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Effect of Pipe Inclination on the Hydrodynamics of Slug Flow

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Abstract

There is a general lack of studies addressing the optimization of hydrocarbon flow conditions in pipes passing through hilly terrains. Most of the studies carried out on two-phase flow are for fluids flowing through vertical and horizontal pipes. For studies carried out on inclined pipes, a large proportion are on air-water mixtures. To address the aforementioned challenge, there is a need to study the hydrodynamics of slug flow in various pipe inclinations with a focus on fluids with properties that replicate the behavior of effluents seen during crude oil production.

This study provides a foundational perspective into the physical phenomenon that governs the behaviour of slug flow and the variation of slug flow parameters as the pipe deviated from horizontal to vertical. To clarify the effect of pipe inclination on the hydrodynamics of slug flow, the characteristics of fully developed multiphase air-silicone oil mixture flowing in a 67 mm diameter pipe and inclined at 0, 30, 45 and 90 to the horizontal was investigated. Fluid flow properties over the range of superficial gas and liquid velocity were measured using Electrical Capacitance Tomography (ECT) and analyzed using Probability Density Function (PDF) and Power Spectral Density (PSD) plots to determine; mean void fraction, void fraction in the liquid slug and Taylor bubble, structure velocity, slug frequency and slug unit.

The mean void fraction decreased as the pipe inclination advanced from 0° to ~45°, it then increased between ~45° and 90° to the horizontal; the angle at which it begins to increase seems to be around 45°. The void fraction in the liquid slug increases as pipe inclination tends towards the vertical from the horizontal axis. In the case of the void fraction of the Taylor bubble, no unique trend was observed as the pipe inclination changed. The slug frequency increased with pipe inclination and liquid superficial velocity at a constant gas superficial velocity. In addition, the structure velocity increased as the pipe inclination advanced from 0° to 45°, it slightly decreased again between 45 and 90 to the horizontal. The slug unit in horizontal pipes is far greater than that obtainable in pipes inclined between 30° and 90°, at superficial velocities of 0.05 m/s and 0.157 m/s. However, at higher superficial velocities between 0.262 m/s and 0.514 m/s, the slug unit ranges from 0.6 to 1.8 m for all pipe inclinations. It was also confirmed that for upward inclined flow, the dominant flow pattern is intermittent flow.

Introduction

Multiphase flow is a common occurrence in a number of engineering operations involving fluid production and transportation. What makes multiphase flow in the petroleum industry peculiar are the complexity of fluids encountered, larger diameters, longer lengths of the pipes, hostile environments and difficulties associated with the characterization and prediction of the phase distribution, which is generally attributed to the existence of moving multi-boundary and turbulence (Xiaodong, 2005). The progressive complexities of oil and gas production initially in shallow water, and now in arctic climate ultra-deep water has elevated capital cost in these region hence production facilities and systems require designs with greater accuracy than in the earlier years of the industry. In addition, the use of multiphase flow lines and commingling of dissimilar fluids could trigger flow assurance challenges such as pipe corrosion and erosion, and plugging of piping systems (Brill, 2010).

Slug flow is a prominent multiphase flow regime encountered in flow lines and regarded as one of the most problematic flow pattern in the oil and gas industry (Ragab et al., 2015). It is the alternate flow of gas pockets and liquid slugs in a flow line characterized by large variation in pressure and flow. The large pressure and flow variations due to intermittent no or low oil period poses undesirable consequences such as intolerable emergency stops, reduced production capacity and high maintenance cost. Slug flow is of great concern because it results in unsteady loads on pipes and equipment, large pipeline vibration at T-junctions and bends, which contributes to fatigue failure and high corrosion rates. It is also associated with higher-pressure drop compared to other flow regimes. Hence, it is vital to determine the maximum possible impact of slugs to encounter in a flow system for the purpose of equipment design and flow assurance mitigation.

There is need to understand the dynamics of fluids flowing through pipes at angles, as inclined pipelines are quite common in production systems. This understanding is of particular interest in deepwater exploration and production with the prevalent complexities of hilly terrains and long tie backs to production facilities. Flow in directional wells and pipes passing through terrains are typical examples of multiphase flow in inclined pipes. Researchers have made significant progress in the study of multiphase flow in pipes, however, majority of studies on two-phase flow are for vertical and horizontal pipes. For a decent number of studies carried out on inclined pipes, majority were on air-water mixtures. The outcome of exceptional multiphase flow studies by Baker (1954), Mandane et. al (1974) and Taitel and Dukler (1974), Beggs and Brill (1973) and Spedding et al. (1982) on multiphase flow have since been used as the standard in the industry, although, most of the fluids considered were air-water mixtures in horizontal, near horizontal and vertical pipes.

Therefore, the industry faces a challenge to broaden knowledge and develop technologies capable of efficiently transporting effluents especially in offshore locations where flow lines can be substantially long before reaching production facilities. With this in mind, it is paramount to predict the possible problems that may be encountered due to slug flow while taking into account the angle at which the pipes are inclined in order to design optimal facilities capable of withstanding its anticipated behaviours and consequences.

The focus of this study is on the effect of pipe inclination on an air-silicone oil mixture in slug flow regime flowing through a 67 mm pipe inclined at 0°, 30°, 45° and 90° to the horizontal using electrical capacitance tomography (ECT) data. The following parameters were analysed: (1) mean void fraction, (2) void fraction in the liquid slug, (3) void fraction in Taylor bubble, (4) structural velocity, (5) slug frequency and (6) slug unit. This work finds major application in the petroleum industry, which is constantly making effort to gain in-depth understanding and develop new technologies to mitigate flow assurance challenges.

Methodology

To study the effect of pipe inclination on the hydrodynamics of slug flow, data from an experiment (Abdulkadir et al., 2014) conducted within the Chemical Engineering Laboratory at the Nottingham University were used. To ensure the repeatability of the data obtained, the experiment was carried out twice with an average standard deviation of 2%. A brief description of the experiment facility for data acquisition and procedure for data analysis for two-phase flow in upward inclined pipes is presented below.

Overview of the Experiment

Air-Silicon oil mixture was circulated using pumps to replicate multiphase flow in upward inclined pipes. A 67 mm-diameter, 6 m long acrylic pipe was mounted on a rigid steel frame that could be rotated around a pivot to produce inclination angles between −90° and +90° with the horizontal. For this study, the test pipe section was rotated between 0° to 90°. The flow was fully developed when the ratio of length to diameter (L/D) is in the range of 60-100 (Liu, 1993). The L/D is 90 for the experiment dimension hence the flow is fully developed.

Silicon oil (liquid phase) and compressed air (gas phase) were used for this study. Silicon oil was used as the liquid phase because it has similar flow properties to petroleum products. It also has a high shear resistance, hence no change in viscosity when subjected to high pressures unlike synthetic or mineral oils.

Data Acquisition

An Electrical Capacitance Tomography (ECT) was used to record the resulting patterns created for the different mixture circulation rate, at an acquisition frequency of 1000 Hz over 60 s of each run. Two rings of electrodes were placed around the circumference of the test rig at a given length above the injection inlet of the pipe section for the measurement of the instantaneous distribution of the flow phases. The two sensor rings, placed at 4.4 m and 4.489 m upstream of the mixer inlet to measure the liquid hold up of the mixture, enabled the determination of the structure velocity of elongated bubbles and its associated liquid slugs.

The physical properties of the air-silicone oil mixture and pipe parameters are listed in Table 3.1 below.

Table 1—Properties of pipe and experimental fluids

Pipe		**Fluid**	**Density** (kg/m^3)	**Viscosity** (kg/ms)	**Surface Tensi** (N/m)
Diameter (m)	0.067	Air	1.18	0.000018	
Length (m)	6	Silicone oil	900	0.0053	0.02

A flow chart showing the experimental data measurement and processing is shown in Figure 1.

