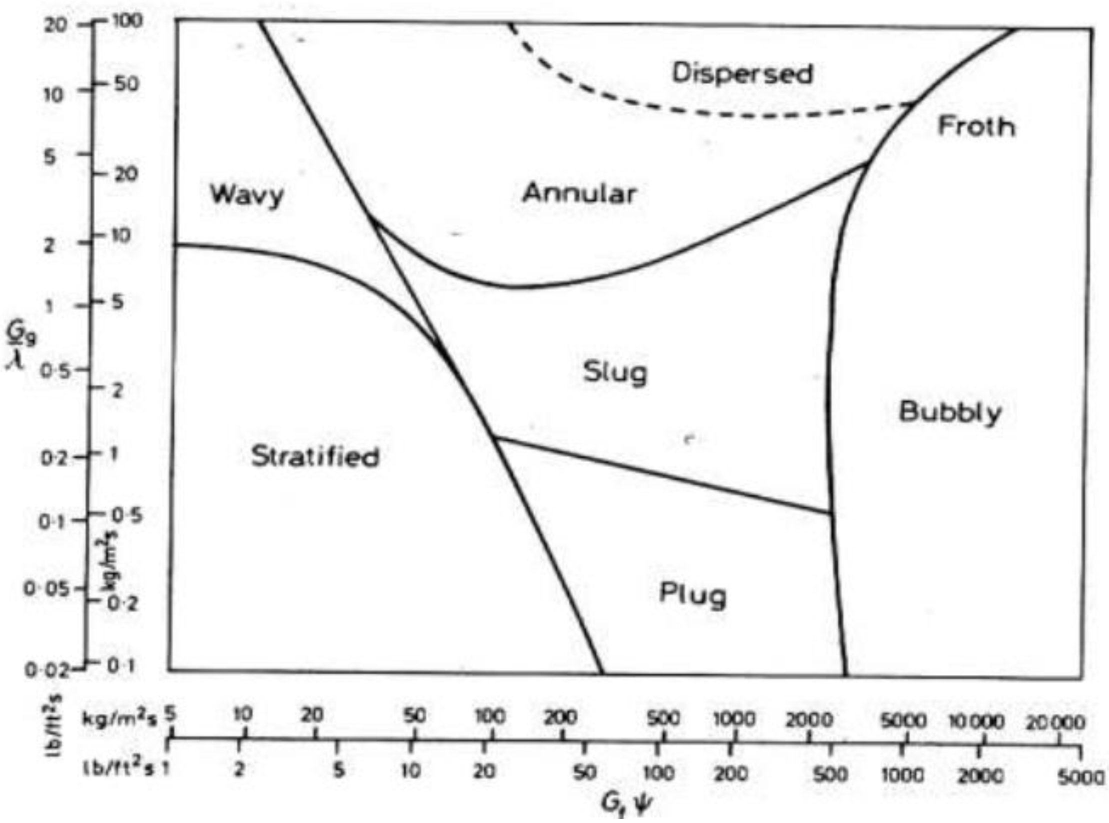

Figure2. 3 Baker's horizontal flow pattern map (Baker, 1954)

Other common pattern maps for horizontal two-phase flows include that developed by Mandhane et al. (1974) through experimental work and that developed by Taitel and Dukler (1976) through theoretical modeling.

(Mandhane, Gregory, & K., 1974) developed a flow regime map similar to Baker's using a larger database of observations. (Mandhane et al., 1974) compared the commonly used flow pattern maps using extensive data base that covered wide range of physical properties and flow parameters. The effect of pipe diameter was taken into account by using superficial velocities of liquid and gas as the coordinate axes.

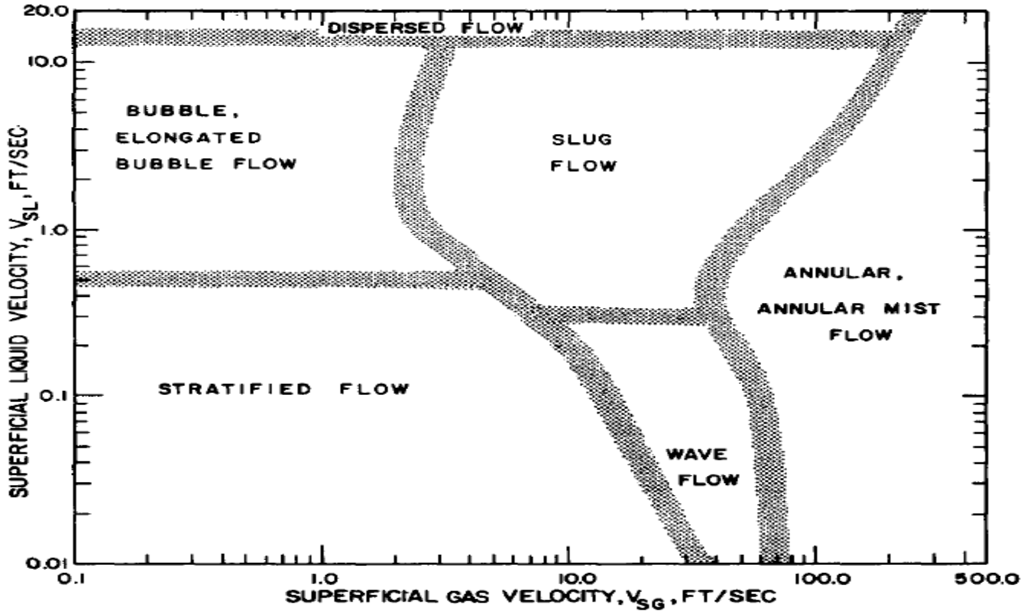

Figure2. 4 Mandhane et.al horizontal flow pattern map

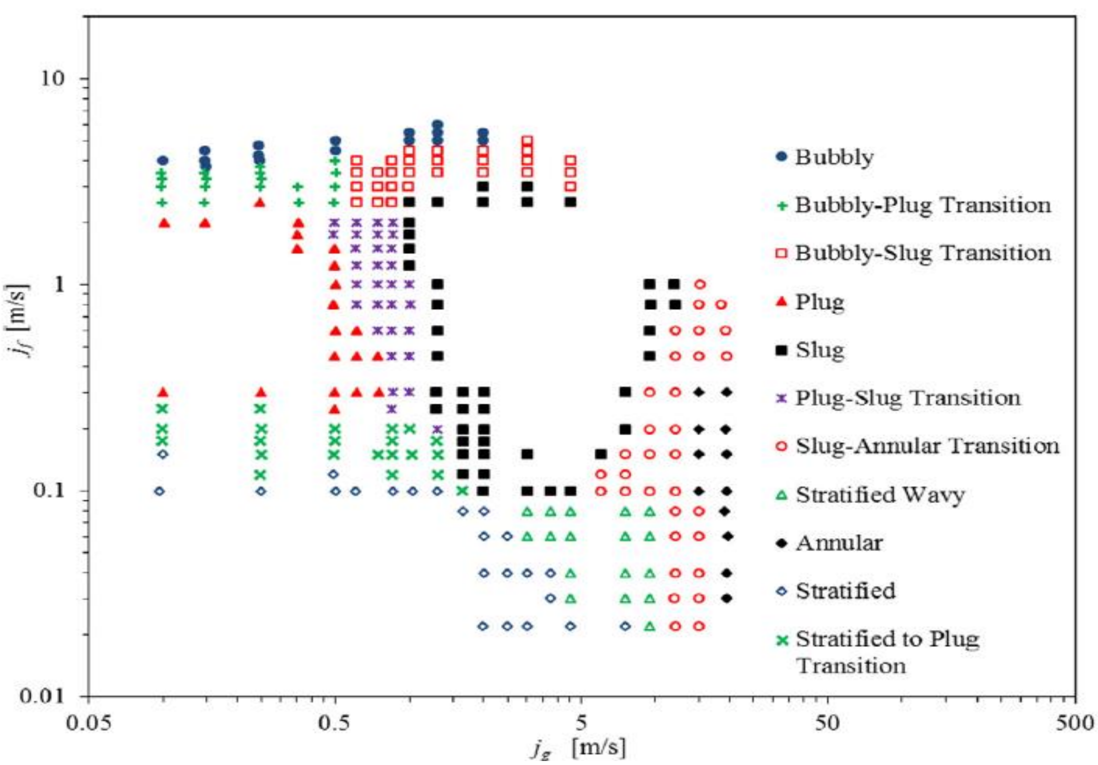

Figure2. 5 Flow regime identification results on horizontal air-water two-phase flow by Kong et.al 2017

