The effect of inclination on slug characteristics in three phase, oil/water/gas flow in large diameter pipes

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ABSTRACT

Multiphase experiments have been carried out in a 10-cm ID, 36 m long multiphase pipeline to examine the effect of inclination on slug characteristics such as slug frequency, slug velocity, liquid film velocity, height of the liquid film, and Froude number. Studies were performed for superficial liquid velocities of 0.5 and 1.0 m/s and superficial gas velocities between 2 and 6 m/s in horizontal, +2 degree and +5 degree pipes. Mixtures of oil and ASTM Substitute Seawater were used in the liquid phase and carbon dioxide was used in the gas phase. Oil with a viscosity of 2.5 cP was used for the study. The water cut was maintained at 40%. The system was maintained at a pressure of 0.13 MPa and temperature of 25 °C.

The results show that the height of the liquid film decreased with an increase in superficial gas velocity in all cases. The height of the liquid film increased with the increase in inclination, which led to an increase of slug frequency.

As inclination increases, the slug translational velocity did not change significantly. However, the liquid film velocity decreased with increase in inclination due to gravitational force. At low liquid and gas velocities, the liquid rolled back down the pipe in both 2 and 5 degrees inclination. The Froude number remained at almost the same value with increase in inclination.

NOMENCLATURE

ASTM = American Society Testing Material
D = Pipe diameter, m
V = Velocity, m/s
Fr = Froude number, dimensionless
g = Acceleration due to gravity, m/sec^2
h = Height of the liquid film, m

Subscripts

sL = superficial liquid
m = mixture of gas and liquid
t = translational
LF = liquid film
eff = effective

Greek Letters

ν = slug frequency, sec^{-1}
θ = inclination of the pipeline, degrees

1. INTRODUCTION

The simultaneous flow of oil/water/gas mixtures in the pipeline is encountered frequently in the petroleum industry since water and carbon dioxide gas are injected into the well to enhance the oil recovery as the well gets depleted. Many oil fields are located in remote places such as subsea and Alaska. It is not practical to have a separation facility at the well site in this area. Therefore, the multiphase mixture is combined from several wells and transported in a single pipeline to a central gathering station. Numerous changes in pipeline inclination are always encountered since the distance from the well to central gathering stations is often many miles. These changes in inclinations affect the flow pattern and flow characteristics.

Slug flow is the dominant flow regime found in oil and condensate flowlines and the existence of slug flow can cause serious problems to the pipeline. Corrosion rate and pressure drop are very high in the slug flow regime since the front of the slug creates a highly turbulent mixing zone. Sun and Jepson (1992) showed that slug flow has regions with high shearing forces and flow turbulence that destroy the liquid boundary layer close to the wall. These regions can remove corrosion products and protective corrosion inhibitor films from the pipe wall. It has been noted by Kang et al. (1998, 1999) that the corrosion rate and pressure drop in the slug flow regime can be reduced significantly when drag reducing agents (DRA) were added in the pipeline. They also found that slug characteristics could be changed with addition of DRA.

Taitel and Dukler (1976) studied the effect of inclination on flow regime maps based on data from air/water flow in small diameter pipes. They proposed a model for predicting the flow regime boundaries. Stanislav et al. (1986) published flow regime maps for air/oil flow in a 2.6 cm diameter pipe for upward inclinations. Wood (1989) studied the effect of small changes in pipeline inclination on flow regimes for air/water flow in a 5 cm diameter pipe. The effect of inclination on flow regimes for three phase, oil/water/gas flow in a large diameter pipe has been studied by Kang et al. (1996). They showed that the stratified flow disappears almost entirely and slug flow dominates the flow regime map when the pipe is inclined upward.

The effect of slug frequency on corrosion rate in a 10 cm diameter pipe has been studied by Jepson et al. (1997). They showed that the corrosion rate increases with increase in the slug frequency. They also proposed a model for predicting corrosion rate including the slug frequency and crude oil type.

