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THE EFFECT OF SLUG FREQUENCY ON CORROSION IN HIGH PRESSURE, INCLINED PIPELINES

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ABSTRACT

The effect of inclination on flow regimes and individual flow characteristics has been studied and the subsequent effect on corrosion has also been examined. Experiments were carried out in high pressure, 10 cm diameter, inclinable flow loops using brine, one oil with water cuts of 100, 80, and 60%, using carbon dioxide gas at pressures up to 1.13 MPa and temperatures up to 90 C. When the pipe is inclined upwards, the stratified flow regime virtually disappears and slug flow dominates the flow regime map. In the film region between slugs, water layers at the bottom of the pipe were still found. Oil/water mixtures flow above the water layer.

The slug frequency and Froude number change with increase in inclination. The slug frequency is higher for the inclined flows than horizontal flows at the same conditions. Further, near to the change of inclination, the slug frequency is almost double that found at distances 10 -15 m along the inclined pipe.

The Froude numbers of these slugs are similar to those found in horizontal flows. However, values as high as 17 have been recorded. These were not noted in horizontal flows and are very turbulent slugs with regions of severe wall shear forces at the slug front.

The corrosion rate increased substantially as the slug frequency was increased to about 80 slugs per minute. Above this, there was little change in the corrosion rate.

At a fixed slug frequency, the corrosion rates have been found to increase with an increase in Froude number, carbon dioxide partial pressure, and temperature.

Keywords : Corrosion, inclined multiphase flow, slug flow, phase distribution, bubble impact, shear

stress, oil/water composition, large diameter pipelines, partial pressure of carbon dioxide, temperature.

INTRODUCTION

Multiphase pipelines are now commonly used for transporting oil and gas wells which are located in remote sites, e.g. subsea. These flowlines are designed assuming that they are mostly horizontal. However, there are changes in topography due to hilly terrain, and considerable changes in the types of flow and flow regimes can occur. Substantial levels of corrosion has been found where changes of inclination taken place. There is little understanding of the flow and corrosion in these situations.

The effect of gravity in horizontal and slightly inclined three phase flow produces stratification of the phases. At the bottom of the pipe, a water layer is often present with oil flowing above it. Figure 1, produced by Lee et al. (1993)[1], indicates the flow regimes that exist in these pipelines. They proved that the extra liquid phase changes the flow regime transitions obtained from two phase liquid/gas flows. Smooth and wavy stratified flows occur at low liquid and gas velocities.

At higher gas and liquid velocities, slug flow, an intermittent flow regime, is observed. Sun and Jepson (1992)[2] and Zhou and Jepson (1994)[3] show that the front of the slug is a highly turbulent, mixing zone where gas is entrained. They indicated the presence of regions of high wall shear stress at the bottom of the pipe and these lead to high levels of corrosion there. Flow regime maps for oil/water/gas flow were produced and a typical one is shown in Figure 2.

The effect of flow regime on corrosion has been studied by Green, Johnson and Choi (1989)[4]. Instantaneous values of corrosion in horizontal slug flow were several orders of magnitude higher when the slug passed by. The effect of slug frequency was not determined. Slug frequency data for flow in small diameter pipes at atmospheric conditions have been provided by Gregory and Scott(1969)[5] and Nicholson et. al.(1978)[6]. For large diameter pipes, some limited information is given by Jepson and Taylor(1992)[7].

Taitel and Dukler (1976)[8] examined the effect of inclination on flow regimes and produced a model for predicting the flow regime transitions. This was based on data from the flow of air/water in small diameter pipes at ambient conditions. This is widely used in industry. Stanislav et. al. (1986)[9] produced flow pattern data for incline flow at low pressures and show that if the pipe is inclined upwards, the slug flow regimes occupies a much wider region of the flow map and the stratified flow regime only occurs at very low liquid velocities.

Many models have been established to predict corrosion rates in pipelines. De Waard, Lotz and Milliams (1991)[10] predict "worst case" corrosion rates. Later, the effect of liquid velocity on corrosion rate was appended by De Waard and Lotz (1993)[11]. They also showed that a maximum in the corrosion rate could be expected as the temperature was increased from 60 to 80 C. This was based on the assumption of the formation of a protective layer of iron carbonate at the pipe wall.