2.6 Flow pattern identification using PDF

(Jones Jr, O. C. Zuber, 1975) used the photon attenuation technique, to measure the time-varying, cross-sectional averaged void fraction. This system utilized a dual x-ray beam device for a two-phase mixture of air and water, flowing vertically. (Costigan & Whalley, 1997) developed the PDF methodology of (Jones Jr, O. C. Zuber, 1975) further using segmented impedance electrodes and successfully classified flow patterns into six: Discrete bubble, spherical cap bubble, stable slug, unstable slug, churn and annular flow as shown in the figures below

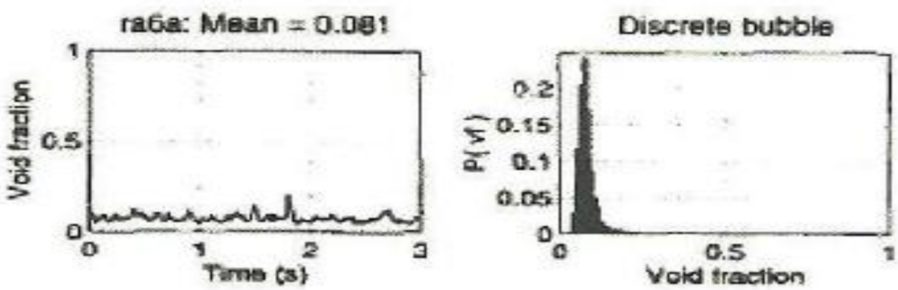

Figure2. 6single peak at low void fraction that represents bubble flow

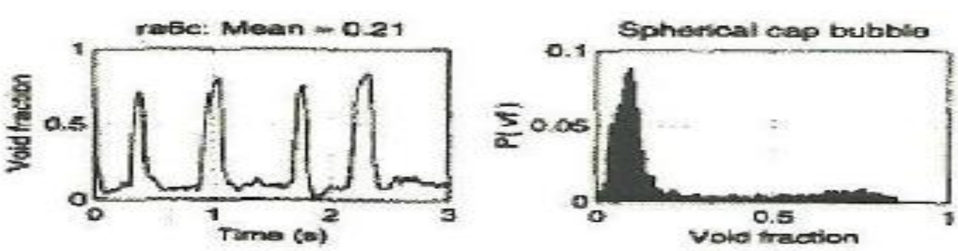

Figure2. 7single peak at low void fraction accompanied by a broadening tail that depicts spherical cap bubble

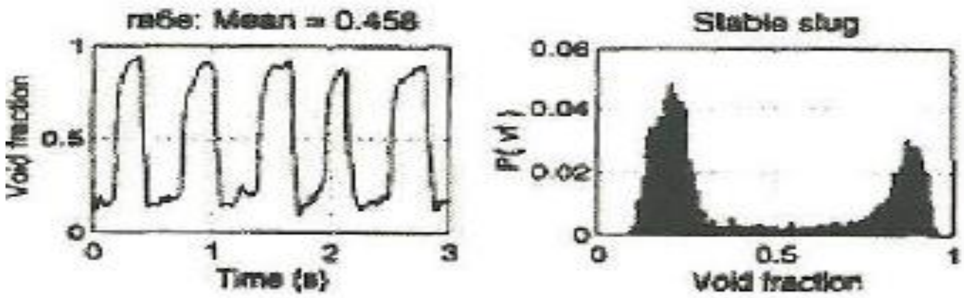

Figure2. 8double peak feature with the higher peak (at low void fraction) and the lower peak (at higher void) fraction signifies stable slug flow

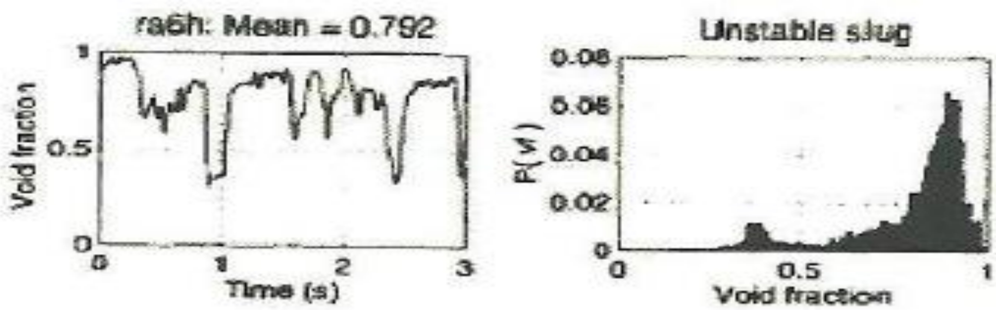

Figure2. 9 double peak with the lower peak (at low void fraction) and the higher peak (at higher void fraction) signifies unstable slug flow

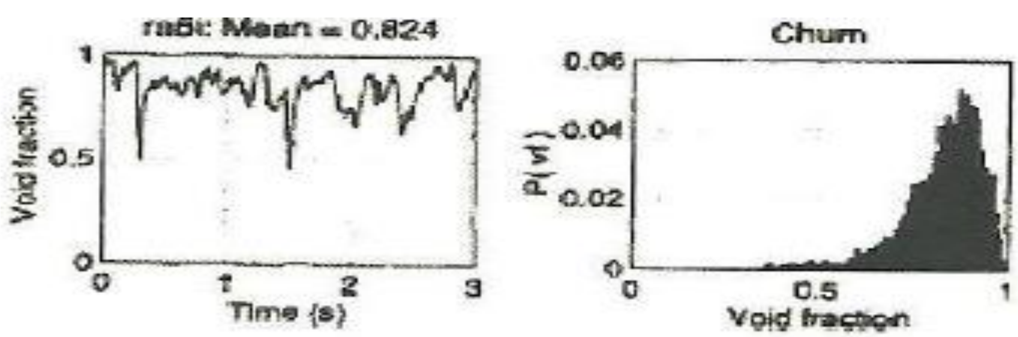

Figure2. 10single peak at a high void fraction with a broadening tail (churn flow)

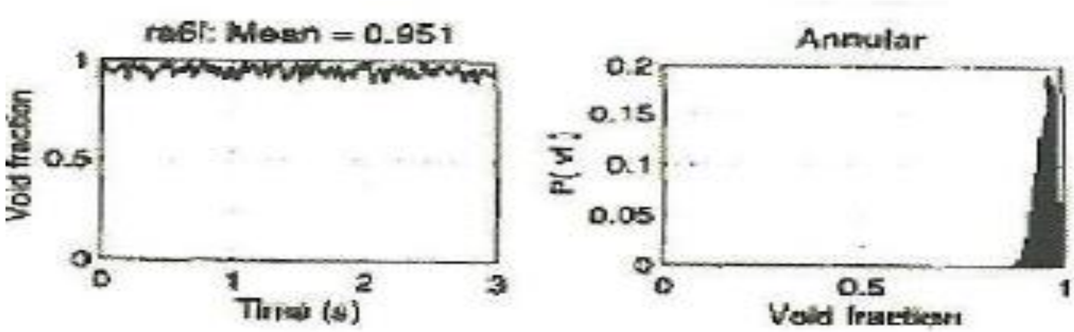

Figure2. 11single peak at high void fraction defined as annular flow.

2.7 Flow pattern Transition

To predict the flow pattern existing at a particular flow condition, there is a need to have adequate knowledge about the various flow patterns in existence, and their transitions from one pattern to the other. This is because, the interaction between the bubbles resulting in the breakup and coalescence, and interactions between the pipes, makes it difficult to determine and describe the flow pattern existing at a time. Initially, the gas bubbles are smaller and widely distributed in the liquid phase. The bubbles at this stage are rounded and tend to move upward along the pipe. As the gas velocity increases, the bubble size also tends to increase; they then coalesce and form larger bubbles. As they move upwards in the channel, they become unstable due to the interaction between the pipe walls; resultantly they break up forming numerous large bubbles which move up and down the channel. The bubbles at a point in time become very large, filling the entire channel with films of liquid formed in between the pipe and the bubble. Several works have been done on flow pattern transition. Some of which include;

2.7.1 Experimental study of horizontal air-water plug-to-slug transition flow in different pipe sizes

Authors: Kong R., Rau A., Kim S., Bajorek S., Tien K., and Hoxie C., (2018)

Ran Kong et al., 2018 investigated the plug-to-slug transition in horizontal air–water two-phase flow in small (38.1 mm) and large (101.6 mm) diameter pipes. An extensive database was established to study the local interfacial structure in plug-to-slug transition flow. Detailed measurements across the flow area were performed for nine and six test conditions in small and large pipes, respectively, at three different axial locations downstream of the inlet using the local four-sensor conductivity probe. The extensive database describes the local distributions of void faction, interfacial area concentration, Sauter-mean diameter and bubble velocity across the entire cross-sectional flow area.

