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PIPE INCLINATION EFFECTS ON HIGH VISCOSITY OIL-GAS TWO PHASE FLOW CHARACTERISTICS

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Abstract

There is a growing interest in the exploration of high viscous unconventional reserves attributable to its huge reserves amidst an increasing decline in low viscous conventional reserves. In this paper, the effects of upward pipe inclination and liquid viscosity on two phase flow characteristics have been carried out experimentally in a 0.0256m ID pipe inclined at an angle of 15°. Air and mineral oil were used as test fluid with oil viscosities ranging from 0.7-5.0 Pa.s. The superficial velocities of gas and liquid velocities were varied respectively from 0.3 to 10 m/s and 0.06 to 0.3 m/s. Electrical tomographic capacitance sensor readings and visual observations revealed four flow patterns. Two phase characteristics measured include pressure gradient, liquid holdup, and slug flow features, i.e. slug frequency and slug liquid holdup. Analysis of the pressure gradient exhibited a gradual increase with increasing superficial gas velocity at a constant superficial liquid velocity which steeped when the superficial liquid velocity was increased. A similar trend was observed for pressure gradient as the angle of inclination is increased.

***Keywords**: Pressure gradient; liquid holdup; Flow pattern; Liquid viscosity; and ECT.*

1. Introduction

In the petrochemical, geothermal and nuclear industries, gas-liquid two phase flow in pipes is the most occurring phenomenon. A lot of studies have been carried in the literature on low viscosity two phase flows. However, with the diminishing reserves of "conventional" light crude oil, increased production costs amidst increased world energy demand over the last decade, industrial interest has shifted to the production of the significantly and more abundant "unconventional" heavy crude oil attributable its increasing importance as a veritable energy source. In addition to the fact that it accounts for over two-thirds of the world total oil reserve.

The existing technologies for the extraction, processing, and transportation adopted for heavy oil is costly due to their natural composition (i.e., viscosity) thereby making their production expensive, difficult to transport and refine. This whole process is quite expensive when compared to conventional crude oil. However, with improvement in technology, this once costly energy source is quickly becoming a more viable alternative. Hence, there is the need to carry out a further investigation so as to enhance its further production at reduced cost. The exploration of this vast resource for easy production and transportation requires a good understanding of multiphase flow system for which the knowledge of the effect of fluid viscosity is of great importance. Two phase flow are expected to exhibit a significant behaviour in high viscosity oils when compared to low viscosity oil as many flow characteristics such as flow pattern, slug mixing zone, and bubble entrainment.

A lot of study addressing the effects of pipe inclination on two phase flow have been carried out for low viscosity liquid while a handful of such studies address the behaviour of two phase flow in medium viscosity oil. There is relatively little that has been done on liquid viscosity range above 0.5 Pa. s in addition to the effects of pipe inclination. This study will, therefore, focus on relatively higher liquid viscosity range (i.e., 0.7-5.0 Pa. s) thereby creating a new databank that could be used to improve the understanding of the hydrodynamics of high viscosity liquid. The existing studies on low and medium liquid viscosity effects on two phase flow characteristics in inclined pipes are presented below.

A comprehensive pioneer study on the effects of pipe inclination on two phase flow in 20 mm ID pipe was carried out by [1] using air and water as test fluids with the test fluids in 20 mm ID pipe at varying pipe inclinations. He reported that pressure gradients are significantly affected by angles of inclination. [2] later developed a prediction model for two phase flow in inclined pipeline noting that pressure drop is greatly affected by the liquid holdup in the slug unit. Correspondingly [3] conducted experiments using 0.0508 and 0.0629 m ID inclined pipe to study effects of inclination. The authors noted that liquid holdup was strongly affected by pipe angle of inclination. The study saw the development of one of the most used prediction tool for pressure gradient and liquid holdup in the petroleum industry.