This laboratory has conducted a great deal of work on multiphase flow and has shown that the flow has a large effect on the corrosion mechanisms. Several important parameters help define the effect that slug flow has on corrosion. These include the slug frequency and the Froude number. Sun and Jepson (1992)[2] show that the Froude number calculated in the liquid film gives a measure of the levels of turbulence and associated wall shear and void fraction in the mixing zone at the front of the slug. This is defined as:

$$Fr = \frac{v_t - v_{LF}}{\sqrt{g h_{EFF}}} \qquad (1)$$

where v_t = translational velocity of the slug
v_{LF} = average velocity of the liquid film
g = acceleration due to gravity
and h_{EFF} = effective height of the liquid film.

Zhou and Jepson (1992)[12] and Menezes and Jepson (1994)[3] examined slug flow in 10 cm diameter, horizontal, high pressure flow loops and indicated that the corrosion rate increased with increase in Froude number, carbon dioxide partial pressure, and temperature respectively.

This study outlines on the effect of inclination on the flow parameters such as flow regime and slug frequency, and their subsequent effect on corrosion rates.

EXPERIMENTAL SETUP

A schematic outline of the experimental flow loops used in this study are shown in Figure 3. One system is made out of 316 stainless steel that can operate at pressures up to 150 bar. Oil/water mixtures are stored in a 1.2 m^3 tank. A thermostat connected to two heaters in the tank maintain a preset temperature. The liquid is pumped from the tank by a 30 kW variable speed, centrifugal pump into a 7.5 cm internal diameter pipe where the flow rate is measured by a turbine meter.

Carbon dioxide gas is supplied to the systems from a 20,000 kg receiver maintained at a pressure of 25 bar. The flowrate of gas is determined from a variable area flow meter. The gas and liquid are then mixed using a tee and the multiphase mixture passes into a 18 m long, 10 cm internal diameter pipeline. The flow then passes through a separator, recombined, and then returns along a second 18 m long pipeline and back to the tank. The gas is vented and the liquid mixture recycled. There is a test section is each pipeline.

In parallel with the stainless steel loop is an identical low pressure, plexiglass system that can operate up to 4 bar. Here, the flow characteristics can easily be observed.

Both systems are mounted on a frame that can be inclined from the horizontal to the vertical. At each inclination, the two pipelines on each loop allow both upflow and downflow to be studied simultaneously.

In the test section corrosion measurements were made using flush mounted electrical resistance (ER)and metal coupons made out of 1018 carbon steel. A sampling tube is used to determine the variation of the flowing void and oil/water fractions across a vertical diameter and to measure the oxygen content, pH and dissolved iron in the system. Pressure taps are connected to a fast response pressure transducer. This allows the measurement of the pressure gradient and from the variation in pressure in slug flow, the slug frequency can be determined.

The liquids used in this study are ASTM saltwater and two oils. At 40 C, the oils have densities and viscosities of 800 and 900 kg/m^3 and 2 and 96 cp respectively.

Carbon dioxide partial pressures of up to 0.79 MPa, water cuts of 100, 80, 40, and 20%, and liquid and gas velocities ranging from 0.1 to 2 m/s and 1 to 20 m/s respectively have been studied at an inclination of 5 degrees. These experiments are performed at 40 C.

The effect of inclination and pressure on the flow regime transitions have been studied. For slug flow, the effect of inclination on slug frequency and its corresponding effect on corrosion rate has been determined.

RESULTS

From both visual observations and from the pressure transducer readings, the effect of inclination on flow regime transitions was studied. It was found that the flow characteristics were changed greatly . At 5 degrees upward inclination, for all the flow rates studied, the stratified flow regime was not present in any form, smooth or wavy.

The flow regime map at pressures of 0.27, 0.79, and 1,13 MPa is shown in Figure 4. The map is dominated by the slug flow regime. Plug flow, which is similar to slug flow, except that no mixing zone is present at the front of the plug. Consequently, there is no gas entrainment and little turbulence present. These do not have a substantial effect of the corrosion rates. Plug flow is present over more of the map as the pressure increases. Increasing pressure does not change the slug/annular transition greatly. This has also been noted by other workers, e.g. Taitel and Dukler (1976)[8].