The effects of superficial gas velocity, superficial liquid velocity, pipe size and development length on evolution of the interfacial structure were obtained. Also, the one-dimensional transports of the two-phase flow parameters were investigated.

The plug-to-slug flow was studied with increasing superficial gas velocity j_g at superficial liquid velocity (j_f = 2.0 m/s) in the small pipe (38.1 mm) and at j_f = 3.0 m/s in the large pipe (101.6 mm).

It was found that;

1 The number of small bubbles in the liquid plug/slug increases significantly in plug-to-slug transition with increasing j_g which was generated by the strong shear between the gas slug and liquid film.

2. The size of small bubbles decreases with increasing j_g or increasing j_f. The distribution of small bubbles is more uniform due to the additional bubble-induced turbulence as j_g increases.
3. The bubble velocity of both small and large bubbles were found to be asymmetric in horizontal plug/slug flow, with highest value at the top half of the pipe, which is similar to the liquid velocity profile as measured in previous studies.
4. Increasing j_g, development length, or decreasing j_f slightly increases the depths of the plug/slug bubbles; however, significant growth of plug/slug bubbles is observed in the axial direction.
5. The contribution from large bubbles to total void fraction increases as pipe size increases, while the distribution of total void fraction is similar. The sizes of both small and large bubbles increase as pipe size increases. Increasing pipe size has negligible effects on the bubble velocity and bubble velocity fluctuation intensity.

2.7.2 Experimental investigation of horizontal air–water bubbly-to-plug and bubbly-to-slug transition flows in a 3.81 cm ID pipe

Authors: Kong R., Kim S., Bajorek S., Tien K., and Hoxie C., (2017)

Ran Kong et al., 2017 investigated the horizontal air–water bubbly-to-plug and bubbly-to-slug transition flows in a 3.81 cm ID pipe. Experimental database established using the local four-sensor conductivity probe in a 3.81 cm inner diameter pipe to study the two-phase flow structures and transition mechanisms in these transition flows.

Comprehensive local time-averaged two-phase flow parameters which include void fraction, interfacial area concentration, bubble Sauter mean diameter, and bubble velocity.

The bubbly-to-plug transition was investigated by decreasing j_f at a fixed j_g = 0.33 m/s. The following were observed as j_f decreases:

1. Gas phase is more concentrated near the upper wall due to the decreasing role of turbulent mixing.
2. The local peak value of interfacial area concentration (a_i) first increases due to both the increasing void fraction (α) and the nearly constant bubble size in high j_f region (j_f > 4.00 m/s). The local peak value of a_i then decreases as j_f decreases further due to bubble coalescence.
3. The radial profile of D_{sm} becomes more skewed with decreasing j_f, and there is a significant increase in bubble size at the occurrence of the transition.
4. Bubbles move slower, and the relative difference between the maxima and the minima in normalized bubble velocity profile becomes more pronounced at the beginning of transition.

The bubbly-to-slug transition was investigated by increasing the gas flow rate at a fixed liquid flow rate j_f = 4.00 m/s. The following observations were made as j_g increases:

1. Gas phase is more uniformly distributed due to the increasing bubble- induced turbulence.

2. Local peak values of α and a_i first increase and then decrease, but area-averaged values of these parameters continuously increase.
3. Flow visualization study suggests that bubbles in high j_g conditions (j_g > 1.00 m/s) are generated through shearing off from large bubbles.
4. Bubbles move faster throughout the pipe cross-section in high j_g conditions (j_g > 0.51 m/s). The relative difference between the maxima and the minima in normalized bubble velocity profile becomes more pronounced at the beginning of transition, as observed in bubbly-to-plug transition.

2.7.3 Transition of plug to slug flow and associated fluid dynamics

Authors: Thaker J., and Banerjee J., (2017)

Plug to slug transition and associated dynamics of bubble detachment from the elongated bubble was analyzed using flow visualization and local velocity measurements. Experiments were reported for 13 different inlet flow conditions of air and water phases. Images of plug/slug flow structures were captured at a rate of 4000 FPS using FASTCAM Photron camera and the local values of axial liquid velocity were measured using LDV system synchronized with a 3D automated traverse system. It was noted that flow visualization can identify transition condition (in terms of inlet flow conditions) only, but local velocity measurements are required for estimating the dynamics associated with the transition. The following were observed;

1. Combining the local measurements (using LDV) and flow visualization (captured images), it was concluded that the sudden jump in velocity from the liquid film to the liquid slug is responsible for bubble detachment from elongated bubble tail.

2. Liquid plug/slug velocity profiles exhibit nearly fully- developed single phase liquid flow character with the maximum velocity occurring near the centre line.
3. The velocity profile in the liquid slug and liquid film regions are influenced almost equally by the increase in Re_{SL} which implies that liquid flow rate (Re_{SL}) is not responsible for sudden increment in difference of velocity between liquid film and liquid slug regions.
4. Increase in Re_{SG} leads to the drastic difference in magnitude of local velocity between the liquid slug and liquid film regions. This signifies that Re_{SG} has pronounced influence on increment in liquid slug velocity, but a little influence on liquid film velocity.

In conclusion, investigations reported in this article using local measurements emphasize that Re_{SG} plays a dominant role for on- set of bubble entrainment process inside the liquid slug leading to transition from plug to slug flow pattern.

2.7.4 Characterization of horizontal air–water two-phase flow

Authors: Kong R., and Kim S., (2017)

Experimental studies were performed to characterize horizontal air–water two-phase flow in a round pipe with an inner diameter of 3.81 cm. A detailed flow visualization study was performed using a high-speed video camera in a wide range of two-phase flow conditions to verify previous flow regime maps.

Verification of flow regime transition boundaries

In order to assess the current horizontal flow regime maps and to improve the accuracy of flow regime prediction in horizontal pipes, a flow visualization study was performed in horizontal air–water two-phase flow. In the process of determining flow regimes, captured two-phase flow videos were classified into horizontal two-phase flow regimes defined as bubbly, plug, and slug, stratified and annular flow.

The newly developed regime transition boundaries in this study generally agree well with Mandhane et al.'s (1974) map. There is a disagreement at the transition from bubbly-to-plug and bubbly to- slug flows. Unlike Mandhane et al.'s (1974) map, the present results suggest that the transition from bubbly flow to plug/slug flow depends on jg. In Mandhane et al.'s (1974) map, transitions occur at a constant j_f = 4.20 m/s regardless of j_g. However, the present results suggest that the transition is dependent on j_g.

The effects of gas and liquid flow rates on various local two-phase flow parameters such as void fraction, interfacial area concentration, bubble velocity, and bubble Sauter mean diameter were investigated in this section.

The frictional pressure loss in horizontal bubbly flow was predicted using Lockhart–Martinelli method. For all the twelve conditions studied, the coefficient C = 24 was found to give the best agreement with the data with the minimum average percent difference of ±1.10%.

2.7.5 Horizontal two-phase flow pattern recognition

Authors: Monni G., De Salve M., and Panella B., (2014)

Air–water two-phase flow in a test section consisting of a horizontal Plexiglas pipe of internal diameter 19.5 mm and total length of about 6 m was characterized. Wire Mesh Sensor (WMS) was adopted to characterize the air–water two-phase flow and local, chordal, cross-section void fraction values were derived from the sensor data. The superficial velocity ranged from 0.145 to 31.94 m/s for air and from 0.019 to 2.62 m/s for water. The flow patterns observed are stratified–Bubble–slug/plug–annular. The identification of flow pattern and flow characterization was done in terms of void fraction profiles and characteristic times. From the analysis of the time evolution of the local void fraction and of the parameter M(t), the flow was characterized in terms of the void fraction profile shape and other parameters like phases distribution, liquid level, mean void fraction in the different pipe regions, characteristic frequencies

2.7.6 Intermittent flow parameters from void fraction analysis

Authors: Fossa M., Guglielmini G., and Marchitto A., (2003)

Experimental investigation was done on air-water horizontal intermittent flows in 40 and 60 mm inner diameter pipes. The operating conditions cover the 0.3–4.0 and 0.6-3.0 m/s gas and liquid superficial velocity ranges, respectively. A new procedure was proposed to characterize the flow through the statistical analysis of the instantaneous cross-sectional averaged void fraction obtained by means of ring impedance probes. The main intermittent flow parameters, such as slug frequency and length, time average void fraction, minimum and average liquid film height were evaluated based on the statistical analysis. The procedure was further validated through flow visualizations obtained from a fast digital video camera. The reliability of the proposed method was confirmed using direct measurements and extensive comparisons with available data. Two empirical correlations were proposed for slug frequency and minimum and average liquid film levels in stratified regions which quite well agree with authors' data and literature values.