Weisman and Kang [4] gave one of the most important works on flow patterns in inclined pipelines. Their experiments were conducted on test facilities with pipe internal diameters of 0.012, 0.025 and 0.051 m pipelines for which correlation for the transition of annular flow for all pipeline inclinations was proposed:

$$\left(Fr_{sg}\right)\left(KV_{sg}\right) = 25\left(\frac{V_{sg}}{V_{sl}}\right)^{0.625} \tag{1}$$

Kutateladze number, $KV_{sg}\left(= V_{sg}/[g(\rho_L - \rho_G)\sigma]^{0.25}\right)$ and Froude number, $Fr_{sg}\left(= {V_{sg}}^2/gD\right)$ are functions of the superficial gas velocity.

Transition to dispersed bubbly flow was given by:

$$\left[\frac{(-dP/dz)}{g\left(\rho_l - \rho_g\right)}\right]^{0.5}\left[\frac{[g(\rho_L - \rho_G)D^2]}{\sigma}\right]^{0.5} \geq 9.7 \tag{2}$$

$-dP/dz$ is the frictional pressure gradient of the single phase liquid flow in the pipe and σ is the interfacial tension.

The transition to stratified-wavy flow was given by:

$$ {Fr_g}^{0.5} = \left(V_{sg}/V_{sl}\right)^{1.1} \tag{3}$$

For the separated-intermittent transition, the correlation proposed was thus:

$$\left[\frac{\sigma}{gD^2\left(\rho_l - \rho_g\right)}\right]^{0.20}\left[\frac{[DG_G]}{\mu_G}\right]^{0.5} = 8\left[\frac{V_{sg}}{V_{sl}}\right]^{0.16} \tag{4}$$

Transition from bubbly to intermittent flow is given by:

$$\frac{{V_{sg}}^2}{gD} = 0.2\left[\frac{V_m}{gD}\right]^{1.56}(1 - 0.65\cos\theta)^2 \tag{5}$$

θ is the pipeline inclinaton from the horizontal.

Gomez [5] also proposed a correlation given below for liquid holdup in slug body by correlating numerous experimental data from a variety of pipe diameters and inclinations

$$E_s = e^{-(0.45\theta + C\,Re)} \qquad 0 < \theta \leq 90° \tag{6}$$

where θ is the angle of inclination from the horizontal, $C = 2.48 \times 10^{-6}$ and the Reynolds number, Re is defined as:

$$Re = \frac{\rho_L V_M D}{\mu_L} \tag{7}$$

Most recently, studies involving the use of medium viscosity oil have been investigated. Among these studies are those by [6] who investigated horizontal slug flow pressure drop models in viscous oils of range 0.48 Pa.s. They noted an enlarged intermittent flow region in the flow pattern map existed with increasing oil viscosity. Gokcal [7-8], later investigated the effects of high viscosity liquids on two-phase oil-gas flow in horizontal and near horizontal pipes. They corroborated the findings of [6] which noted an enlarged intermittent flow region. Their investigation revealed huge discrepancies between experimental results and the model predictions. They concluded that an increase in oil viscosity enhances the intermittency of the flow. The experimental results were used to evaluate different flow pattern maps, models and two-phase flow correlations.

Furthermore [9] experimentally studied inclination effects on flow characteristics of high viscosity oil/gas two-phase flow. The study in which 400 experimental tests were carried out using oil viscosity ranging from 0.181 to 0.585 in a 0.0508 m ID pipe for ±2° angles of inclinations.

2. Experimental setup

2.1. Test facility description and measurement procedure

The experimental setup used for this investigation as shown in the schematics presented in Figure 1 is comprised of the following core sections: the fluid (oil, air, and water) handling section, test measurement/observation section and the instrumentation and data acquisition section. The test facility consists of a 5.5 m long and 0.0254 m internal diameter pipe fabricated from Perspex material. The observation and measuring instruments were placed at a distance of at least 100 pipe diameters from the last injection point to ensure full development of flow. Injection points were installed upstream of the test section for oil, and water.

A progressive cavity pump (PCP) with a capacity of 2.18m^3/hr., is used to pump water through the test facility. Water volumetric flow rate is metered using an electromagnetic meter manufactured by Endress+Hauser, Promag 50P50 D50, with a range of 0 – 2.18 m^3/hr. Water was injected vertically through a Tee-section upstream of the main test line about 70 pipe diameters from the viewing sections.