The study of flow regime transitions and slug characteristics for air/water flow in a 30 cm diameter pipeline has been carried out by Jepson and Taylor (1993). It was shown that the transitions from stratified to slug flow and from slug to annular flow differ substantially compared to the results from smaller diameter pipes. They also attempted to incorporate the effect of pipe diameter on slug frequency. The correlation between the non-dimensional group (vD)/ V_{sL} and the mixture velocity, V_m is given as follows:

$$\frac{vD}{V_{sL}} = 7.59 \times 10^{-3} V_m + 0.01$$

Kouba and Jepson (1989) showed that the strength of the slug is proportional to the Froude number calculated in the liquid film ahead of the slug. The Froude number is calculated from the following correlation.

$$Fr = \frac{V_t - V_{LF}}{\sqrt{g h_{eff}}}$$

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental layout of the system. Prescribed volumes of oil-water mixtures are placed in a 1.2 m^3 stainless steel storage tank (A), which is equipped with two 1-kw heaters and 6m long, 2.5 cm diameter stainless steel cooling coils to maintain the constant temperature. Oil-water mixture from the storage tank is pumped into a 7.5-cm diameter PVC pipeline by a 2.2 kw stainless steel centrifugal pump (C). The liquid flow rate is measured using an orifice plate (E) connected to an OMEGA pressure transducer and is controlled using a bypass system in the valves (D).

Carbon dioxide gas from a 20,000-kg storage tank (F) is introduced into the system through a 5 cm ID black steel pipeline. The gas flow rate is controlled by a flow-regulating valve and is measured using two gas flow meters. The gas is then mixed with the liquid at a tee junction (G). The multiphase mixture flows through a 3-m long flexible hose (10 cm ID), and then enters into an 10-cm ID, 18-m long Plexiglas pipeline. A high-speed camera was used to record the images of moving slugs. Slug characteristics such as slug frequency, slug translational velocity, the height of the liquid film ahead of the slug, and liquid film velocity were determined a digital VCR and high resolution monitor. The slug translational velocity of the slug and the liquid film velocity were determined using a cross correlation type technique. For slug velocity, the time taken for the slug front to travel a distance of 1m was determined. For liquid film velocity, the liquid wave or the gas bubble movement is tracked. The multiphase mixture then flows along a similar downward section and is returned to the tank and gas is vented to the atmosphere. A back pressure regulator, which is connected to the exhaust is used to regulate the pressure in the system.

Table 1 shows the test matrix for the study. In this experiment, carbon dioxide is used as the gas and standard ASTM salt is used as a substitute for sea water.

Table 1. Test Matrix

Oil	2.5 cP at 25 °C
Input Water Cut	40 %
Pressure	0.13 MPa
Temperature	25 °C
Inclination	0, +2 and +5 Degrees
Superficial Liquid Velocity	0.5 and 1.0 m/s
Superficial Gas Velocity	2, 4 and 6 m/s

3. RESULTS AND DISCUSSIONS

3.1 Height of the Liquid Film

Figures 2 and 3 show the effect of inclination on the height of the liquid film at superficial liquid velocities of 0.5 and 1.0 m/s respectively. It was observed from both Figures that the height of the liquid film decreased with the increase in superficial gas velocity and increased with the increase in superficial liquid velocity at all inclinations. For example, for horizontal pipes at a superficial liquid velocity of 0.5 m/s, the height of the liquid film decreased from 4.2 cm to 3.7 cm with the increase in superficial gas velocity from 2 to 6 m/s. At a superficial gas velocity of 4 m/s, the height of the liquid film increased from 4.0 cm to 4.3 cm with the increase in superficial liquid velocity from 0.5 to 1.0 m/s.

It can be seen from both Figures that the height of the liquid film increased with the increase in inclination at the same superficial liquid and gas velocities. At superficial liquid and gas velocities of 0.5 and 4 m/s, the height of the liquid film increased from 4.0 cm to 4.2 cm and from 4.0 cm to 4.4 cm with the inclination from 0 to +2 degrees and from 0 to +5 degrees respectively. At a superficial liquid velocity of 1.0 m/s, the height of the liquid film increased from 4.5 cm to 4.9 cm with the increase in inclination from 0 to +5 degrees.

3.2 Liquid Film Velocity

At superficial liquid velocities of 0.5 and 1.0 m/s, the effect of inclination on liquid film velocity is shown in Figures 4 and 5 respectively. It can be seen from both Figures that the liquid film velocity increased with the increase in both superficial liquid and gas velocities. At a superficial gas velocity of 4 m/s and 2 degrees inclination, the liquid film velocity increased from 0.77 to 1.43 m/s with the increase in superficial liquid velocity from 0.5 to 1.0 m/s.