CHAPTER THREE

METHODOLOGY

3.1 Data Acquisition

The data was obtained from experiments carried out by (Mukhtar Abdulkadir, 2011) using an inclinable rig (-5^{o} to 90^{o}) in the Chemical Engineering Laboratory of the University of Nottingham to study air-silicone oil flows in vertical and horizontal orientations. The experimental facility was made up of a testing section made from transparent acrylic glass pipes of 67 mm diameter pipes and 6m long. The behavior of the air-silicone oil mixture was examined using advanced instrumentation: Electrical capacitance tomography (ECT) and Wire Mesh Sensor (WMS). ECT provides images of phase distribution by exploiting differences in electrical permittivity between the phases of a multiphase flow mixture within a process vessel or pipeline.

3.2 Data Processing

The time series raw data was processed to obtain the void fraction for different experimental runs. The void fraction data for planes 1 and 2 of each experimental run were used in a MACRO cross correlation template to obtain the bubble velocity after inserting the total number of data (12000), sampling frequency (200Hz) and distance between the sensors (0.089m). Power spectral density (PSD) was ran in macro after inserting the total number of data (12000) and sampling frequency (200Hz) to obtain the dominant frequency in each run. The gas velocity V_G was obtained using the equation;

$$V_G = U_{SG} / \alpha \qquad 3.1$$

Where U_{SG} is the superficial gas velocity and α is the void fraction. The length of the bubble was obtained from the relationship;

$$L = U_{ST} / F. \qquad . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad . \qquad .3.2$$

Where U_{ST} is the translational velocity and F is the frequency obtained from PSD.

3.3 Flow regime identification using flow pattern map, time series analysis and PDF

The use of flow pattern map is an easy way of determining flow regime. The Horizontal flow pattern map of (Mandhane et al., 1974) was used to determine the various flow regimes for the dataset. This was achieved by superimposing the U_{SL} against U_{SG} plot of the dataset on the (Mandhane et al., 1974) flow pattern map.

The Shoham‟s (2006) flow pattern map was also used to determine the various flow regimes for the dataset. This was achieved by superimposing Shoham‟s mechanistic model in U_{SL} against U_{SG} plot of the dataset, and setting the fluid properties, the pipe geometry and the interfacial boundary of the phases, after which the model was run to determine the flow regimes of the experimental dataset.

Another method to identify the flow regime in this work was the use of time series analysis and PDF. The time series analysis was done by plotting the void fraction data against time.

The PDF was done by creating bins of width 0.01 in 100 cells and getting frequency to identify the dominant void fractions then dividing by the total number of data points.

3.4 Analysis of the acquired data:

Analysis of the time series of void fraction helped in the determination of translational velocity, frequency, lengths of bubble, and the actual gas velocity.

The processed data was interpreted and analyzed to investigate the plug-slug transition. This was done by determining the contribution of gas superficial velocities at different liquid superficial velocities on void factions for the horizontal pipe. The graph of void fraction was plotted against superficial velocity.

An analysis of the effect of superficial gas and liquid velocity on bubble velocity, bubble length and slug frequency was obtained from the plot of increasing gas superficial velocity against bubble length, bubble velocity and slug frequency respectively at constant liquid superficial velocity.

The translational velocity was plotted against mixture velocity to obtain a drift flux model where the distribution parameter Co and drift velocity Ud were obtained from the slope and intercept of the graph respectively.