Oil was stored in a 0.15 m^3 tank capacity manufactured from plastic material and insulated with fibres on the periphery. A variable speed PCP with maximum capacity, 0.72 m^3/hr, was used in pumping oil, Endress + Hausser's Promass 831 DN 50, a Coriolis flowmeter, with range, 0~180 m^3/hr, was used in oil metering. The flowmeter has three outputs; mass flowrate, density, and viscosity with a measurement accuracy of 0.1%, 0.5 kg/m-3 and 0.5% respectively. The HART output from the meter is 4-20mA is connected to a data acquisition system for data gathering. Two main unit operations equipment used in the flow loop include; separator and chillers.

The separator is a rectangular shaped tank with viewing windows to allow for liquid levels and separation process monitoring, and an internal partition having weir for overflow. The multiphase fluid enters the first partition of the separator where the viewing windows are located, initial separation by gravity takes place in this section, the denser phase settles at the bottom while the dense phase moves to the second section for further separation. A mixture of oil, water, sand, and air requires a residence time of at least 10-12 hours for complete separation into its component phases. On complete separation of the phases, oil is recovered and reused.

The temperature control system for oil is a refrigerated bath circulator manufactured by Thermal Fisher®. Copper coils submerged in the oil and water tank are connected to the circulator, by running cold or hot glycol in the coils at specific time intervals, the temperature of oil and water in the tank can be controlled based on heat transfer. The circulator temperature ranges from 0 to +50°C, with an accuracy of ± 0.01°C. To ensure the equitable temperature of the oil, a recirculation flow for about 30 minutes is carried out.

GE Druck static pressure transducers, PMP 1400, with pressure range 0-4 barg and accuracy 0.04% over the full scale is used to obtain the static pressure in the test section; they are placed 2.17 m apart with the first of them 60D from the last injection point to ensure fully developed flows. A differential pressure transducer, Honeywell STD120, with minimum pressure drop measurement of 100 Pa and an accuracy of ±0.05% is used to measure the differential pressure.

The temperature of the test fluids on the test section is measured by means of J-type thermal couples with an accuracy of ±0.1 °C placed at different locations. Data acquired from the flowmeters, differential pressure transducers, pressure transducers, and temperature sensors are saved to a Desktop Computer using a Labview® version 8.6.1 based system.

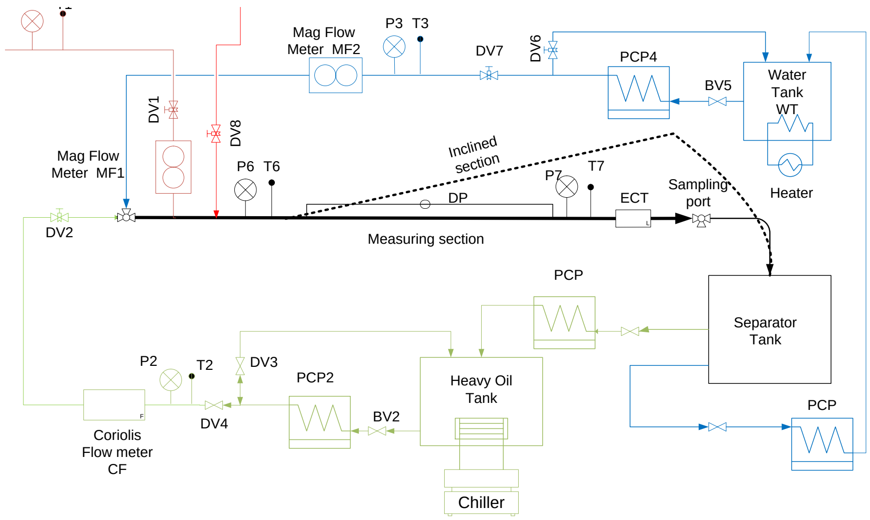


Figure 1. Schematics of the 1 inch test facility

The system consists of a National Instruments (NI) USB-6210 connector board interfaces that output signals from the instrumentation using BNC coaxial cables and the desktop computer. Three Sony camcorders, DSCH9 with 16 megapixels, high definition, and 60GB HDD are used for video recordings during the test to aid visual observations. The test facility schematic is shown in Figure 1 above.