It is seen that the liquid film velocity decreased with the increase in inclination in all cases since gravity forces decelerate the liquid film. At superficial liquid and gas velocities of 0.5 and 2 m/s, the liquid film velocity decreased from 0.66 to 0.53 m/s and then from 0.53 to 0.21 m/s with the increase in inclination from 0 to 2 degrees and 2 to 5 degrees respectively. At 5 degree inclination a fluid fall back effect was observed. The liquid film rolls back due to the influence of gravity. It was observed that at higher superficial gas velocity, the effect of inclination on the liquid film velocity was reduced. This is because at higher superficial gas velocity, the liquid film velocity is more dependent on the gas velocity and the shear at the gas-liquid interface.

3.3 Slug Translational Velocity and Froude Number

Figure 6 presents the effect of inclination on slug translational velocity at a superficial liquid velocity of 0.5 m/s. It can be seen that the slug translational velocity increased with the increase in superficial gas velocity. It is also seen that the slug translational velocity did not change significantly with inclination.

The Froude number determines the turbulent intensity of the slug. The Froude number generally increases with the increase in gas velocity at the same liquid velocity and slightly decreases with the increase in liquid velocity at the constant gas velocity. The Froude number increased from 4.6 to 13.7 with the increase in superficial gas velocity from 2 to 6 m/s in horizontal flow as shown in Figure 7. Figure 7 shows the effect of inclination on the Froude number at a superficial liquid velocity of 0.5 m/s. It can be seen that the Froude number had the almost same value with inclination since the liquid film velocity decreased and the height of the liquid film increased with the increase in inclination.

3.4 Slug Frequency

Figure 8 shows the effect of inclination on slug frequency at a superficial liquid velocity of 0.5 m/s. It can be seen that the slug frequency increased with the increase in inclination for given superficial liquid and gas velocities. At a superficial gas velocity of 2 m/s, the slug frequency increased from 9 to 20 slugs/min. and then from 20 to 35 slugs/min. with the increase in inclination from 0 to 2 degrees and from 2 to 5 degrees respectively. The reason is that as inclination increases, the height of the liquid film increases, which leads to more waves bridging the pipe for the same superficial liquid and gas velocities.

Figure 9 shows an equivalent plot for a superficial liquid velocity of 1.0 m/s. It can be seen from Figures 8 and 9 that the slug frequency increased with an increase of superficial liquid velocity at the same conditions. For example, at a superficial gas velocity of 6 m/s and in a horizontal pipe, increasing superficial liquid velocity from 0.5 to 1 m/s resulted in an increase in the slug frequency from 10 to 22 slugs/minute. This is because more liquid produces more slugs.

It is seen from Figure 9 that a very similar trend for the effect of inclination was observed. For example, the slug frequency increased from 19 to 36 slugs/min. and from 36 to 54 slugs/min. with the increase in inclination from 0 to 2 degrees and from 2 to 5 degrees respectively.

A correlation for slug frequency between -15 to +15 degrees inclination was developed based on experimental data at the Institute for Corrosion and Multiphase Technology. This correlation has a good agreement with experimental data between -15 and +15 degrees of inclination for low viscosity oil and for gas flow rates of up to 6 m/s. A semi-log plot of the non-dimensional group $(\nu D)/V_{sL}$ versus the mixture velocity, V_m and inclination of pipeline, θ is given as follows:

$$\mathrm{Log}\frac{\nu \times D}{V_{sL}} = a \times V_m + b$$

where, $a = 4\times10^{-5} \times \theta^3 + 5\times10^{-4} \times \theta^2 - 2.5\times10^{-2} \times \theta + 0.07$

$b = -4\times10^{-4} \times \theta^3 - 4.1\times10^{-3} \times \theta^2 + 0.2 \times \theta - 1.7$

4. CONCLUSIONS

Experiments have been carried out to examine the effect of inclination on slug characteristics such as slug translational velocity, the height of the liquid film, slug frequency, and Froude number.

The height of the liquid film increased with the increase in inclination at the same superficial liquid and gas velocities.