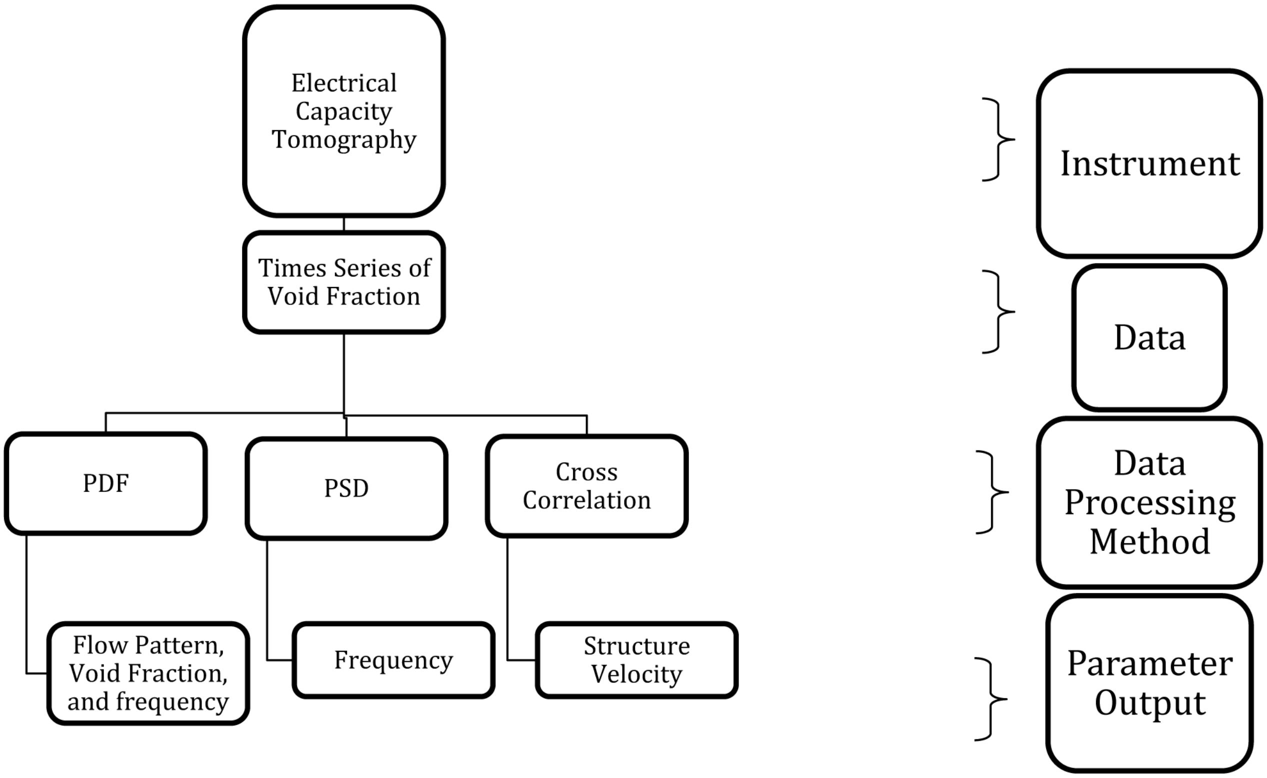

Figure 1—Data processing flow chart

Results and Discussion

Flow Regime Identification

The Probability Density Function (PDF) approach proposed by Khatib and Richardson (1984) and Costigan and Whalley (1996) was used to determine the flow regime generated at varying liquid and gas superficial velocities. PDF is a more objective method of flow pattern identification than visualization (use of high speed video system or the naked eye).

Determination of Slug Flow Parameters

Mean Void Fraction, Void Fraction in the Liquid Slug and Taylor Bubble

The void fraction in the liquid slug and Taylor bubble were determined using the Probability Density Function (PDF) approach proposed by Khatib and Richardson (1984), and Costigan and Whalley (1997). This technique exhibits the repetition of each void fraction occurrence through amplitude and time variation. The number of data points in bins of width 0.01 centered on void fractions from 0.005, 0.015, 0.030, …, 0.095, is counted and then divided by the total number of data points. They confirm the dominant void fractions which are observed at each flow condition. Discrete random variables can be plotted in a histogram which shows the frequency (on the ordinate) as a function of some measured parameter (on the abscissa for a given class width). The frequency distribution is collection of classes which are of equal size and cover the entire range of data without over lapping. For a slug flow regime, the probability density function is twin peaked, the higher and lower void fractions are recorded as the Taylor bubble and liquid slug void fraction respectively for each pipe inclination.

The mean void fraction is obtained from the liquid holdup measured by the ECT sensors and averaging the values of liquid hold-up of the fluid flowing in the pipe.

$$\langle \boldsymbol{\alpha_k} \rangle_{\boldsymbol{T}} = \frac{\boldsymbol{1}}{\boldsymbol{N}} \sum_{\boldsymbol{n-1}}^{\boldsymbol{n-N}} \boldsymbol{\alpha_k} \tag{1-1}$$

α_k Instantaneous volumetric fraction of the phase k (either gas or liquid) and N is the number of data points in the time series.

Structure Velocity

The structure velocity was determined by performing a cross correlation between the time varying void fraction data measured by the ECT-planes located at 4.4m (Plane 1) and 4.489m (Plane 2) in the test pipe section. This represents the time for the individual slugs to travel between the two planes from which the structure velocity was evaluated. The input required for its computation are the liquid holdup of the two planes, number of data, sampling frequency of the ECT and distance between the two planes. Each signal is distinguished by two variables; the amplitude and frequency of the fluctuations.

The degree of linear dependence between two time series data sets, a & b are evaluated as the covariance of a & b in the limit as the sample approaches infinity by the cross correlation operation.

For any time delay τ, the co-variance function between a (t) and b (t) is

$$\boldsymbol{C_{ab}} = \mathrm{E}[\{\boldsymbol{a(t)} - \mu_{\boldsymbol{a}}\}\{\boldsymbol{b(t+r)} - \mu_{\boldsymbol{b}}\}] \tag{1}$$

$$= \lim \frac{\boldsymbol{1}}{\boldsymbol{T}} \int_{\boldsymbol{0}}^{\boldsymbol{T}} [\{\boldsymbol{a(t)} - \mu_{\boldsymbol{a}}\}\{\boldsymbol{b(t+\tau)} - \mu_{\boldsymbol{b}}\}]\mathrm{dt} = \boldsymbol{R_{ab}(\tau)} - \mu_{\boldsymbol{a}}\mu_{\boldsymbol{b}} \tag{2}$$

Where

$$\boldsymbol{R_{ab}} = \lim \frac{\boldsymbol{1}}{\boldsymbol{T}} \int_{\boldsymbol{0}}^{\boldsymbol{T}} \boldsymbol{a(t)}\, \boldsymbol{b(t+\tau)}\mathrm{dt} \tag{3}$$

The correlation co-efficient is defined as follows

$$\boldsymbol{\rho_{ab}}\ (\boldsymbol{\tau}) = \frac{\boldsymbol{C_{ab}}}{\sqrt{\boldsymbol{C_{aa(0)}C_{bb}(0)}}} = \frac{\boldsymbol{R_{ab}(\tau)} - \mu_{\boldsymbol{a}}\mu_{\boldsymbol{b}}}{\sqrt{(\boldsymbol{R_{aa(0)}} - \mu_{\boldsymbol{a^2}})(\boldsymbol{R_{bb}} - \mu \boldsymbol{b^2})}} \tag{4}$$

A computational MACRO programme was used to determine the structure velocity of the Liquid slug body.

The structure velocity is the sum of the Taylor bubble drift velocity and the contribution of the mixture velocity in the preceding slug. The structure velocity of the Taylor bubble is given as (Nicklin, 1962; Mao and Dukler, 1985);

$$\boldsymbol{v_{TB}} = \boldsymbol{C_0 v_M} + \boldsymbol{v_D} \tag{4}$$

The translational velocity v_{TB} of the nose of an elongated bubble behind a liquid slug is expressed as a function of the mixture velocity of the slug, v_M. Bendiksen (1984) proposed a formula for the Taylor bubble translational velocity in horizontal and upward inclined pipe flow. It is given as

$$\boldsymbol{v_D} = \boldsymbol{C_0 v_M} + 0.54\sqrt{\boldsymbol{gd}}\cos\theta + 0.35\sqrt{\boldsymbol{gd}}\sin\theta \tag{5}$$

Where d is the pipe diameter, g the acceleration of gravity and θ is the inclination angle measured from the horizontal (Taitel and Brill, 1999).

Slug Frequency

The slug frequency is the number of slugs passing through a defined pipe cross-section in a given time period. Power Spectral Density (PSD) methodology as defined by Bendat and Piersol (1980) was applied to determine the frequency of periodic structures (slugs). This is a measure of how the power in a signal changes over frequency and, therefore, it describes the power (or variance) of a time series as a function of frequency.

The method presents the power spectrum density functions in terms of direct Fourier transformations of the original data and it is defined mathematically as follows,

$$\boldsymbol{S_{ab}}(f) = \int_{-\infty}^{+\infty} \boldsymbol{R_{ab}(\tau)}\, \boldsymbol{e^{-j2f\tau}} \mathrm{d}\boldsymbol{\tau} \tag{6}$$

Slug Unit

Slug unit is the summation of the slug length and the Taylor bubble. The slug unit was determined by dividing the structure velocity by the slug frequency.