2.1.1. Electrical capacitance tomography (ECT)

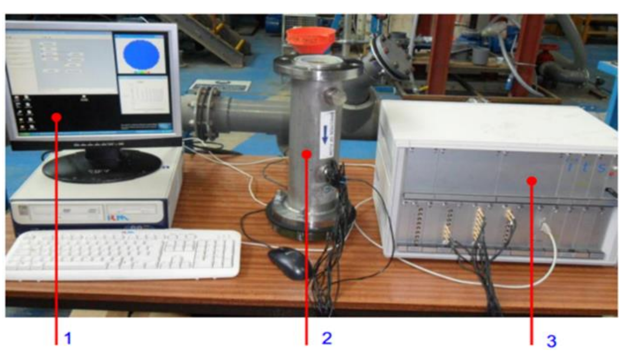
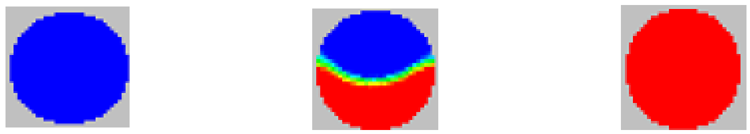


Figure 2. ECT System; (1)-Computer System, (2)-ECT Sensors embedded in the pipe and (3)-Data Acquisition System

As part of this preliminary experimental investigation, a process tomography equipment; Electrical Capacitance Tomography (ECT) designed by Industrial Tomography Systems, ITS, Manchester, UK was used. This tomography equipment has the capability to instantaneously obtain, reconstruct and display factual information of phase distribution inside the pipe is comprised of 3 units: a capacitance sensor, a capacitance measuring unit and a control computer as depicted in Figure 2. The precept of this equipment is based on the permittivity difference of dielectric materials with electrodes lined at the periphery of pipe, for detection of mixture permittivity.

2.1.2. ECT static calibration test

The calibration of the ECT sensors is done to establish a scale for its tomography display with different phases represented by a different code. In this experimental investigation, oil which has the highest density and permittivity is coded in red while air with lowest density and permittivity is coded in blue as shown in Figure 3 The test was carried out using the 3-inch sensor, air and mineral oil CYL680 at room temperature. Prior to calibration, the pipe housing with ECT sensors are carefully cleaned, and each electrode is connected to the acquisition box in a correct sequence. The low and high reference results are respectively obtained by taking a reading from the empty pipe and when the pipe section is completely filled with oil with an allowable time given to ensure that there are no small gas bubbles entrained in the liquid phase.



0% (Low Ref.) 50% 100% (High Ref.)

Figure 3. Tomographic images of liquid holdup

2.1.3. Viscosity measurements

Figure 4. Brookfield DV-I™ prime viscometer

Generally, the viscosity is termed as the measure of the resistance of a fluid to flow. It is the measure of the gradual fluid deformation by shear or tensile stress caused by internal friction of fluid molecules flowing at different velocities. Though the test liquid (CYL680) used for this investigation were specified by industrial manufacturers; it was necessary however to validate their claims before the commencement of experimental runs for the purpose of enabling viscosity variations with temperature for the test matrix. Measurement of the oil's viscosity using Brookfield DV-I™ prime viscometer (see Figure 4) at different temperature was carried out in the laboratory and compared with the manufacturer's specifications data shown in Figure 5.