A very important parameter is the slug frequency since, at a given location, it determines how many of the turbulent zones associated with each slug pass over that location with time.

When the pipeline is set at an inclination of 5 degrees, visual observations show that the flow is substantially changed. Close to the pipe inlet, many slugs were being generated but many of these died out as they moved up the pipe. At distances of about 10 - 15 m along the pipe, slugs with a more constant frequency were noted. This shows that the slug frequency was greater near to changes of inclination. Data for 2 cP oil with a 60% water cut at 1.5 bar and 40 C is presented in Figures 6 and 7. At the upper sections of the pipe, at superficial liquid velocities of 0.1 and 0.5 m/s, the slug frequencies decreased from values of approximately 40 per minute to 25 per minute as the gas velocity is increased from 1 to 8 m/s. At the higher liquid rates, about 70 slugs per minute are present at high gas velocities. Decreasing water cut from 100% to 60% had little effect on slug frequency. A comparison of Figure 5 for 100% water, and Figure 6 for 60% water, show that the slug frequency is greater in inclined pipes than those for horizontal flow at the same conditions.

Figures 5, 6, and 7 show the effect of inclination on slug frequency. For horizontal pipelines, Figure 5 indicates that the slug frequency initially decreases with increase in gas velocity up to about 6 m/s. Above this value, the slug frequency does not change much with increase in gas velocity. At a gas velocity of 8 m/s at a liquid superficial velocity of 1 m/s, approximately 60 slugs per minute are moving along the pipe. At lower liquid rates, the liquid film ahead of the slug is much thinner and consequently, fewer slugs are noticed. At a given liquid flow rate, high gas velocities give higher values of Froude number.

At 2 m from the change of inclination, Figure 7 shows that the slug frequencies are much greater than those higher up the pipe. At low gas and high liquid velocities, frequencies ranging from 100 - 200 slugs per minute were recorded . For lower liquid rates, the frequencies are in the range of 50 - 90 slugs per minute. The slug frequency at the lower section was almost double that at the upper region for the range of conditions studied.

As indicated by Sun and Jepson (1992)[2], another important parameter is the Froude number in the liquid film region. The Froude numbers for the slugs at the lower part of the pipe are given in Figure 8. It can be seen that increasing the gas velocity from 1 to 9 m/s increases the Froude number from 2 to 13. The higher velocity increases the translational velocity of the slug, v_t, as shown in Equation (1) resulting in an increase in Froude number. The highest levels of wall shear stress and turbulence occur at Froude numbers greater than 9. At the upper section, the Froude numbers were higher with values as high as 17 being recorded. This is due to lower film heights in the upper section.

Visual observations of the film region between slugs showed that a water layer at the bottom of the pipe is present with an oil/water mixture above it.

The effect of slug frequency on corrosion rate is shown in Figures 9 and 10 for water cuts of 100 and 80 % at 1.5 bar and 40 C for horizontal pipes. The results indicate that the corrosion rate increases linearly as the frequency is increased from 20 to 80 slugs per minute. Above 80 slugs per minute, there is little increase in corrosion rate. This is seen at each Froude number with the corrosion rate being greatest at the highest Froude number. For example, for a water cut of 100% and 20 slugs per minute, the corrosion rate increased from 1.8 to 2.8 mm/year as the Froude number is increased from 8 to 13..

CONCLUSIONS

The results of this study clearly demonstrate that a full understanding of the flow encountered in multiphase pipelines is essential to understand the corrosion processes. Pipeline inclination or change of inclination has a significant effect on the flow regime transitions and flow characteristics. At an inclination of 5 degrees, the slug flow regime dominates the flow regime map and has a large effect on the corrosion.

For inclined pipes, away from the inlet, slugs of greater frequency than those of horizontal flows are present. Close to the change of inclination, the slug frequency is approximately double that found at a distance 10 - 15 m along the pipeline. More frequent slugs are found at the higher liquid velocities. As the gas velocity is increased, the slug frequency decreases initially and then tends to a constant value.