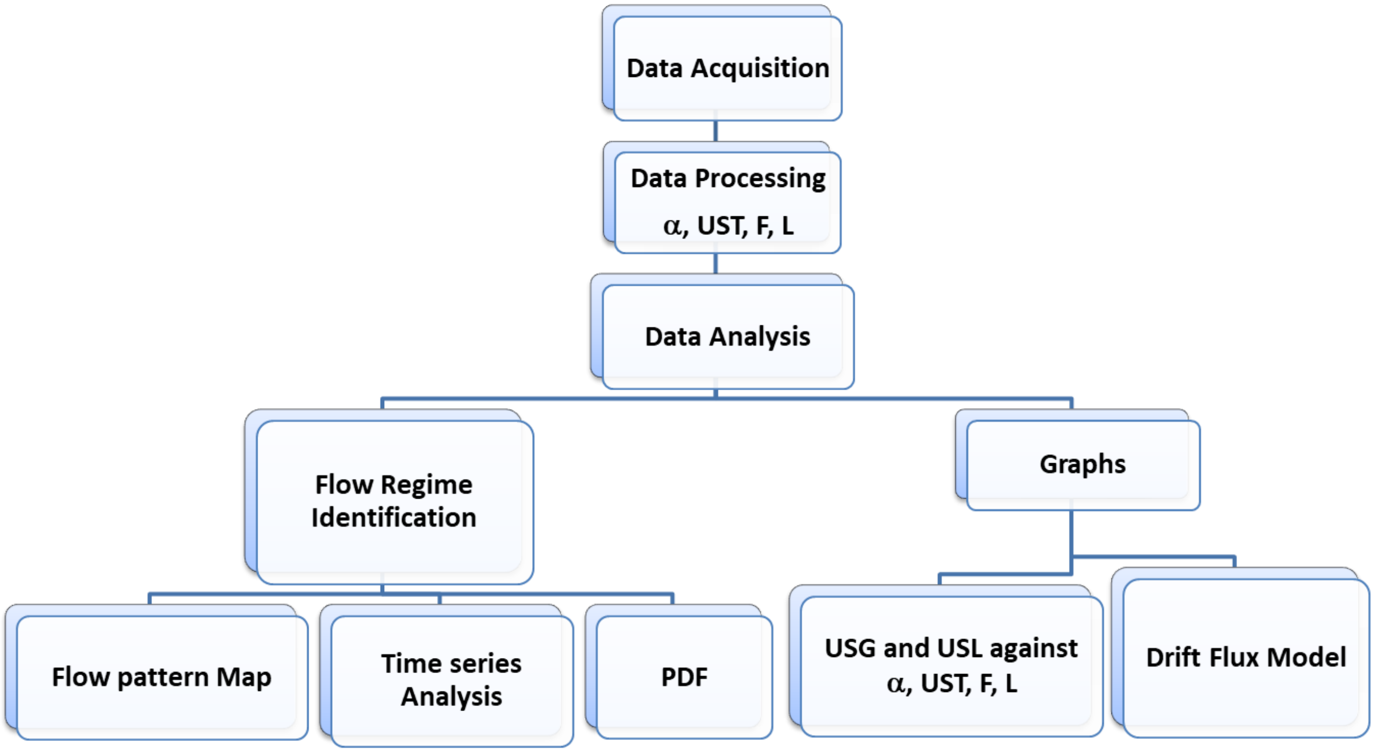

Figure3. 1Flow Diagram for the methodology

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Flow Regime Identification

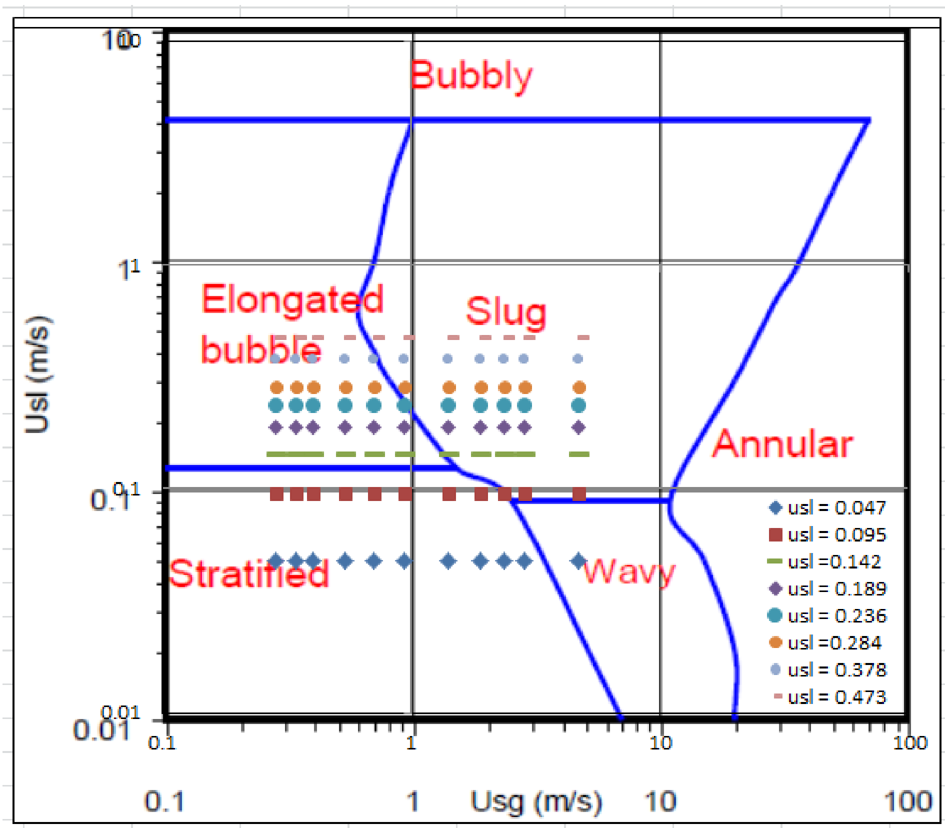

Figure4. 1Flow regime identification for the experimental data on the Horizontal flow pattern map of (Mandhane et al., 1974)

From the figure above, the intermittent flow regime for the experimental data begins at the liquid superficial velocity of 0.142m/s. It also shows the transition from plug to slug flow for the experimental data set.

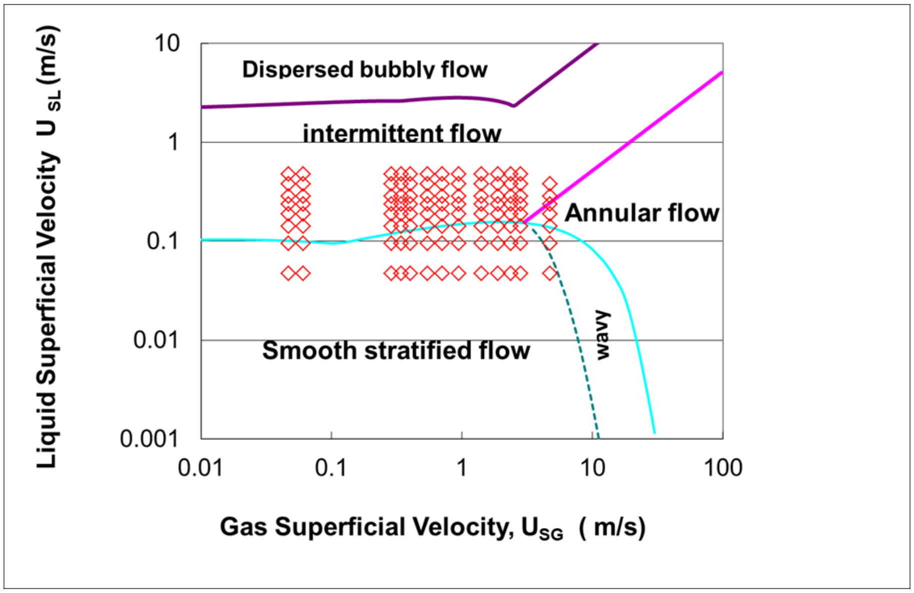

Figure4. 2Shoham's flow pattern map for experimental dataset

Figure 4.2 above shows the flow regimes of the experimental data using Shoham's flow pattern map. It can also be seen as observed in the Mandhane et.al map of figure 4.1 that the plug and slug flow exist at liquid superficial velocity of about 0.142m/s. The figure shows that stratified flow occurs at liquid superficial velocities of 0.047 and 0.095m/s. Annular flow also occurs at gas superficial velocity of 4.73m/s.

The Shoham's map is closer to the results obtained for PDF as compared to the Mandhane et.al map. This is because the Shoham's model considered the fluid properties and the pipe geometry.

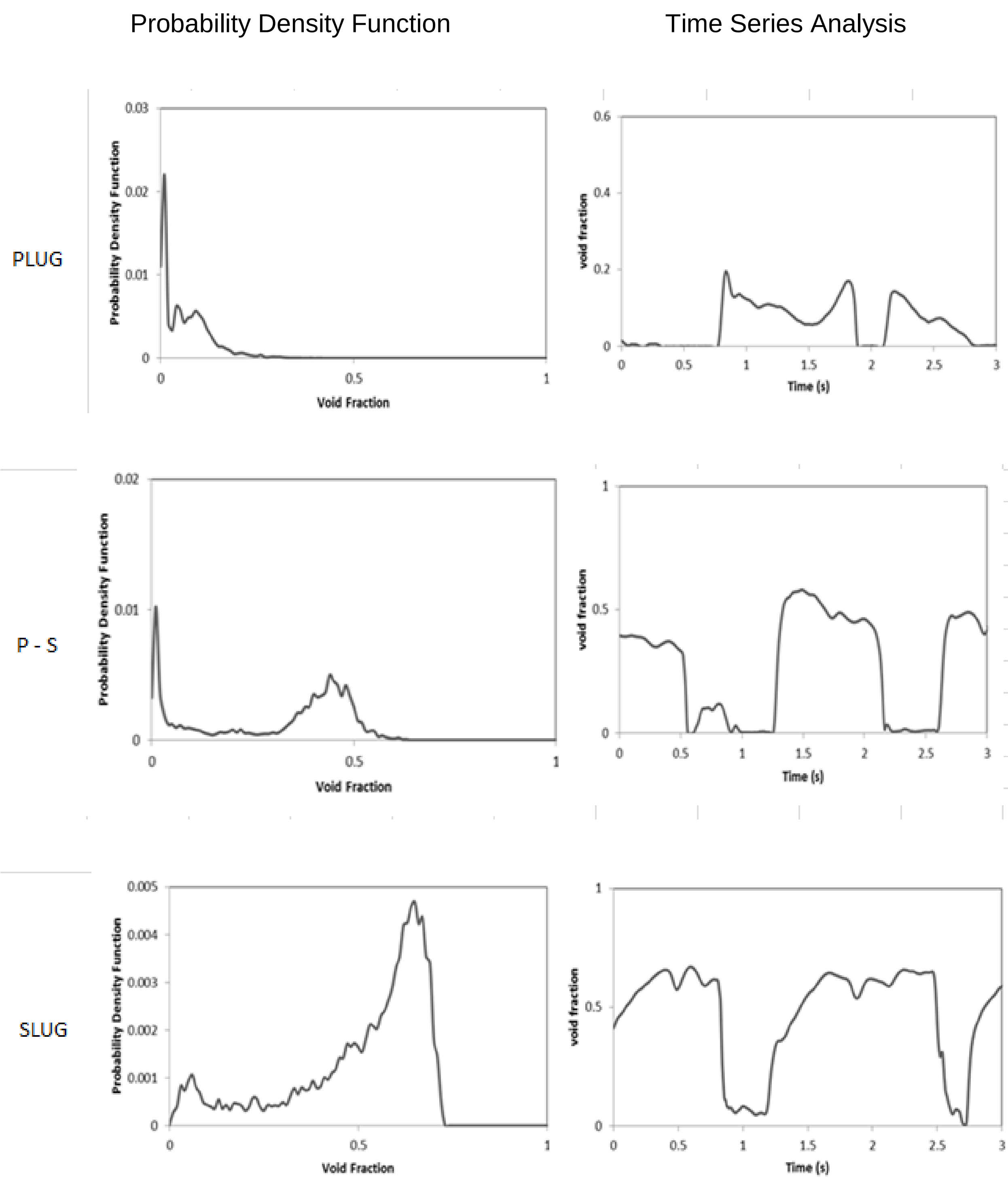

Figure4. 3 Typical PDF and time series plots for (a) plug flow (b) Plug – slug transition (c) slug flow

The figures above show the PDF plots of plug-slug transition of the experimental data for a fixed liquid superficial velocity of 0.378m/s and gas superficial velocities of 0.05, 0.40 and 0.95m/s

Figure 4.2(a) represents the PDF of plug flow at a liquid and gas superficial velocity of 0.378 and 0.45m/s respectively. It has a single at a very low void fraction of about 0.1

Figure 4.2(b) shows the transitional PDF from plug to slug flow at liquid and gas superficial velocities of 0.378 and 0.4 m/s respectively. It shows the characteristics of both regimes with two peaks at void fractions of about 0.1 and 0.45.