The liquid film velocity decreased with the increase in inclination in all cases since gravitational forces decelerate the liquid film.

The slug translational velocity did not change significantly with inclinations of up to +5 degrees.

The Froude number had the almost same value with inclination since the liquid film velocity decreased and the height of the liquid film increased with the increase in inclination.

The slug frequency increased with the increase in inclination for given superficial liquid and gas velocities. The reason is that as inclination increases, the height of the liquid film increases, which leads to allowing more waves bridging the pipe for the same superficial liquid and gas velocities.

The correlation for slug frequency between -15 to +15 degrees inclination has been developed based on experimental data. This correlation has a good agreement with experimental data for low viscosity oil and for gas flow rates of up to 6 m/s.

5. ACKNOWLEDGEMENT

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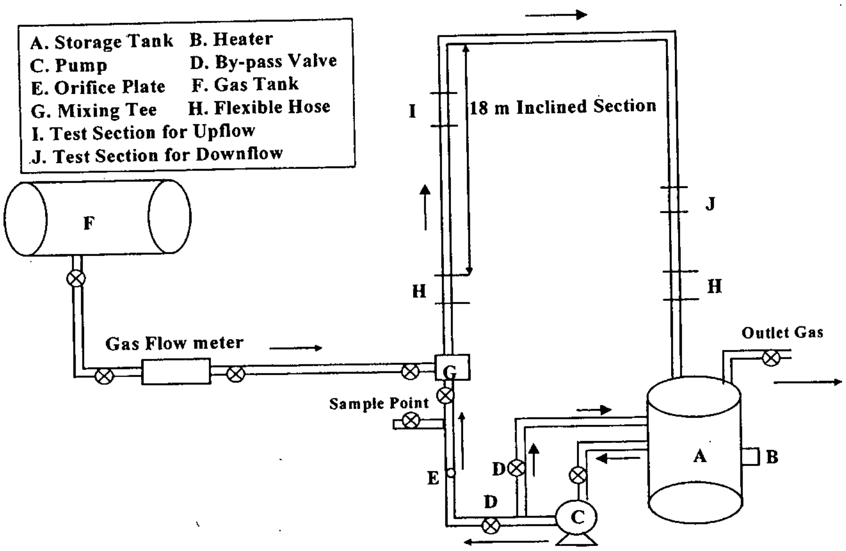

Figure 1. Experimental Layout of Flow Loop

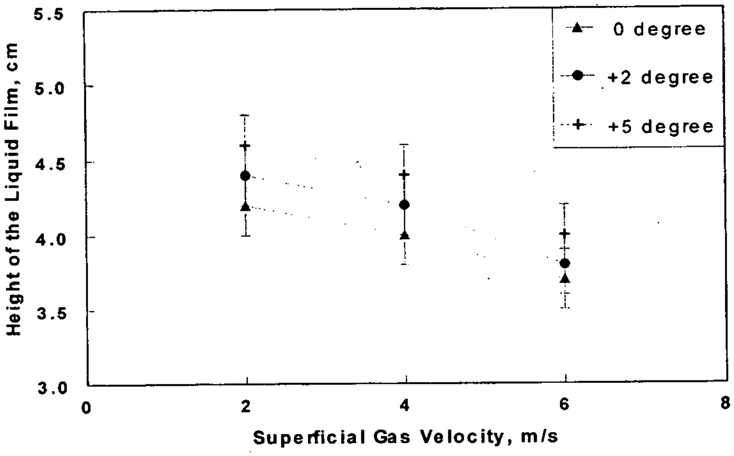

Figure 2. Effect of Inclination on Height of the Liquid Film
Vsl = 0.5 m/s, 40% Salt Water Cut, P = 0.13 MPa