The slug frequency and Froude number have a large effect on the corrosion rate. The corrosion rate increases linearly with slug frequency at each Froude number up to about 80 slugs per minute. Above this value, there is little increase in corrosion rate.

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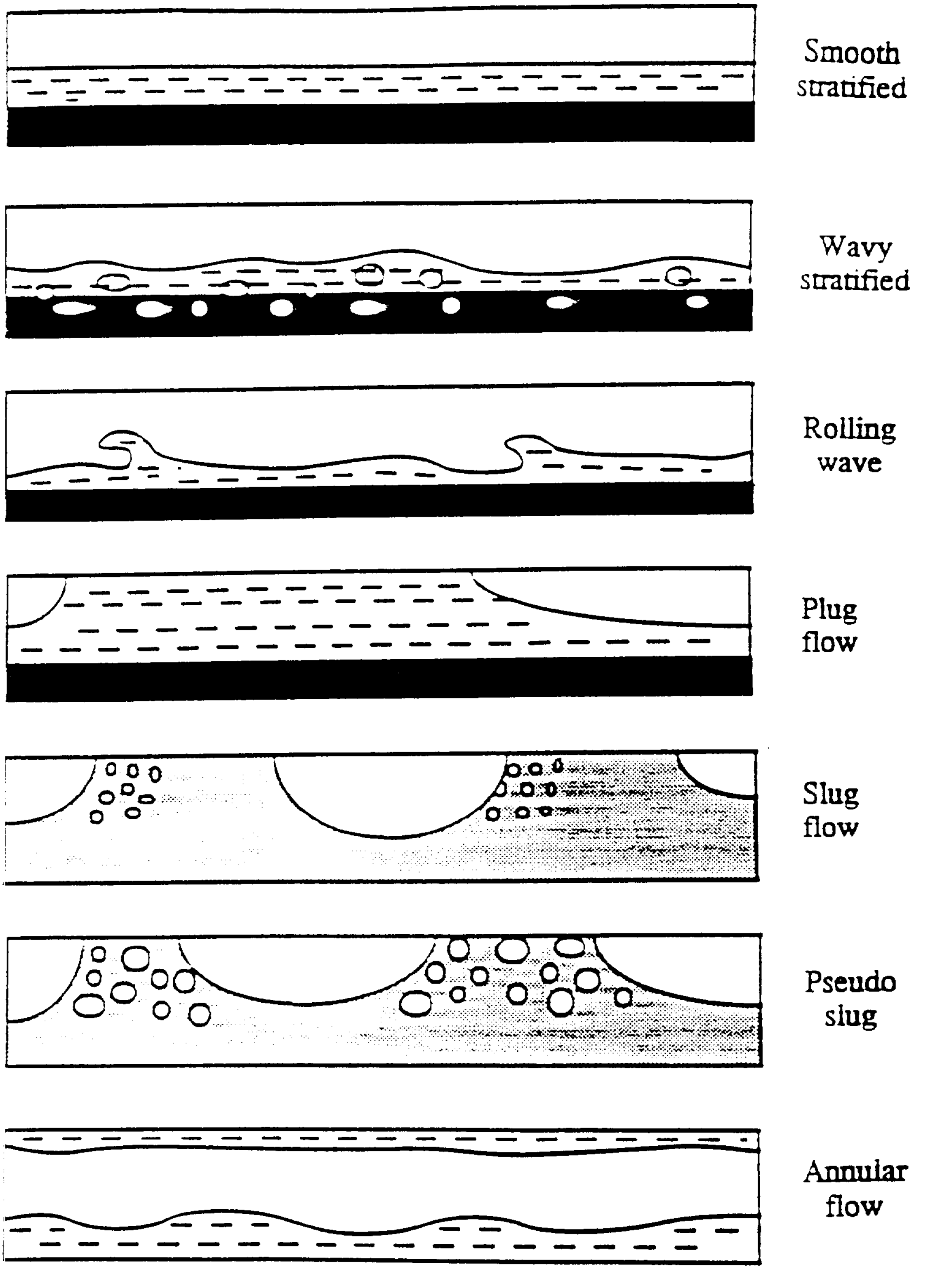