All these agree with those obtained by Pawloski et.al 2016 for air-oil two phase flow in horizontal pipe.

Figure 4.2 (c) gives the PDF of slug flow (liquid and gas superfial velocity of 0.378 and 0.95m/s respectively) where two peaks were observed; a larger one at a void fraction of about 0.6, and a smaller one at a very low void fraction.

According to (Costigan & Whalley, 1997), a double peak with one at low void fraction and the other at a higher void fraction represents slug flow.

Many literatures report that the low void fraction peak represents the tube when filled with oil, which occurs when a slug passes the sensor and the higher void fraction represents the flow regime when the tube contains both air and oil in a stratified type of flow. By similar interpretation, the plug flow PDF has a peak at low void fraction as a result of the tube being filled with oil most of the time.

4.2 Effect of Gas and Liquid superficial velocity on Void fraction

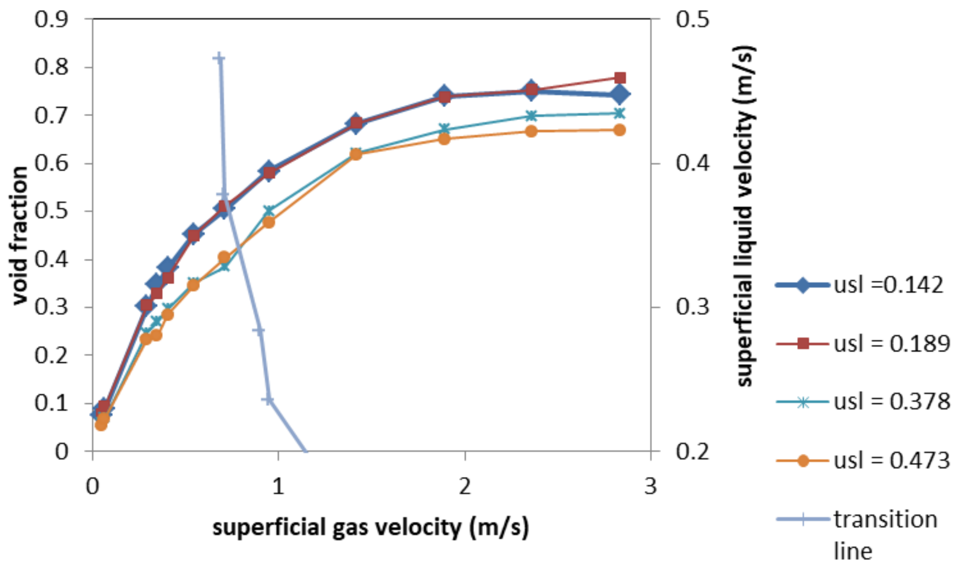

Figure4. 4 Effect of increasing gas and liquid superficial velocity on void fraction

From figures 4.4, the plug-slug transition is investigated for a range of liquid superficial velocity (0.142 – 0.473m/s) and gas superficial velocity of (0.047 – 2.363 m/s).

The transition occurs by increasing gas superficial velocity at constant liquid superficial velocity. The transition from plug to slug was observed at the superficial gas velocity ranging from 0.7 – 1.2m/s. At constant U_{sl}, the void fraction increases with increasing U_{SG} .The void fraction was also found to be decreasing with increasing $U_{SL.}$

As observed in the plots above, the void fraction increases with increasing gas superficial velocity and decreases with increasing liquid superficial liquid velocity. This follows the same trend as observed by (Kong et al., 2018)and (Hernandez-Alvarado et al., 2017). According to (Hernandez-Alvarado et al., 2017), the increase in liquid flow rate will decrease the gas phase residence time leading to a reduction in void fraction.

(Kong et al., 2018) conducted experimental study on plug-slug transition with air-water as model fluid. From their experimental results as well as the flow visualization images, it was reported that the thickness of the gas layer increases as the gas superficial velocity increases which correspondingly decreases the thickness of the liquid film.

4.3 Effect of Mixture Velocity on Bubble Velocity

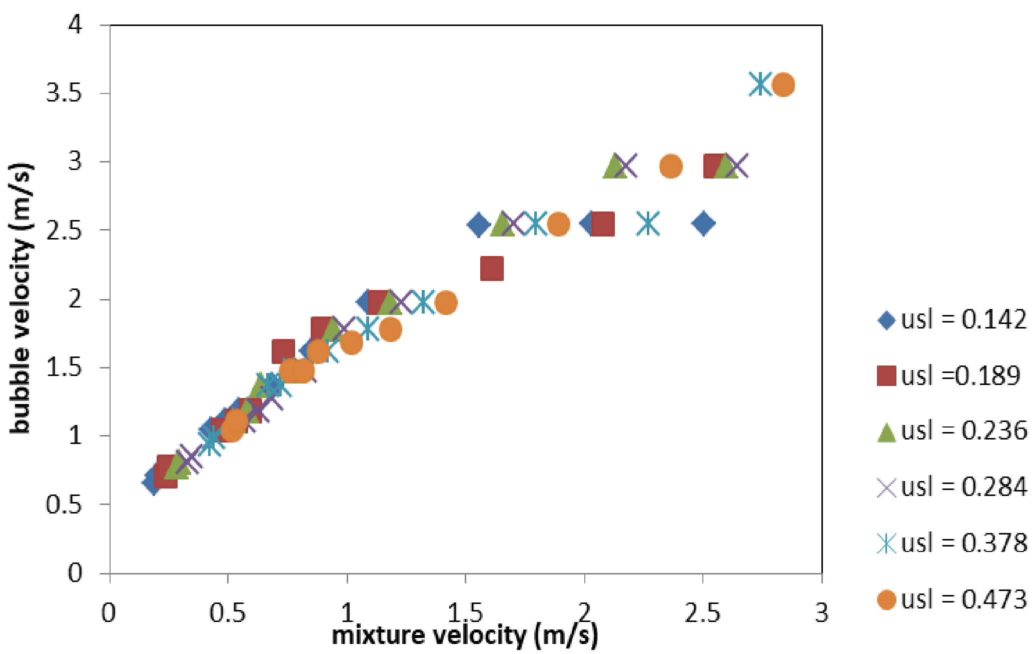

Figure4. 5Effect of Mixture velocity on Bubble velocity

The experimental data acquired shows that the average velocity of bubbles increases with increasing mixture velocity. This is consistent with the report of (Carpintero, 2009) in experimental investigation of developing Plug and Slug flows. It is also consistent with the findings of (Nydal, Pintus, & Andreussi, 1992) that developing slugs travel at the same velocity as regular slugs and these velocities increase with increasing mixture velocity.

(Ernandez-Perez & Azzopardi, 2006) also reported that the bubble velocity has dependence on mixture velocity and is proportional to the mixture velocity for slug flow in horizontal pipes.

4.4 Drift Flux Analysis

Using the drift-flux approach, the slug translational velocity was expressed as a function of mixture superficial velocity (U_M) and drifts velocity (Ud) by Bendiksen (1984) in the form

$U_T = C_o U_M + U_d$ Where C_o for horizontal flow ranges from 1 to 1.2 for ($\theta \geq 0$) and $Fr \leq 3.5$

(Benjamin, 1968) obtained U_d for horizontal flow as $U_d = 0.54 \sqrt{gD}$ According to (Benjamin, 1968), drift velocity is due to gravity current effects, and it's dependent on pipe internal diameter.