2.1.4. Test fluid and experimental range

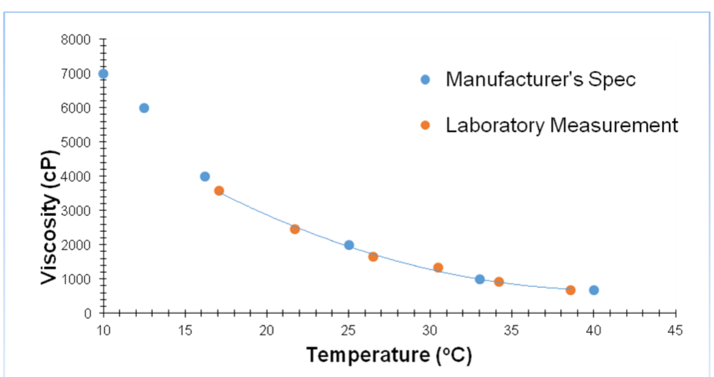


Figure 5. Comparison of oil viscosity measured and supplied by the manufacturer

Mineral oil manufactured by Total with the following properties viscosity: 0.220 Pa·s@40°C, density: 918 kg/m^3 @15.6 °C, API Gravity: 27.67, interfacial tension@25°C 0.031 N/m was used as the liquid phase while air was used as the gas phase for this experiment. The liquid and gas superficial velocities were respectively varied from 0.06 m/s to 2.0 m/s, and 0.3 m/s to 12 m/s. The pipe angle inclination values were from 0-30°.

3. Results

This section describes the experimental runs conducted on the 1 inch 30 degrees inclined test facility for which results for the average liquid holdup, tomographic and stacked tomographic image from ECT, analysis of high speed video recordings used for flow patterns determination were presented. The liquid holdup from ECT was also used for Probability Mass Function (PMF) to aid flow regime identification. Liquid holdup, slug frequency, and pressure gradient results were also presented here.

3.1. Flow patterns classification and determination

Flow patterns play a very important role in two phase flows with each regime exhibiting certain hydrodynamic behaviour. To date, there is no uniform procedure for describing and classifying flow patterns as there are subjective to the researcher’s observation. For the present study, the designation of flow pattern observed in the high viscous oil-gas test were an interpretation of visual observation via viewing the section on the flow line, and analysis of video recordings for this investigation, Slug, pseudo-slug, and the wavy annular flow were observed in the inclined section. However, it is worth noting that the wavy annular flow characterised by rolling waves as shown in Figure 6 was observed as the dominant flow pattern. It was also observed that for oil viscosity was lower than 3.0 Pa.s for all oil and gas superficial velocities considered for this study, wavy annular flow was the only flow pattern observed. The dominance of the wavy annular flow can be attributed to the effect of gravity and viscosity on the flow patterns, i.e. when a pipeline is inclined upwards, gravity forces acting on the oil causes a reduction in oil velocity.

At V_{so} of 0.2 m/s and V_{sg} value ranging from 0.3-3.0 m/s for oil viscosity above 3.5 Pa.s, slug flow pattern was observed. This flow pattern with the front end shape like a cap/bullet is characterized by the wavy interface between the gas and the liquid body (slug) which are relatively short and frequent. Increasing superficial gas velocity is responsible for the oil-gas interface’s instability in the film region as a result of an increase in flow turbulence.

The wavy annular flow was observed when V_{sg} reached 5.0 m/s. The energy dissipated as a result of the increased energy along the flow results in large amplitude of waves at the oil-gas interface with top wall of the pipe significantly wetted by oil such that bulk of the oil remained at the bottom of of the pipe and the gas continually swept the liquid at the interface to the top of the pipe with gas mainly flowing at the core.