Figure 1: Three Phase Oil/Water/Gas Horizontal Flow Regimes

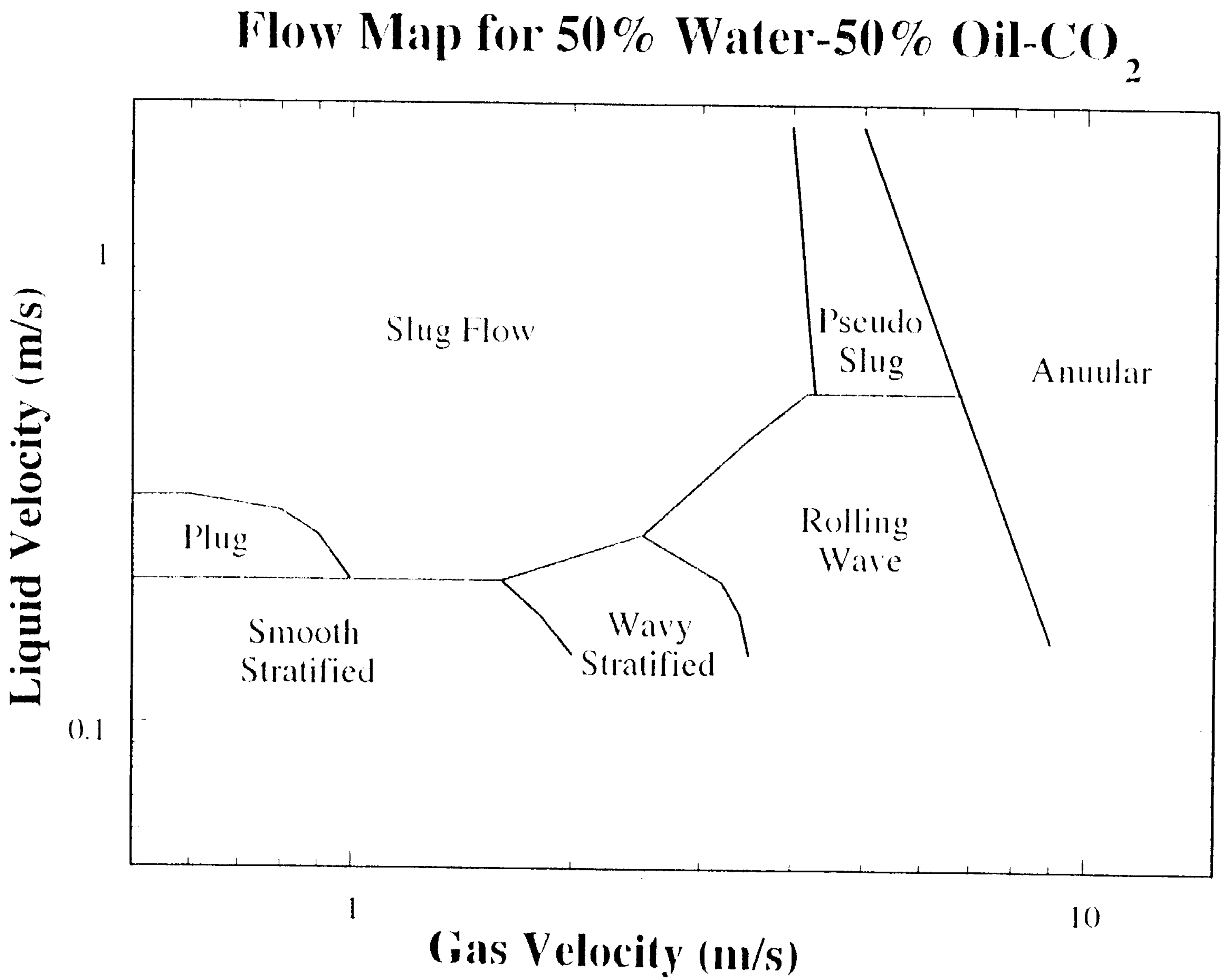

Figure 2. Flow Regime Map for