Starting from the relation,

$$\boldsymbol{U_N} = \frac{\boldsymbol{L_{SU}}}{\boldsymbol{\theta}} \tag{7}$$

Where $\boldsymbol{U_N}$ is the structure velocity, L_{SU} is the length of slug unit, θ is the time for a particular slug to pass the probe.

$$\text{Also frequency, } \boldsymbol{\theta} = \frac{\boldsymbol{1}}{\boldsymbol{f}} \tag{8}$$

$$\text{Therefore } \boldsymbol{L_{SU}} = \frac{\boldsymbol{U_N}}{\boldsymbol{f}} \tag{9}$$

The slug unit is calculated using Equation 3-10

Also,

$$\boldsymbol{L_{SUi}} = \boldsymbol{L_{TBi}} + \boldsymbol{L_{Si}} \tag{11}$$

where $\boldsymbol{L_{TBi}}$ is the liquid slug and $\boldsymbol{L_{si}}$ Taylor bubble lengths respectively.

Results and Discussion

From the PDF results of each experiment analyzed, the range of liquid and gas superficial velocity that resulted in slug flow were used for the study. Slug flow was observed at velocities in the range of 0.391 m/s $\leq U_{SG} \leq$ 1.938 m/s and U_{SG} of 0.047 m/s and 0.071 m/s.

Effect of Pipe Inclination on Slug Flow Parameters

Liquid Slug, Taylor Bubble and Mean Void Fraction

The twin peak averaged void fractions obtained from the PDF shows that the experimental conditions generated a slug flow regime within the pipe. The high and low void fraction peaks corresponds to Taylor bubble and the Liquid slug respectively, this is illustrated in Figure 2 below.

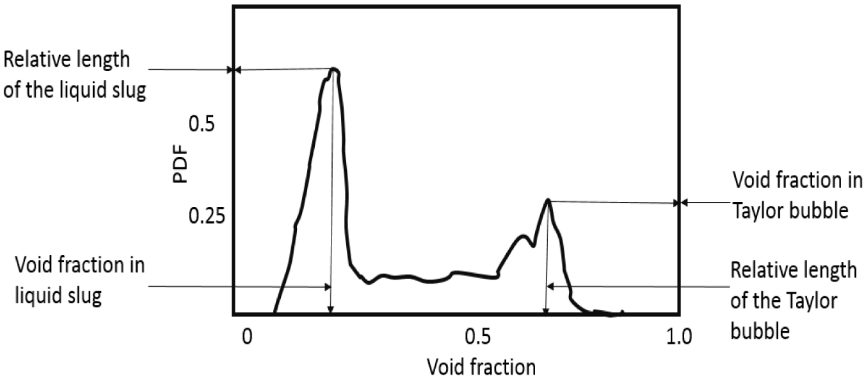

Figure 2—PDF of cross-sectional average void fraction for the case of slug flow measured from the experiments using air–silicone oil.

From the analysis carried out, for a constant liquid superficial velocity, the void fraction in the liquid slug increased as the gas superficial velocity increased.

The plots in Figure 3 and 4 shows the relationship between the pipe inclination and void fraction in the liquid slug.

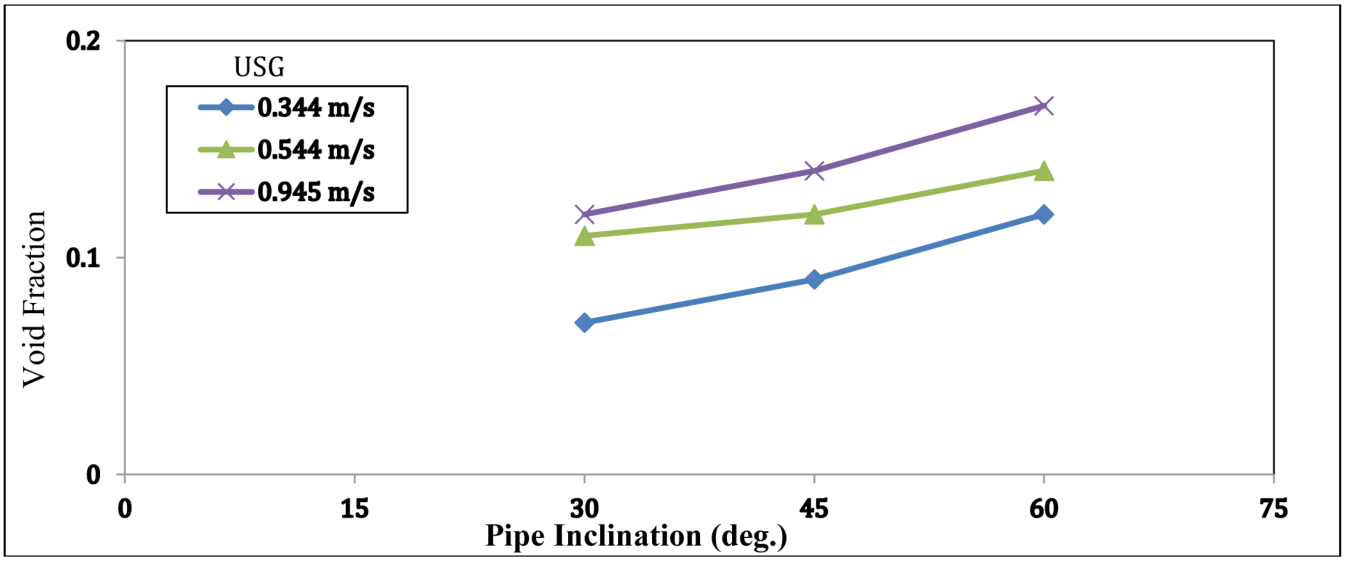

Figure 3—Effect of pipe inclination on liquid slug void fraction USL= 0.047m/s

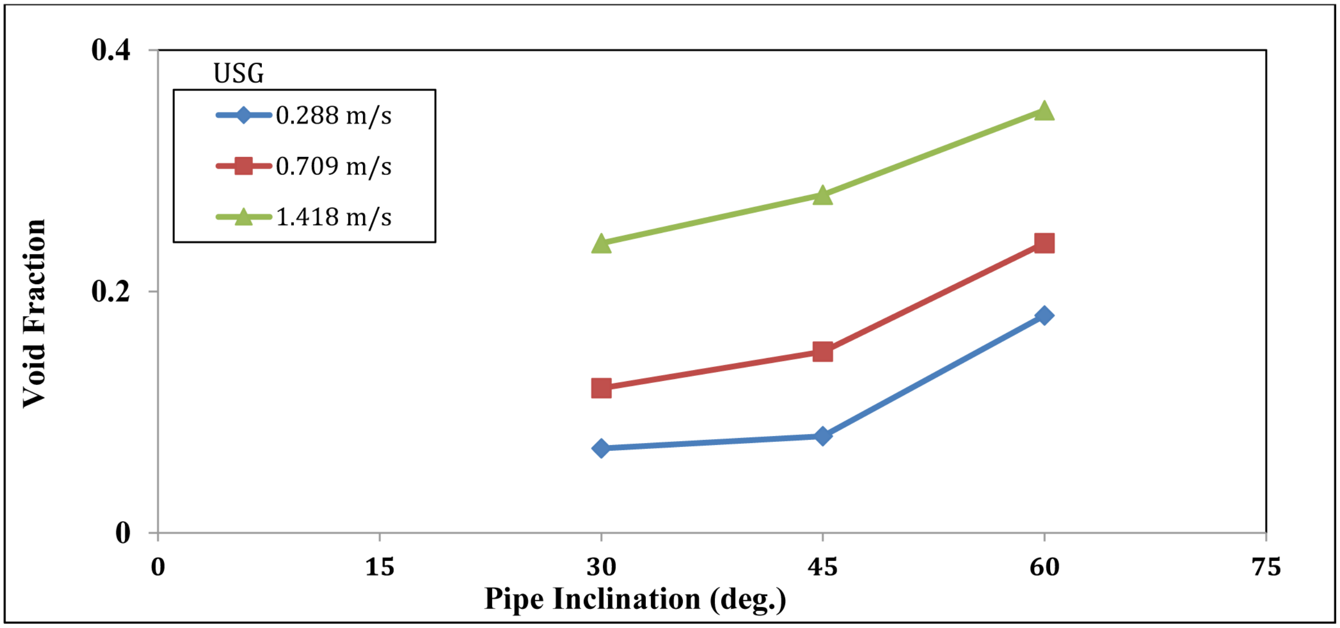

Figure 4—Effect of pipe inclination on liquid slug void fraction US_L= 0.071m/s

The void fraction in the liquid slug increased with increase in the pipe inclination at constant superficial liquid and gas velocity; this is in consonance to the correlation developed by Andreussi and Bendiken (1989) where the pipe inclination, pipe diameter and fluid properties were taken into account. This behavior may be due to bubble entrainment of the liquid film in the slug due to the force of gravity which forces the liquid in the liquid film to fall and impinge the liquid slug thereby leading to flow separation at the bubble tail; hence an increase in bubble population which leads to an increase in the void fraction.