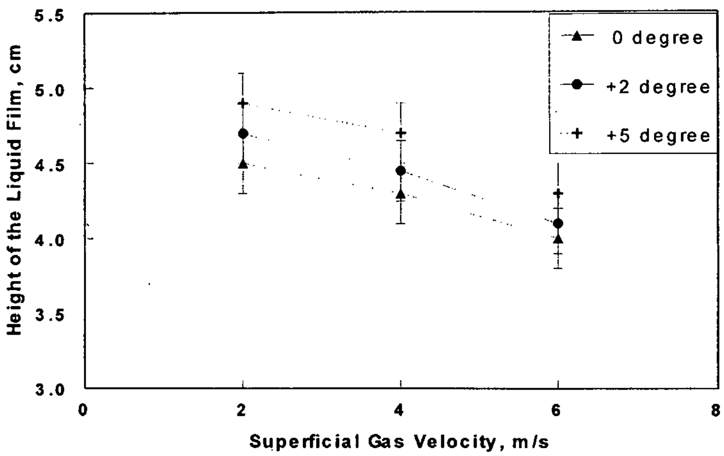

Figure 3. Effect of Inclination on Height of the Liquid Film
Vsl = 1.0 m/s, 40% Salt Water Cut, P = 0.13 MPa

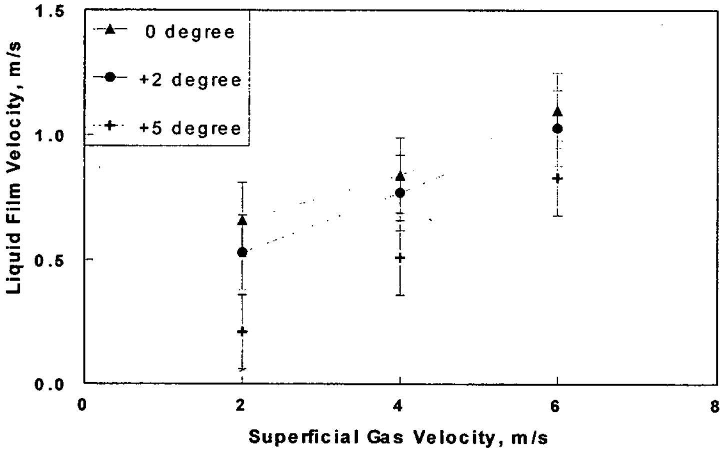

Figure 4. Effect of Inclination on Liquid Film Velocity
Vsl = 0.5 m/s, 40% Salt Water Cut, P = 0.13 MPa

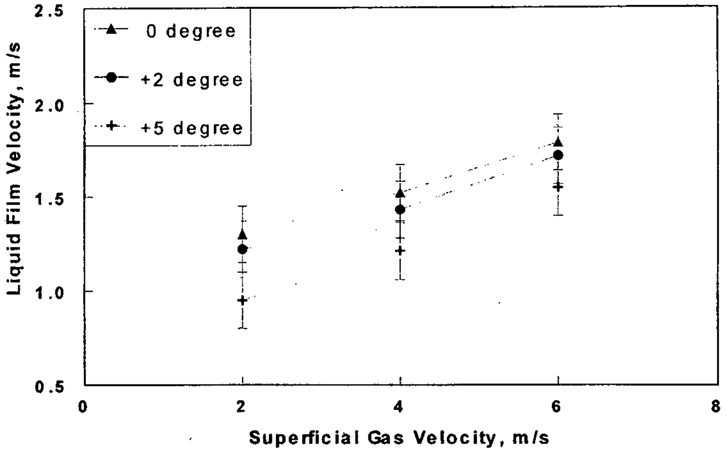

Figure 5. Effect of Inclination on Liquid Film Velocity
Vsl = 1.0 m/s, 40% Salt Water Cut, P = 0.13 MPa

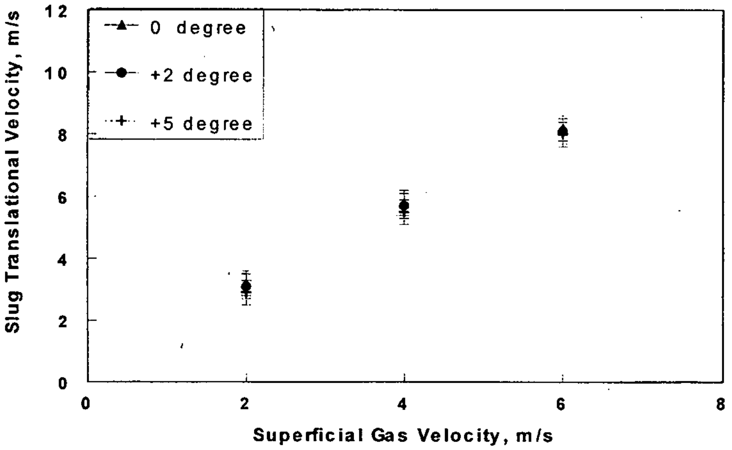

Figure 6. Effect of Inclination on Slug Translational Velocity
Vsl = 0.5 m/s, 40% Salt Water Cut, P = 0.13 MPa