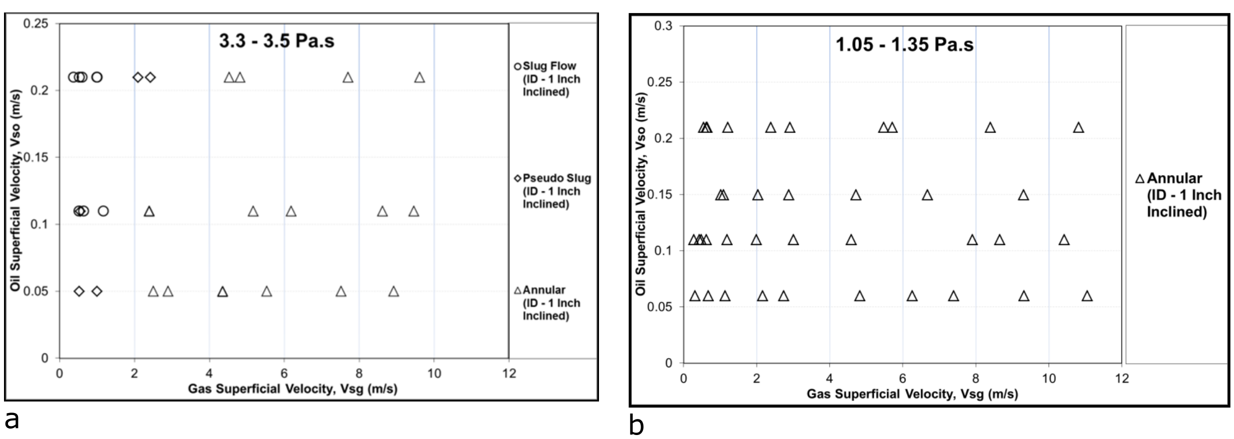


Figure 6. Flow pattern map for oil-gas two phase flows 1-inch inclined test section

3.2. Liquid holdup

Figure 7 shows a plot of inclination effects on time averaged liquid holdup measurement obtained and plotted as a function of gas superficial velocity. As can be seen from the plot, there is a reduction in the measured liquid up with increasing gas superficial velocity credited to an increase in the input gas of content within the cross sectional area of the pipeline. Though the liquid holdup trend at a lower gas flow rate in the inclined pipe is higher when compared to that of horizontal pipe attributed to the effects of gravity and viscosity forces. The trend observed conforms to those reported by [9-10].

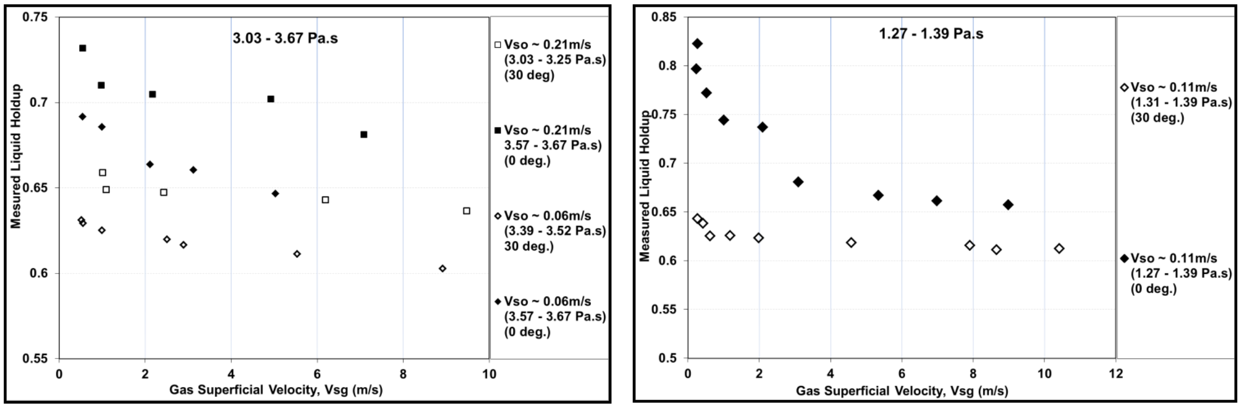


Figure 7. Effects of inclination on liquid holdup plotted as a function of superficial gas velocity for different oil viscosities (a/b)

3.3. Pressure gradient

The pressure gradient is crucial two-phase flow parameter taken into consideration during pipeline design and for the determination of pumping power requirements. This experimental investigation has revealed its strong dependence on the observed flow patterns, input liquid and gas contents, fluid physical properties and pipeline geometry/orientation. Presented in Figure 8 is a plot of pressure gradient for different oil viscosities and input liquid content. Pressure gradient generally increases with an increase in viscosity, and this can be explained by the increased shear on the pipe walls owing to viscosity effects which enhance shear around the pipe walls. Correspondingly, the pressure was observed to increase with an increase in superficial gas velocity due to the fact that pressure gradient is directly proportional to the square of the flow velocity, an increase in the gas superficial velocity will increase the pressure gradient in the pipeline. A similar trend has been reported by [9] and [11]. The initial slight decrease and in some cases slight increase at the lower superficial gas velocities is due to the competing effect of a reduction in pipe wall fouling by the input gas superficial velocity which acts to reduce the pressure drop by reducing the shear in flow and the increase in pressure gradient with an increase in flow mixture