In the case of the void fraction of the Taylor bubble, no unique trend was observed as the pipe inclination changes. In most of the experimental runs, the void fraction increases as the pipe inclination increases from 30° to 45° and decreases as the pipe angle approaches 60°. The same outcome was noticed when the void fractions in each pipe are analyzed independently as the superficial gas velocities varied. This is contrary to observation made by Abdulkadir et al. (2014) where the void fraction in the Taylor bubble increased with gas superficial velocity. This can be explained by the sequential collapse and reassembly of the Taylor bubble or the transitions of slug flow towards another flow regime, most probably, churn flow. The non-unique trend is shown in Figure 5 and 6 below.

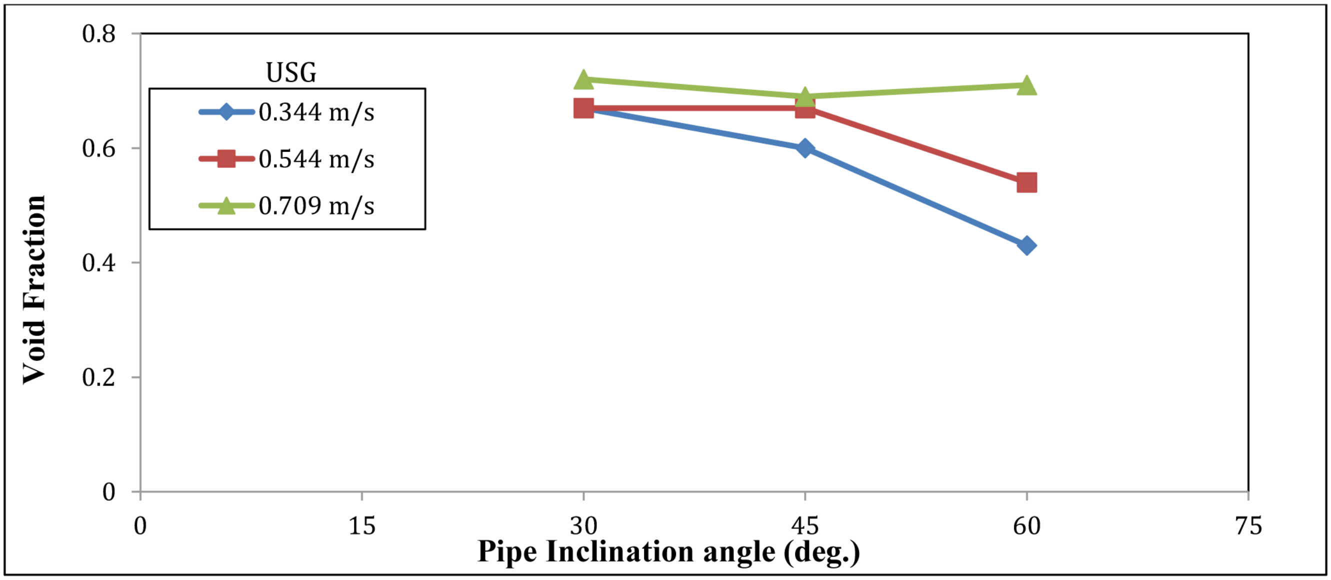

Figure 5—Effect of pipe inclination on void fraction of the Taylor bubble, U_{SL} = 0.047m/s

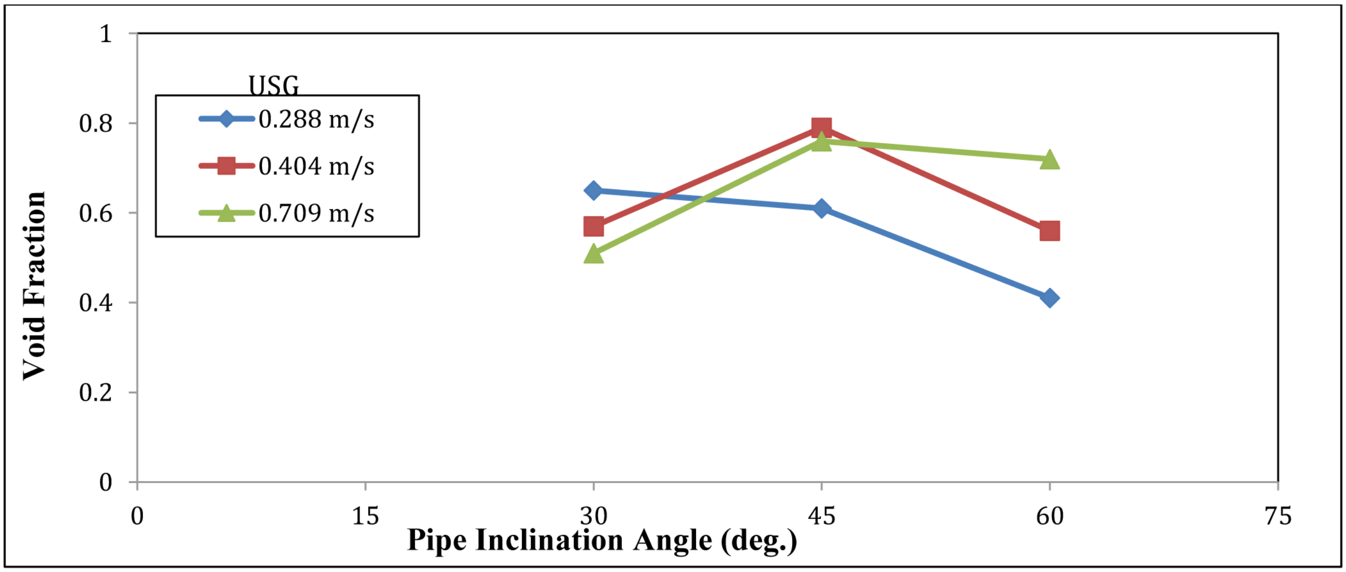

Figure 6—Effect of pipe inclination on void fraction of the Taylor bubble, USL= 0.071 m/s

In practice, the interest is usually on the average volume fractions over the entire time series. A decrease in the average void fraction is observed as the pipe inclination tends towards the vertical axis but increased slightly again between 45° and 90°. This relationship is expressed in Figure 7.

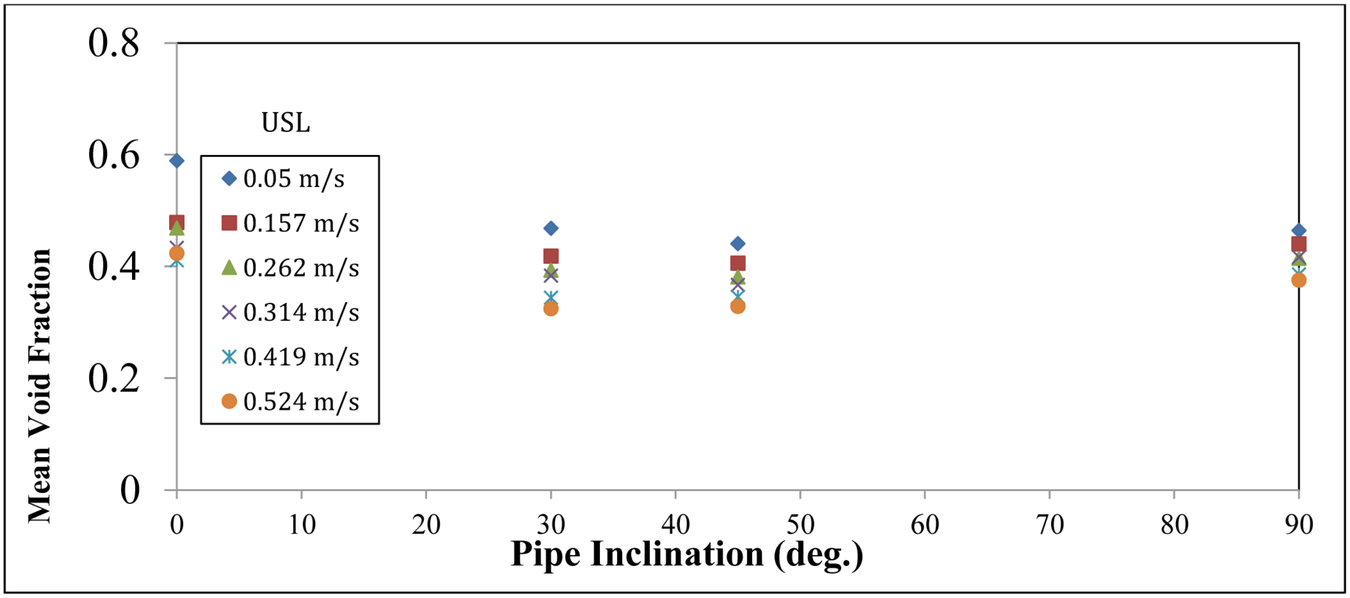

Figure 7—Effect of pipe inclination on mean void fraction U_{sg} = 0.56 m/s

The effect of pipe inclination on mean void fraction or liquid holdup is slight in upward flow. This can be observed in Figure 7 above where void fraction decreased slightly for the higher angles at which the pipe is inclined. The dependence of averaged void fraction on the angle of inclination can be explained as follows: In uphill flow, the gas moves faster than the liquid due to gravity, resulting in intermittent flow and higher liquid holdups. In other words, an increase in liquid slippage occurs and the gas inertia forces are not enough to overcome it; the reverses effect is experienced in downward flow.