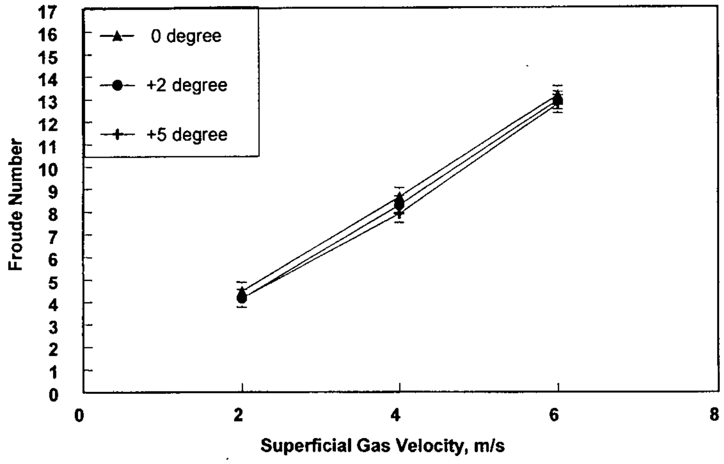

Figure 7. Effect of Inclination on Froude number
Vsl = 0.5 m/s, 40% Salt Water Cut, P = 0.13 MPa

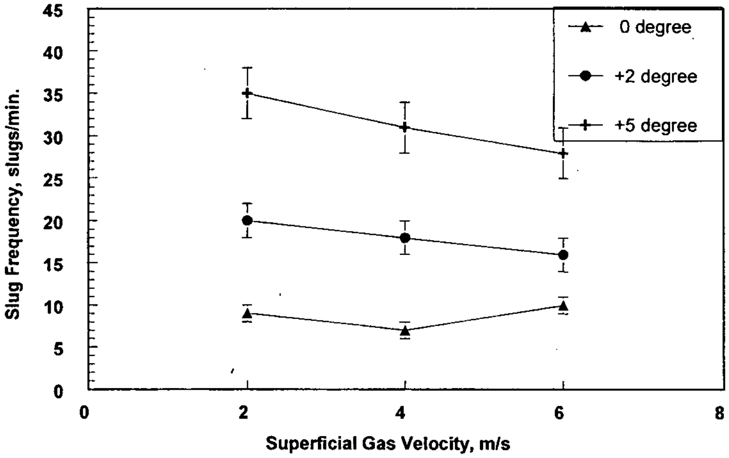

Figure 8. Effect of Inclination on Slug Frequency
Vsl = 0.5 m/s, 40% Salt Water Cut, P = 0.13 MPa

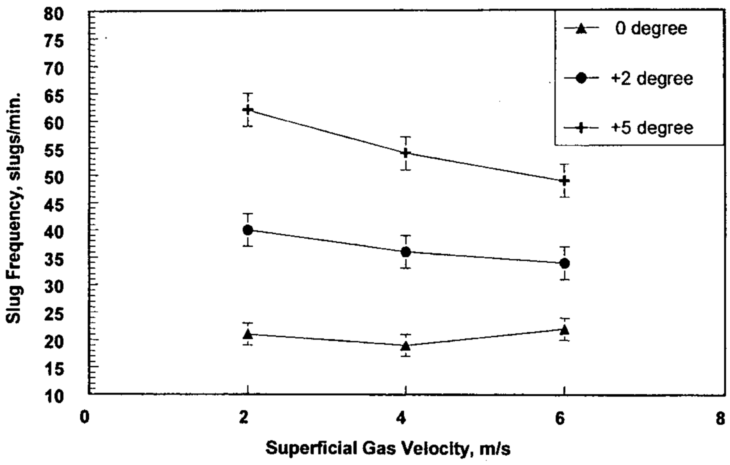

Figure 9. Effect of Inclination on Slug Frequency
Vsl = 1.0 m/s, 40% Salt Water Cut, P = 0.13 MPa