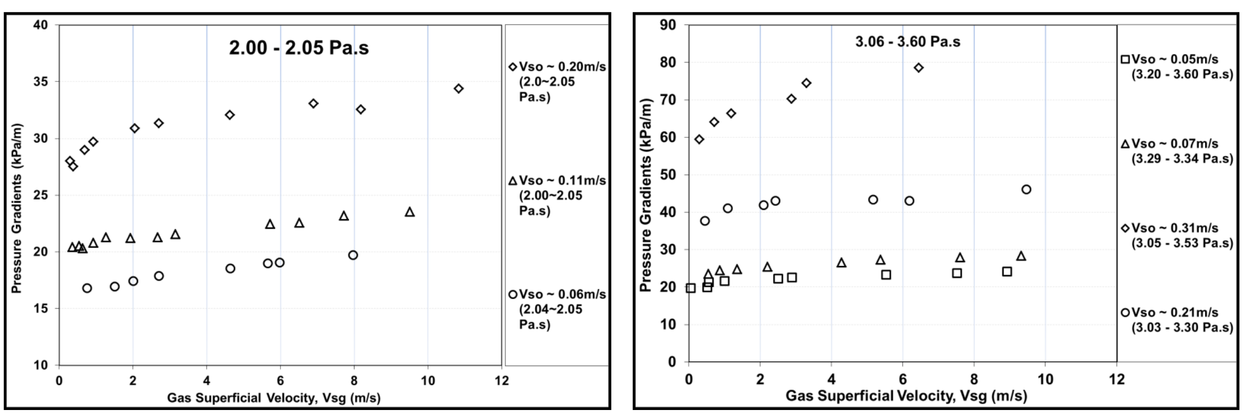


Figure 8. Pressure gradients as a function of superficial gas velocity (a/b)

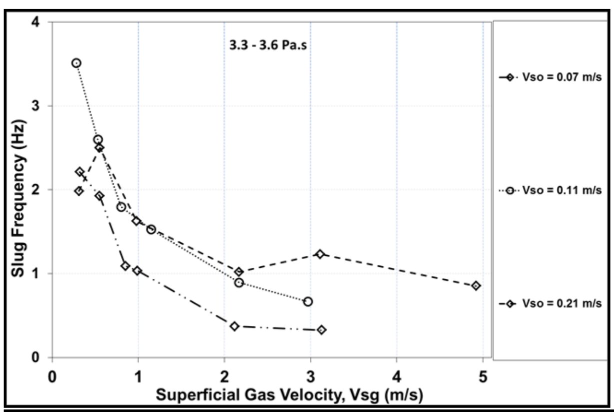
3.4. Slug frequency

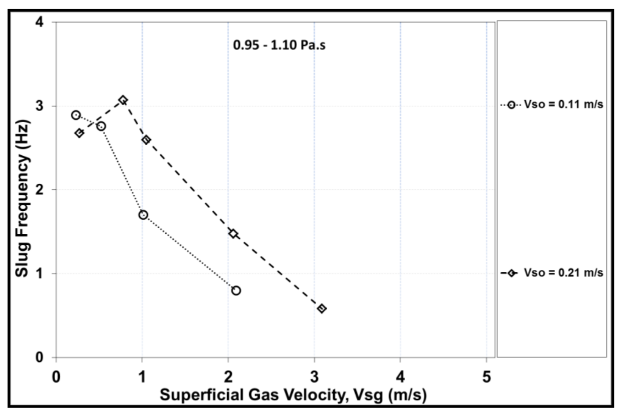
Slug frequency according to [12] is defined as the number of slug units passing at a specific position along a flow line over a certain period of time and an important parameter that needs to be considered during engineering design of pipelines. Slug frequency in this study was estimated from time series plots of liquid holdup variations. Generally speaking, an ideal slug configuration is characterised by crests and troughs which are respectively an indication passage slug body and slug film region. Several investigators in this field have suggested a liquid holdup threshold of 0.75, others 0.7 in order to differentiate between passing liquid slug body and wavy liquid film. For this study, a liquid holdup average was observed as such a threshold based on the estimation of [12] was used as presented in equation 8.

$$\mathrm{H}_{th} = \frac{1}{2}[Max(\mathrm{H}_{th}) - Min(\mathrm{H}_{th})] \quad (8)$$

where H_{th} liquid holdup obtained from ECT.