Between 45° and 90°, there is no significant difference in the mean void fraction at the same flow conditions. This may be due to the insubstantial difference in slip velocity in the range of 45° to 90°. The mean void fraction is in agreement with the range given by Abdulkadir et al. (2014) and Perez (2009) 0.25 $\leq \bar{\varepsilon} \leq$ 0.65 for slug flow regime.

For upward inclined pipes, hydrostatic head is the main contributor to total pressure drop; the hydrostatic head is directly dependent on the mixture density, which is a function of liquid hold up. Based on the liquid hold up and pressure drop relationship, it can be inferred that for pipes inclined upwards between 0° and 180°, the maximum pressure drop will be attained when the pipe is vertical (inclined at 90°).

Structure Velocity

A sample of the time series plot using of the cross-correlation Excel VBA program is shown in Figure 8.

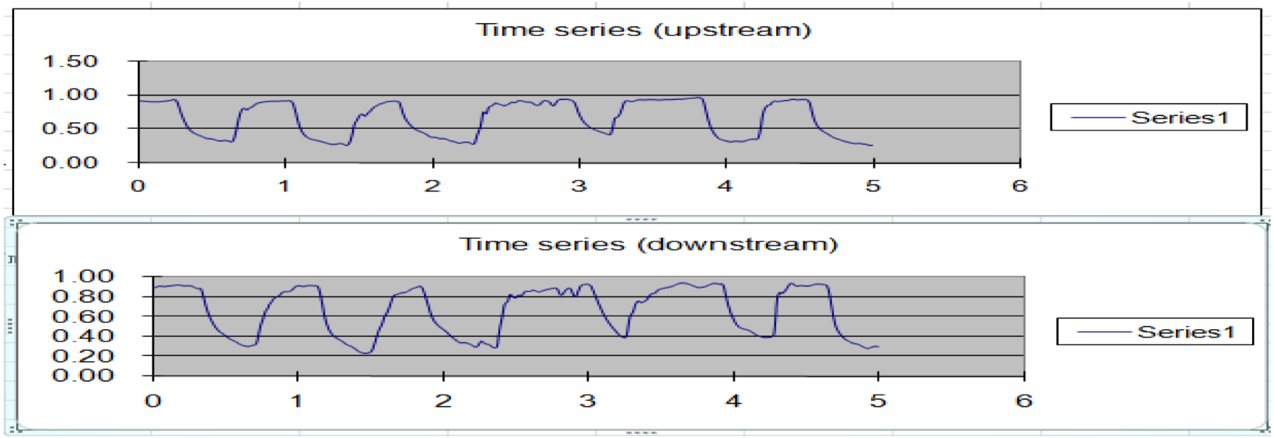

Figure 8—Effect of pipe inclination angle on void fraction of the Taylor bubble, USL= 0.071 m/s

The effect of pipe inclination on structure velocity was studied using the results obtained from the software at U_{SG} of 0.56 m/s. The relationship is illustrated in Figure 9.

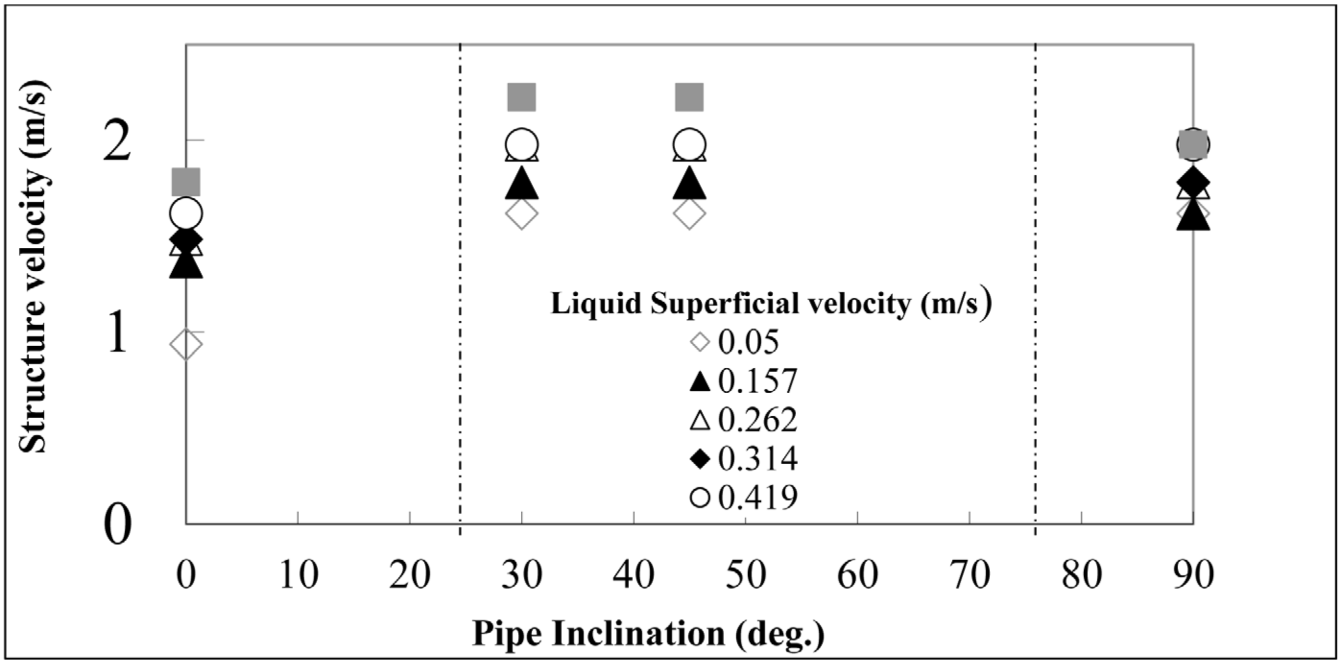

Figure 9—Effect of pipe inclination on structure velocity

It was observed that the structure velocity increased as the pipe inclination advances from 0° to 45°, it decreased again between 45° and 90° to the horizontal. The exact angle at which it begins to decrease is not clearly defined based on the available data. It is worth noting that in a similar study by Perez (2008), the reverse behaviour was noticed between 40° and 60° to the horizontal. This is in agreement with the study carried out by Bonnecaze et al. (1971), Zukoski (1966), Singh and Griffith (1970), Bendiksen (1984), and Hasan and Kabir (1988). Bonnecaze et al. (1971) explains qualitatively that the gravitational potential driving the liquid velocity along the curve surface at the bubble nose increases and then decreases as the angle deviates from the vertical to the horizontal.

Structure velocity calculated using Bendiksen (1984) and Nicklin et al., (1962) empirical correlation are compared to that obtained from the cross correlation of the experimental void fractions as shown in Figure 10 below.

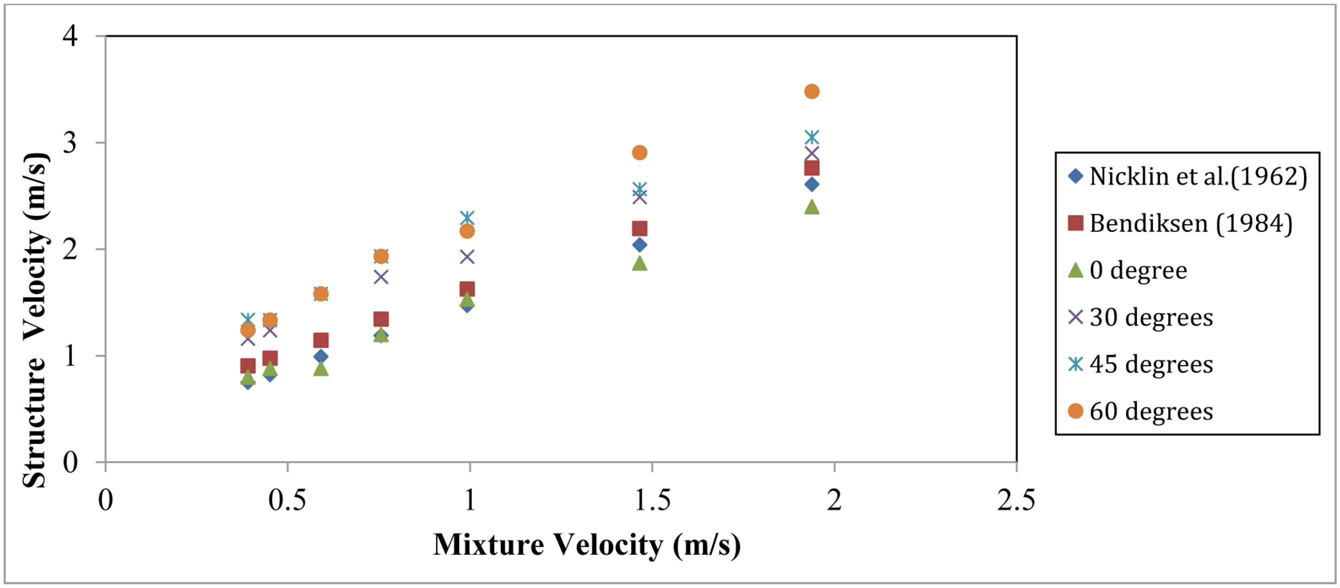

Figure 10—Structure velocity comparison for, to 0°, 30°, 45° and 90° compared to the correlation of Bendiksen (1984) and Nicklin et al., (1962)