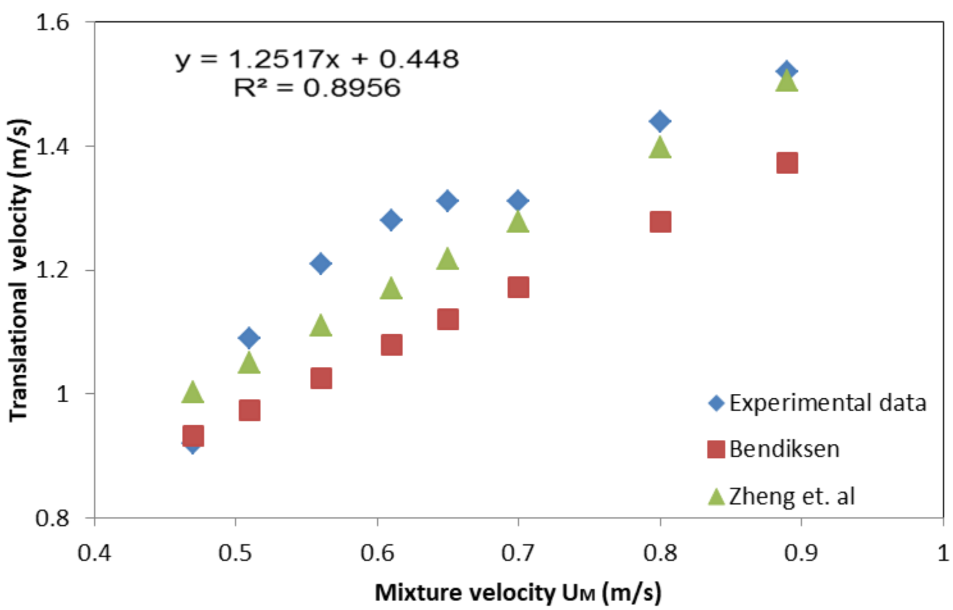

Figure4. 6 Drift flux model for experimental data and correlations

Figure 4.5 above shows the plot of translational velocity against mixture velocity that compares the experimental data with that of correlations of (Bendiksen, 1984) and (Zheng, Brill, & Shoham, 1994). They all follow the linear trend as expected. The experimental data is closer to the correlation of (Zheng et al., 1994) more than it is to that of (Bendiksen, 1984). The values of distribution parameter C_o and drift velocity U_d obtained are in the table below.

Table4. 1Distribution parameter Co and Drift velocity U_d for both experimental data and correlations

	Co	Ud	Ud/√gD
Bendiksen 1984	1.05	0.438	0.540
Zheng et.al 1994	1.20	0.438	0.540
experimental data	1.25	0.448	0.553

From figure 4.6, the slope Co and intercept U_d obtained for this experimental data are 1.25 and 0.55 respectively. The correlating relationship for this experimental data is

$$U_T = 1.25U_M + 0.448 = 1.25U_M + 0.55\sqrt{gD}$$

This is consistent with many other literatures for horizontal flow that the values of Co range from 1.0 to 1.35 and Ud/ √gD from 0 to 0.6

Also, the non-zero intercept from figure 4.5 shows that there is a drift velocity component associated with the bubbles. This result supports the conclusions of (Nicholson, Aziz, & Gregory, 1978) and (Bendiksen, 1984) that a drift velocity exists for the horizontal flow.

Most of the literatures used data mostly for slug flow to obtain Co. The high value of 1.25 for C_o in this work may be as a result of the experimental data that includes that of transition from plug to slug. It may also be a result of difference in pipe diameter (67mm) and model fluid (air-silicone oil) as compared to others of air-water system.

4.5 Effect of Gas and Liquid Superficial velocity on Bubble length

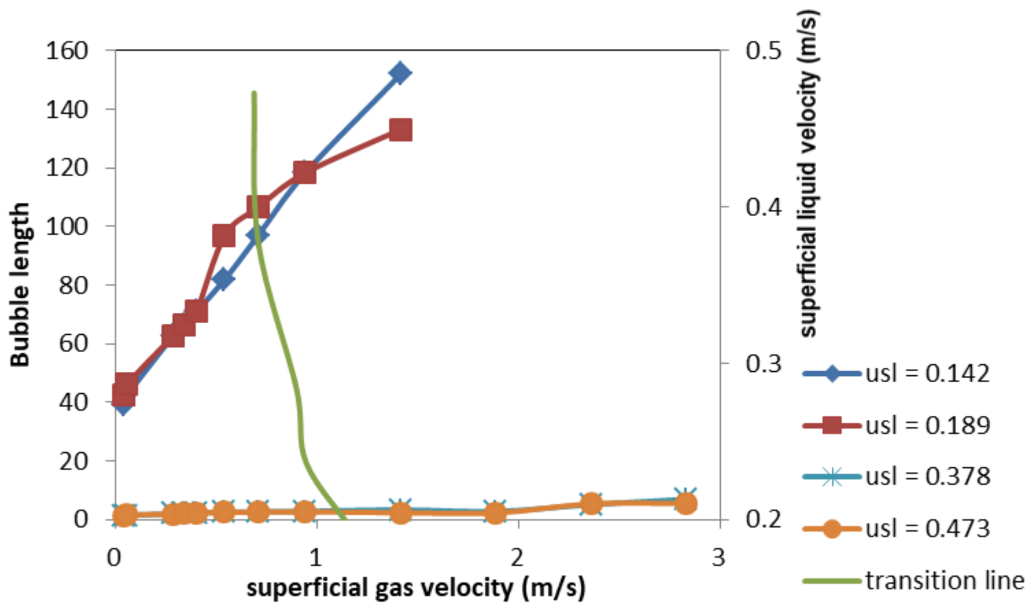

Figure4. 7 Effect of superficial gas and liquid velocity on bubble length

Figure 4.7 shows the influence of the gas superficial velocity on the length of the bubbles obtained from the experimental data. This figure shows that the length of gas slug strongly depends on the gas and liquid superficial velocities. The length of gas slugs increase with the increase of superficial gas and liquid superficial velocity as it transitions from plug to slug flow for Usl of 0.142 – 0.284m/s. A decrease in bubble length was observed at high liquid superficial velocities of 0.378 and 0.473 m/s. Since the bubble lengths were obtained from $translational\ velocity\ / frequency$ and then it is dependent on the slug frequency. The decrease in bubble length results from a very high increase observed in the slug frequency at U_{sl} of 0.378 and 0.473m/s. This decrease agrees with (M. Abdulkadir, Hernandez-Perez, Lowndes, Azzopardi, & Sam-Mbomah, 2016) for slug flow in horizontal pipe. It also agrees with the report of (Dinaryanto et.al, 2016). According to (Kong et al., 2018) using flow visualization, when increasing gas superficial velocity at a constant liquid superficial velocity, length of the plug/slug bubbles increases. The same trend was observed in this work.

4.6 Effect of Gas and Liquid Superficial Velocity on Bubble Velocity

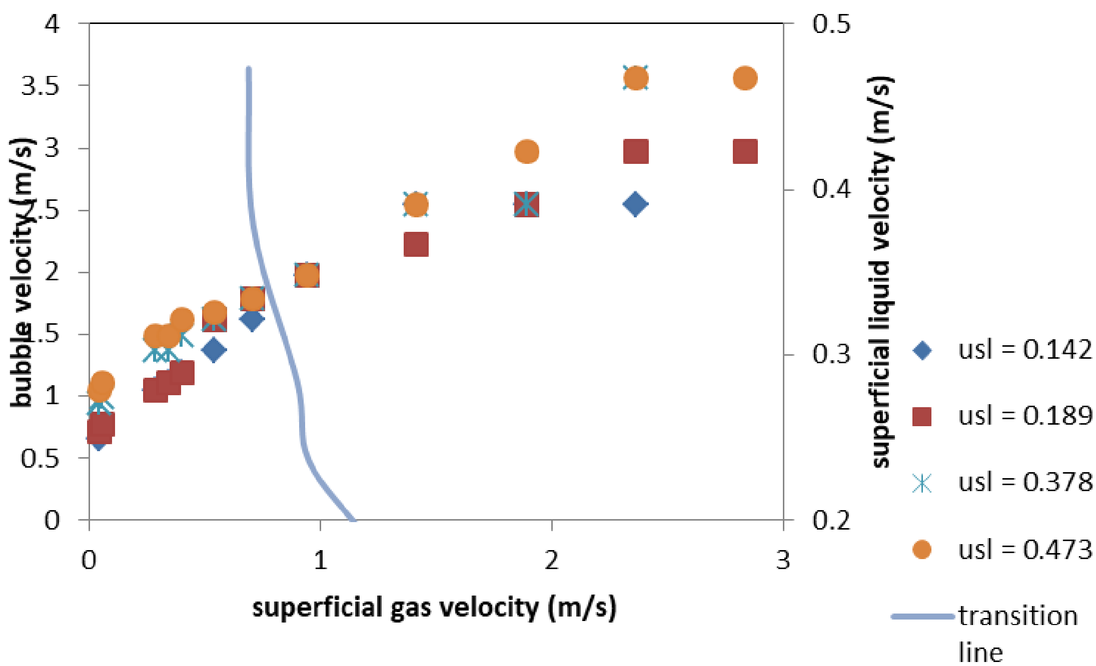

Figure4. 8 Effect of gas and liquid superficial velocity on bubble velocity

From the figure above, it can be observed that the bubble velocity increases with increasing gas superficial velocity. Also, as the liquid superficial velocity increases, the bubble velocity becomes higher. This is in agreement with Kong et.al 2018 for air-water plug to slug transition. It also agrees with Kong et.al 2017 that reports the movement of bubbles being faster at higher liquid superficial velocity in characterizing two-phase horizontal flow.