So as to examine the effect of inclination for a given range of gas superficial velocity at different superficial liquid velocity, slug frequency as a function of gas superficial velocity was plotted as shown in Figure 9. This plot shows a proportionate increase in slug frequency with increasing gas superficial velocity. The frequency reaches a maximum and then starts decreasing even though the superficial gas velocity continues increasing. An increase in the interfacial waves owing to increasing superficial gas velocity results in an increase in slug formation however a point is reached when the gas phase becomes very dominant within the cross section of the pipe which translates into a reduction in the liquid holdup and hence slug frequency. This conforms to the findings of [10] and [13] for a low viscous fluid. Also, the variation of slug frequency relative superficial gas velocity increases with increasing superficial liquid velocity attributed to increased liquid content in the cross sectional area of the pipe as indicated plots below. On the contrary, slug frequency decreases with the inclination, and this can be attributed to intermittent flow region as the angle of inclination increases.





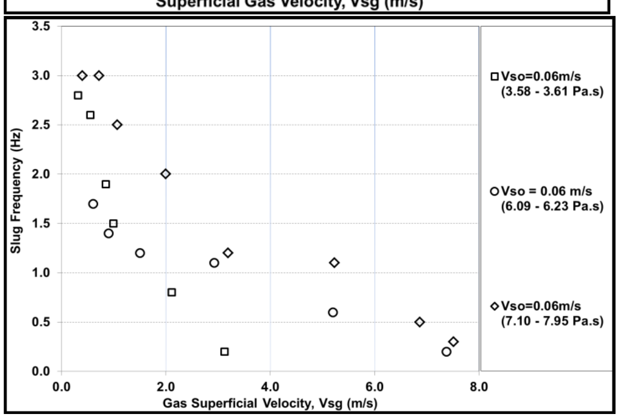


Figure 10 Slug frequency plotted as a function of gas superficial velocity for different liquid viscosities

a b
c
←

4. Conclusion

Two-phase experimental runs were conducted for high viscous liquid–gas flows in both horizontal and inclined pipe to study the effects of inclination and viscosity effects on two phase flow parameters such as flow pattern, pressure gradient, liquid hold up and slug frequency. For the flow configurations, three flow patterns were observed, i.e. slug, pseudo slug and wavy annular which were also observed to be the dominating flow pattern. Advance instrumentation (i.e. ECT) used for measurement provided good tomographic images for flow pattern characterization. Measured parameters revealed strong dependence fluid properties and angle of pipe inclination.

Nomenclature

Symbol	Denotes	Units	Greek letter		
A	*Area*	m^2	μ	*Viscosity*	*Pa.s*
C	*Constant*		ε_s	*Liquid holdup*	
ID	*Internal pipe diameter*	m	ρ	*Density*	kg/m^3
F_r	*Froude number*		$\Delta\rho/-dP/dz$	*Density difference*	
g	*Acceleration due to gravity*	$m.\ s^{-2}$	τ	*Shear stress*	*Pa*
L	*length*	m	*Subscripts*		
$h_{G,L}$	*Height*	m	f	*Film zone*	
N_μ	*Viscosity number*		g	*Gas phase*	
H_L	*Holdup*		l	*Liquid phase*	
N_f	*Inverse viscosity number*		m	*Mixture phase*	
Re	*Reynolds number*		s	*Superficial*	
V_M	*Mixture Velocity*	m/s	t	*Translational*	
V_{SG}	*Superficial Gas Velocity*	m/s			
V_{SL}	*Superficial Liquid Velocity*	m/s			
KV_{SG}	*Kutateladze number*				
S_i	*Wetted perimeter interface*				

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