Both correlations under-predicts the structure velocity for all pipe inclinations apart from the horizontal pipe. Interestingly, Nicklin et al., (1962) correlation is applicable to vertical pipes, however, it underpredicts the structural velocity at angles close to the vertical axis. This may be due to the fluid properties variation as the fluid considered in this experiment is air-silicone oil in contrast to the air and water mixture used by Nicklin et al., (1962).

Structure velocities and corresponding mixture velocities were plotted to estimate the drift velocity and flow coefficient for all pipe inclination considered. The effect of pipe inclination on these velocity parameters is represented in Figures 11-14. The commonly used modified Bendiksen (1984) correlation fit better with experimental data for 0°, 30° and 45°, however for the 90° there is a wide deviation between the two results. This may be due to the under estimation of drift velocity in vertical pipes which is in line with the same limited as the Dukler & Hubbard (1975). In general, the Bendiksen (1984) correlation can be used for predicting the structure velocity at 0°, 30° and 45° but not for 90° to the horizontal.

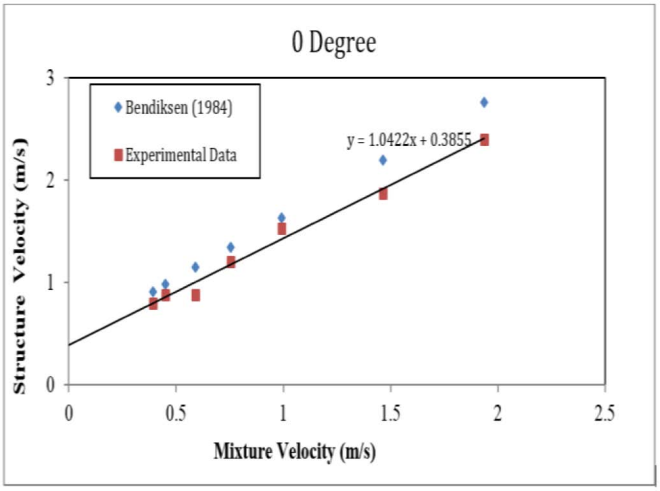

Figure 11—Structure velocity Vs. Mixture velocity for 0 degree

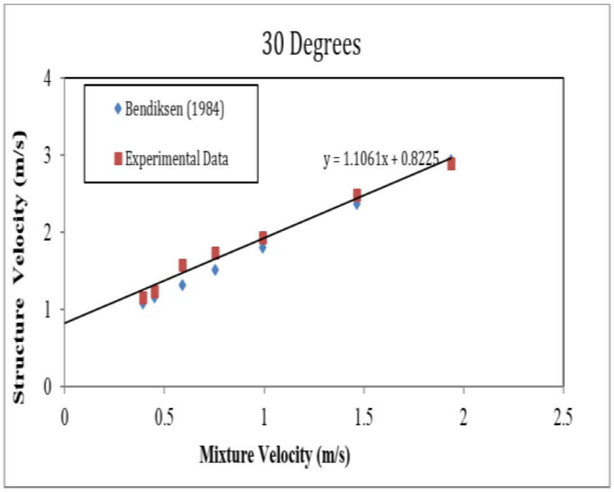

Figure 12—Structure velocity Vs. Mixture velocity for 30 degrees

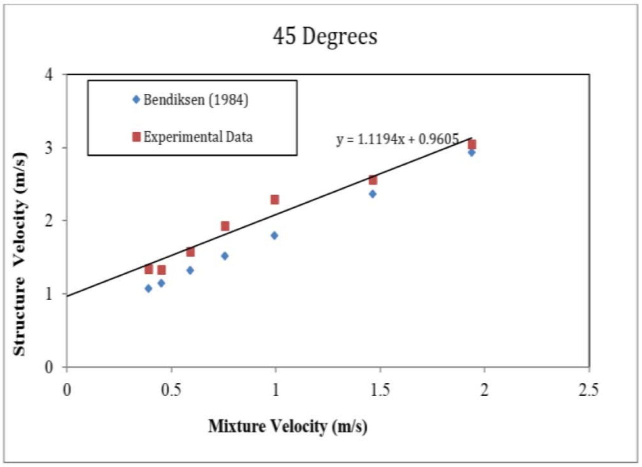

Figure 13—Structure velocity Vs. Mixture velocity for 45 degrees

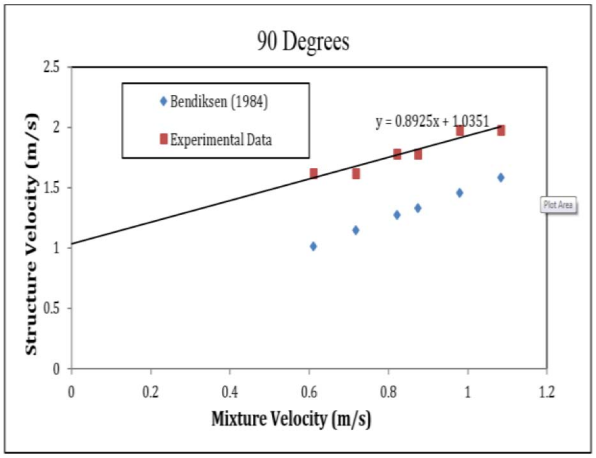

Figure 14—Structure velocity Vs. Mixture velocity for 90 degrees

For the 0° inclination, a non-zero intercept of 0.385 was obtained. This is contrary to the claim by Wallis (1969) and Hubbard (1975) that the drift velocity of the horizontal pipe is zero due to the existence of buoyancy forces in the flow direction. The results obtained for this work is in agreement with the outcome of the research carried out by Bendiksen (1984) and Weber (1981). Therefore, it is not surprising that the

Bendiksen (1984) correlation predicts close values to the experimental results, although it over predicts the structure velocity of the air-water mixture in horizontal pipes.

The flow coefficients are between $0.892 \leq C_0 \leq 1.451$ for the four pipe inclinations. Nickel el al., (1962) empirical correlation has a flow coefficient of 1.2, this value predicts closely for the 0°, 30° and 45° inclined pipes but over predicts the flow coefficient in the 90° inclined pipe. The changes in drift velocity is proportional to variations in pipe inclination. The drift velocity trend is due to gravity current effects (Benjamin, 1968), hence it is expected to increase as the pipe inclination increases. However, it also depends on other factors such as pipe diameter, local slips attributed to pressure gradient and phase distribution. The assumption made by Nicklin et al. (1962) as regards the single Taylor bubble moving in a static liquid can be envisaged as the reason for the variation. In reality, the liquid slug and Taylor bubble are in continuous motion and the higher drift velocity obtained is because of the dispersed bubbles contribution.

Conclusively, a linear dependency is expected between the structure velocity and mixture velocity for two phase flow of liquid with similar properties. The structure velocity trends in other flow patterns are quite different and do not follow this trend, hence, a deviation from this behaviour can be used as an objective method of flow pattern identification.

Slug Frequency

The effect of pipe inclination angle on slugging frequency is illustrated in Figure 15.