4.7 Variation of frequency as a function of Gas and Liquid Superficial velocity

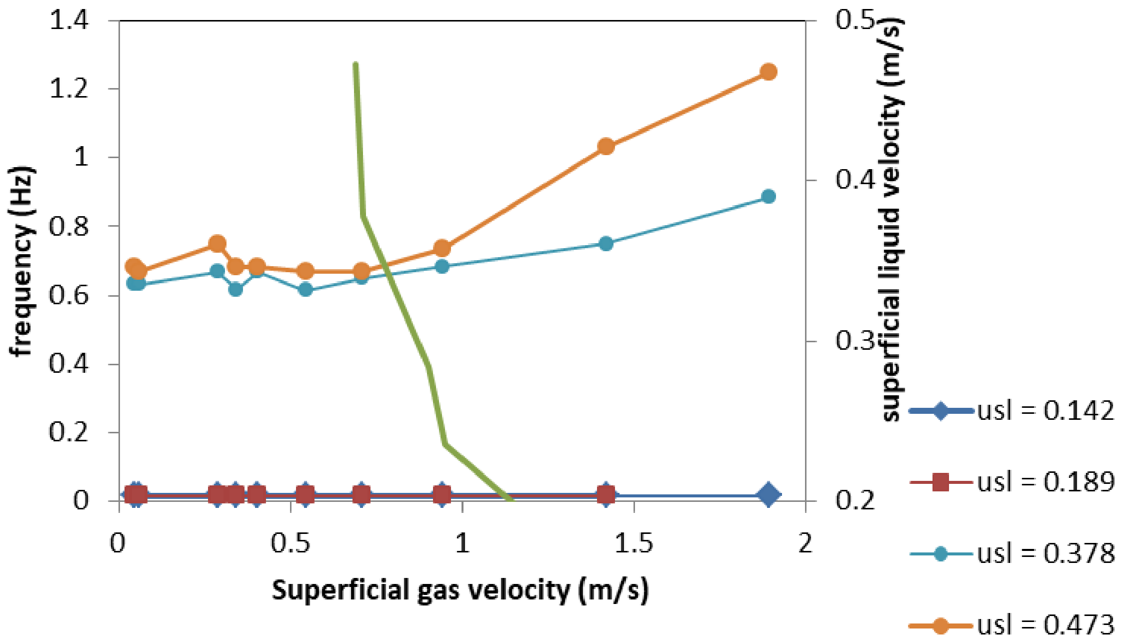

Figure4. 9 Variation of slug frequency with gas and liquid superficial velocity

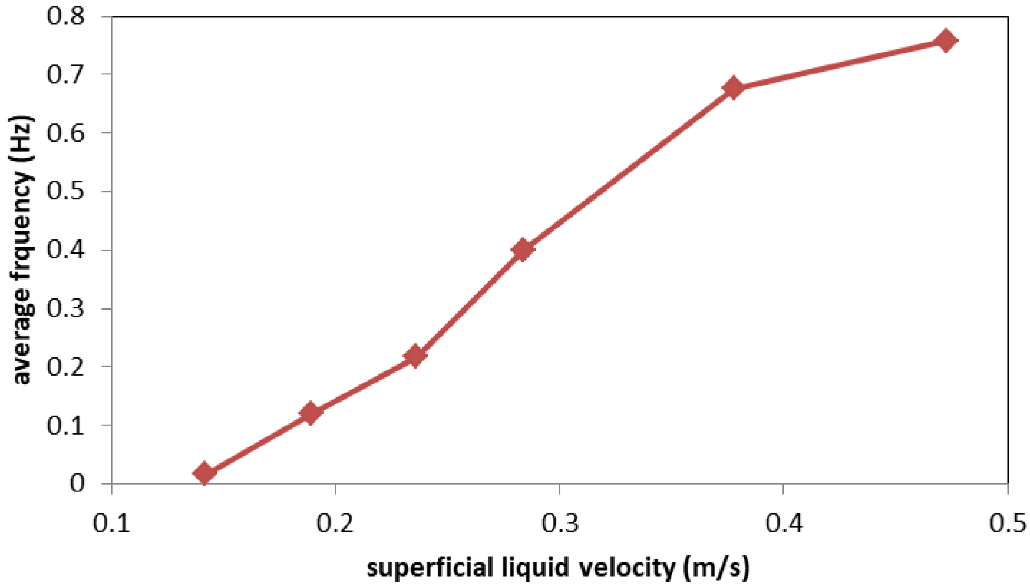

Figure4. 10: Variation of average frequency with increasing liquid superficial velocities.

Figure 4.9 shows a variation of frequency as a function of gas and liquid superficial velocity. The frequency is seen to be slightly dependent on gas superficial velocity. For lower superficial liquid velocity of 0.142 – 0.189 m/s, the frequency remain constant at a value of 0.00167Hz and there is a gradual increase for higher liquid superficial velocity of 0.236 – 0.473 m/s. This shows that frequency depends on liquid superficial velocity. The figure 4.10 clearly shows the increase in frequency with increasing liquid superficial velocity. This same trend was observed by Dinaryanto et al., 2016 in the analysis of the air-water slug two-phase flow in a 26mm internal diameter horizontal pipe. It also follows the trend of (M. Abdulkadir et al., 2016) where he explained that the presence of more liquid may be expected to lead to the generation of more slugs as the gas superficial velocity increases.

CHAPTER FIVE

CONCLUSION

The analysis of experimental data for air-silicone oil plug – slug transition in a 67mm id horizontal pipe was carried out. The transition occurs by increasing superficial gas velocity at fixed superficial liquid velocity. The transition from plug to slug flow for the experimental data was observed at the superficial velocity of between 0.69 – 1.4 m/s. The effect of superficial gas and liquid velocity on void fraction, bubble velocity, bubble length, frequency and drift flux analysis were obtained and compared to those for air-water plug-slug transition in literature.

It can be concluded from this study that;

1. The void fraction increases with increasing gas superficial velocity at constant liquid superficial velocity and also decreases with increasing liquid superficial liquid velocity as reported by (Kong et al., 2018), and Hernandez- Alvarado et al, 2017
2. A strong dependence of bubble length on superficial gas and liquid velocity was established. The length of gas slugs increase with the increase of superficial gas and liquid superficial velocity. A decrease in bubble length was observed at high liquid superficial velocities of 0.378 and 0.473 m/s because of a high increase in frequency at those velocities since bubble length depends on frequency (bubble length = $\frac{UST}{F}$) This is consistent with (M. Abdulkadir et al., 2016), Dinaryanto et al., 2016 and (Kong et al., 2018)
3. The bubble velocity increases with increasing gas and liquid superficial velocity in agreement with (Kong & Kim, 2017) and (Kong et al., 2018)

4. The frequency is slightly dependent on gas superficial velocity but increases with increase in liquid superficial velocity. This has been earlier observed by Dinaryanto et al., 2016 and (M. Abdulkadir et al., 2016)
5. As the dependence of bubble velocity on mixture velocity was reported by (Nydal et al., 1992), (Ernandez-Perez & Azzopardi, 2006) and (Carpintero, 2009), it was observed in this work that the average bubble velocity increases with increasing mixture velocity.
6. The distribution parameter C_o and drift velocity U_d for the drift flux model obtained for this experimental data are 1.25 and 0.55 respectively.

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