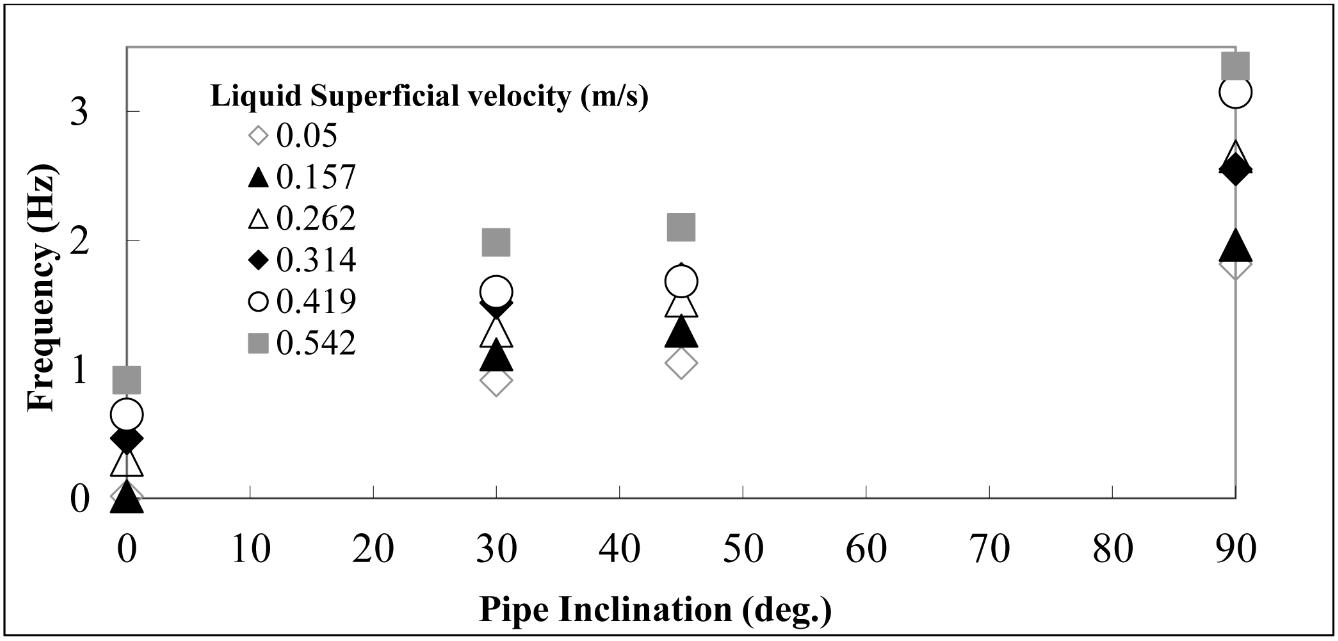

Figure 15—Effect of pipe inclination on slug frequency

The slug frequency increased with pipe inclination and liquid superficial velocity at a constant gas superficial velocity of 0.56 m/s. From the relationship observed in Figure 4. 14 above, under the same flow conditions, slug frequencies in horizontal and vertical flow responds quite differently. The highest variation in slug frequency as the liquid superficial velocity changes is in the vertical pipe (90°). The explanation for this is, an increase in the liquid input will extend the time required to rebuild the level of the film to form the next slug.

For the horizontal case, changes in slug frequency with liquid slug velocities and constant gas velocity are minimal compared to a pipe inclined at an angle close to the vertical axis. This is, at 90°, the slug frequency is more sensitive to changes in the liquid superficial velocity than in a horizontal or near horizontal pipe. For a fluid moving at a liquid superficial velocity less than 0.157 m/s in a horizontal pipe, the slug frequency is zero. Perez (2008) observed this same phenomenon and he stated that at low liquid superficial velocity, mist flow exists; hence, the fluctuations are weaker over a wider range. Based on these observations, it can be inferred that zero slug frequency in the horizontal pipe may be attributed to changes in flow pattern associated with variations in the flow conditions of the two phase mixture. At the stated flow condition, the flow regime is likely an undeveloped slug flow or another flow regime other than slug flow.

Comparatively little work has been reported on slug flow frequency data in inclined flow. Greskovich and Shrier (1972), Heywood and Richardson (1979), Tronconi (1990), Nydal (1991) and Manolis et al. (1995) studied the effect of pipe inclination on slugging frequency and developed correlations for horizontal flow only. Zabaras (1999) developed a correlation that takes into account the effect of pipe inclination by considering 9 angles between 50° and 90° upward pipe inclinations to the horizontal, however, only the correlation between 0° and 11° was accessible for the study.

The commonly used correlation for slug frequency model developed by Gregory and Scott (1969) and the Zabaras (1999) were compared to the experimental results for a horizontal pipe.

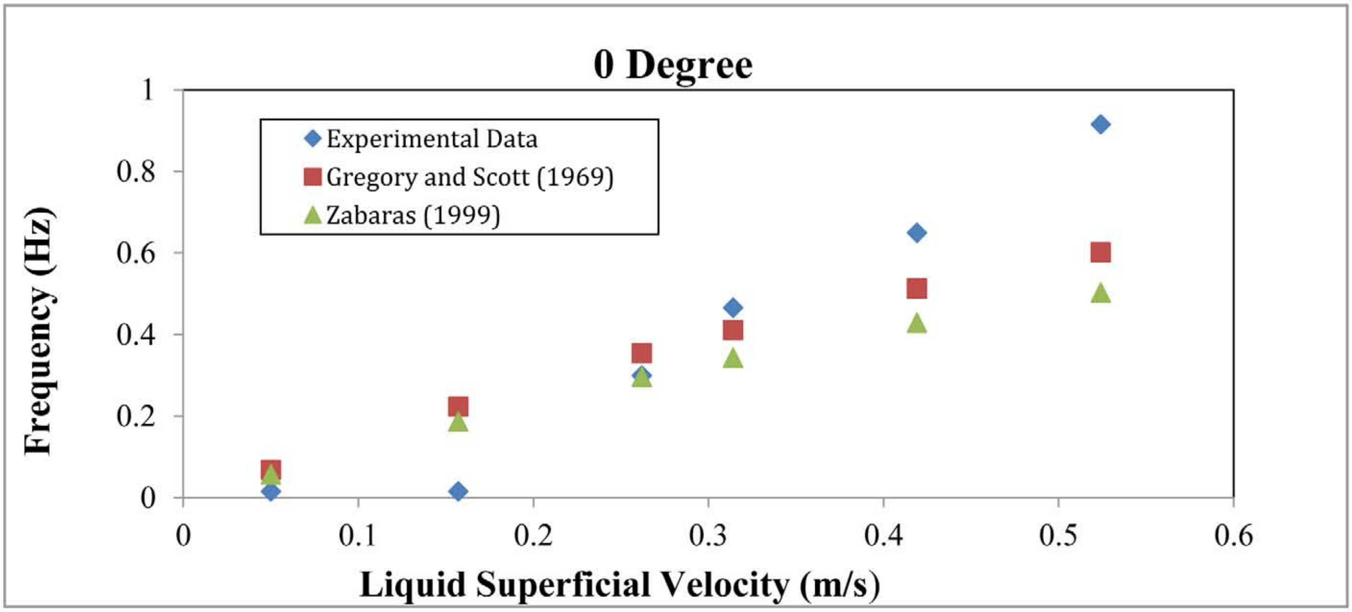

Figure 16—Analyzed result compared with Gregory and Scott (1969) and the Zabaras (1999)

A wide disagreement between the Gregory and Scott (1969) and the Zabaras (1999) correlations and the present data was observed, although, they all follow a particular trend as the liquid superficial velocity changes. Therefore, for inclined pipes, it is expected to follow this trend; however, no correlation fits quite well with the results obtained from the analysis. Hence, correlations used in predicting the frequency of slugging in all pipe inclination are susceptible to being erroneous.

The results shows that the angle at which a pipe is inclined strongly affects the frequency of the periodic structures in intermittent flow such as spherical cap bubbles and Taylor bubbles.

Slug Unit

The slug unit for horizontal pipe at 0.56 m/s gas velocity and a superficial velocity of approximately 0.257 m/s and lower, is far greater compared to the other flow conditions at varying pipe inclinations. This is in agreement with the observation made by Perez (2008) where the slug unit for horizontal flow was reported to be bigger for horizontal pipe than intermediate pipe inclination angle and vertical flow. This may be attributed to the very low slug frequency at a low liquid velocity, this behaviour is illustrated in Figure 17 below.

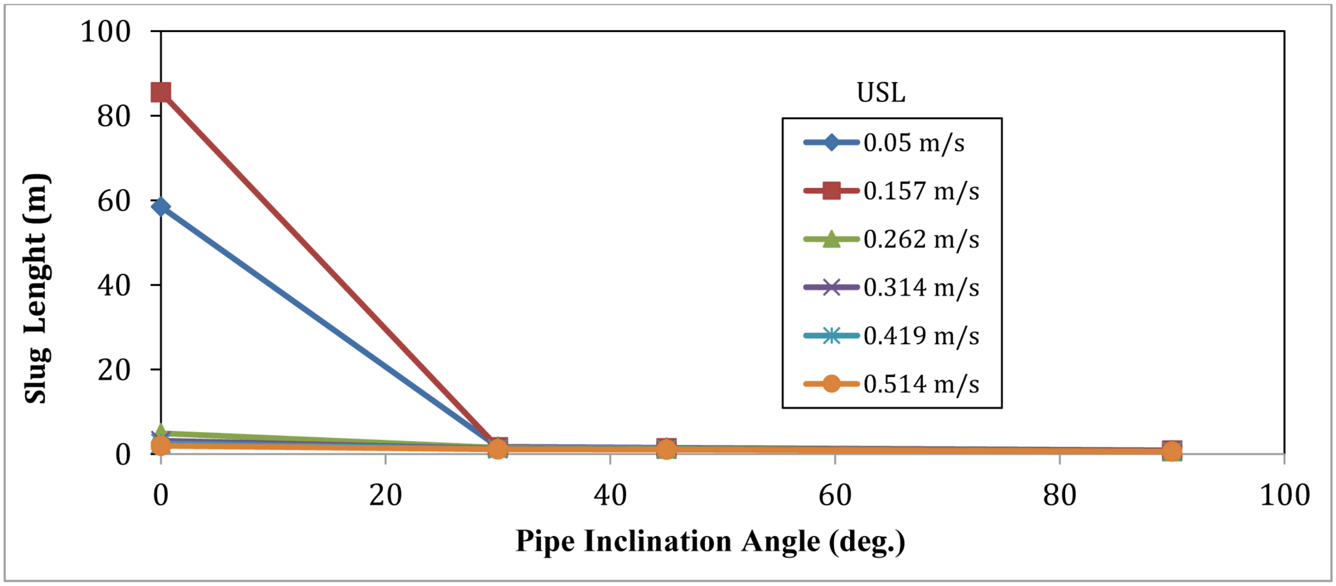

Figure 17—Effect of pipe inclination on slug unit

At higher superficial velocities between 0.262 and 0.514 m/s, the slug unit ranges from 0.6 to 1.8 m for all pipe inclinations. It is worth noting that frequency and slug unit exhibit inverse behaviour as regards changes in pipe inclination, therefore, we can indirectly obverse the effect of pipe inclination on slug unit by studying the frequency behaviour. With increasing liquid velocity, the slug unit reduced as shown in Figure 17. This is as a result of reduction in entrainment of the small bubble; the reverse behaviour should be expected when the liquid velocity is keep constant and the gas velocity is increased.

The impact of pipe inclination on slug length between 30°and 90° is clearly illustrated in Figure 18.

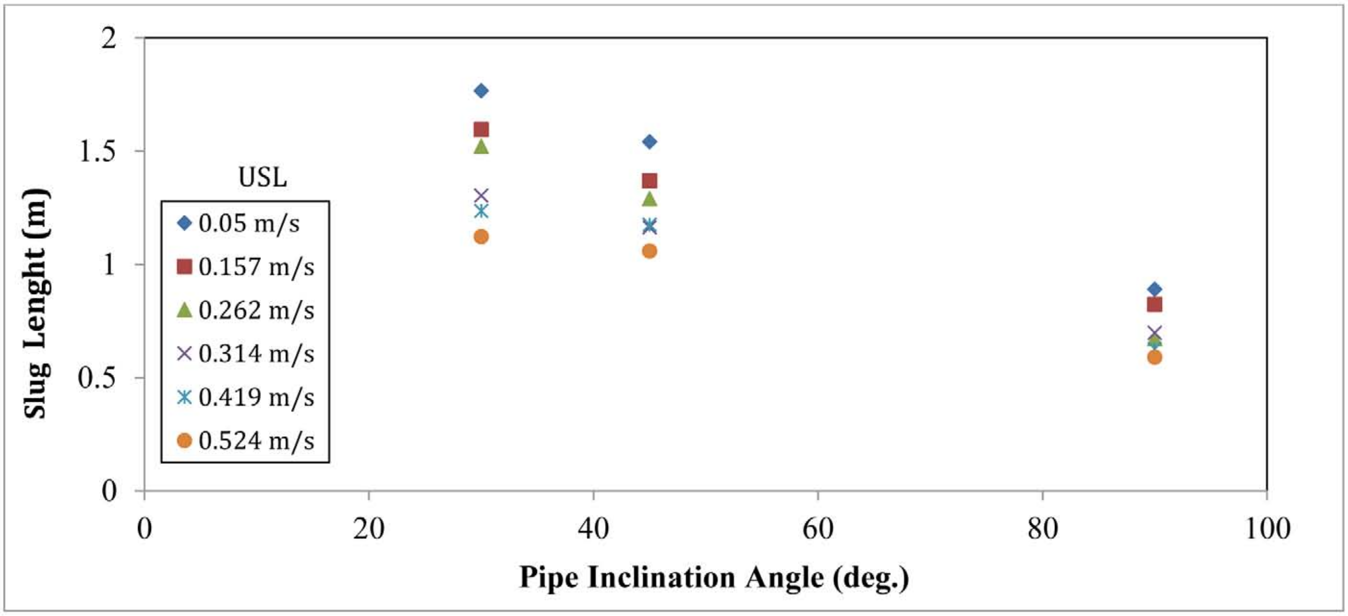

Figure 18—Effect of pipe inclination on slug unit (30° to 90°)

Conclusion

The impact of pipe inclination on slug-flow hydrodynamics has been analysed using data obtained from the Electrical Capacitance Tomography (ECT) probes. The slug characteristics considered were void fraction, structure velocity, slug frequency and slug unit at different inclinations. The parameters were estimated using time series analysis (probability density function and power spectral density).

For the range of flow conditions and data set used for this study, the following conclusions were drawn for upward inclined flow.

1. The mean void fraction decreased as the pipe inclination advanced from 0° to ~45°, it then increased between ~45° and 90° to the horizontal. The angle at which it begins to increase seems to be around 45°.
2. The structure velocity increased as the pipe inclination advances from 0° to 45°, it then decreased between 45° and 90° to the horizontal. The exact angle at which it begins to decrease is not clearly defined based on the available data.
3. A direct relationship between slug frequency and pipe inclination was observed, however, the slug frequency is more sensitive to changes in the liquid superficial velocity in pipes at angles close to 90° than in a horizontal or near horizontal pipe.
4. Based on the liquid hold up and pressure drop relationship, it can be inferred that for pipes inclined upwards, the maximum pressure drop will be attained when the pipe is vertical (inclined at 90).
5. The slug unit in horizontal pipes is far greater than that obtainable in pipes inclined between 30 and 90 degrees at superficial velocity of 0.05 and 0.157 m/s. However, at higher superficial velocities between 0.262 and 0.514 m/s, the slug unit ranges from 0.6 to 1.8 m for all pipe inclinations.
6. The expected linear dependence of the structure velocity on the mixture velocity for slug flow was confirmed.

Slug flow parameters are imperative in the design of multiphase flow pipes and associated equipment. Particularly, liquid holdup is the starting point for most pressure drop and heat transfer predictive models, therefore it is necessary to accurately estimate this parameter at different flow conditions. In addition, slugging frequency is relied upon for separator design and required as an input in a number of mechanistic models such as the cook and Behnia (2000) and Dukler and Hubbard (1975). This study gives new insight into the dynamic phenomena that occur in inclined pipes. It further revealed that pipe inclination angle has some effects on gas-liquid flow.

Recommendation

The study results showed that there was significant divergence between the existing correlation results and the study experimental data. This suggests that there is need to refine the accuracy of models, making them more accurately capture the realities of multiphase flow in pipelines. As such, the following are the recommendations of this study:

1. A comprehensive study on slug flow parameters, taking into account: (i) Pipe inclined at several angles (ii) Crude oil as the multiphase fluid (iii) impact of pipe roughness on flow paramters in an inclined flow system and (iv) Pipe dimensions similar to existing pipelines.
2. Based on these proposed studies, generate robust databanks of experiments and analyse them to develop models that will be more representative of slugging in pipelines.
3. Incorporate these newly developed models into existing commercial software.

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NOMENCLATURE

Symbol	**Description**	**Units**
U_{SL}	Liquid superficial velocity	ms^{-1}
U_{Sg}	Gas superficial velocity	ms^{-1}
A	Cross-sectional Area	m^2
H_L	Liquid-holdup	Dimensionless
D	Diameter of pipe	m
ρ	Density	kgm^{-3}
f	Frequency	H_Z
S	Slip ratio	Dimensionless
g	Acceleration due to gravity	m/s^2
L	Length	m
G	Mass flux	$kgm^{-2}\,s$
μ	Viscosity	$kgm^{-1}s^{-1}$
U_D	Drift velocity	ms^{-1}
U_M	Mixture velocity	ms^{-1}
U_L	Liquid velocity	ms^{-1}
U_G	Gas velocity	ms^{-1}

Greek Letters

ε	Void fraction
λ	No slip liquid holdup
μ	Viscosity
P	Density
Θ	Pipe inclination angle

Subscripts

G	Gas phase
L	Liquid phase
M	Mixture
S	Superficial

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