Three Phase Oil/Water/Gas Horizontal Flow

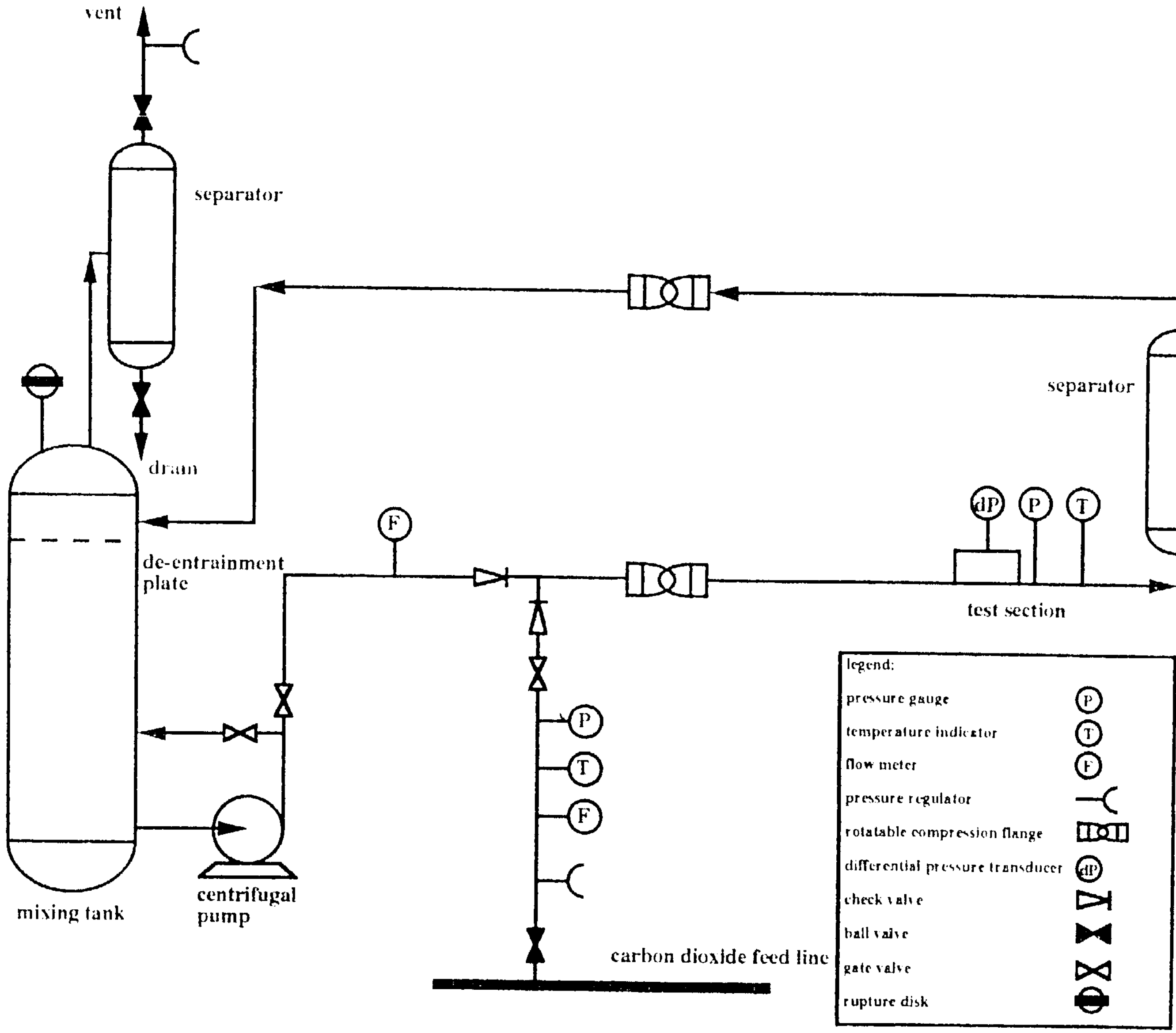

Figure 3. High-Pressure Inclined Flow System

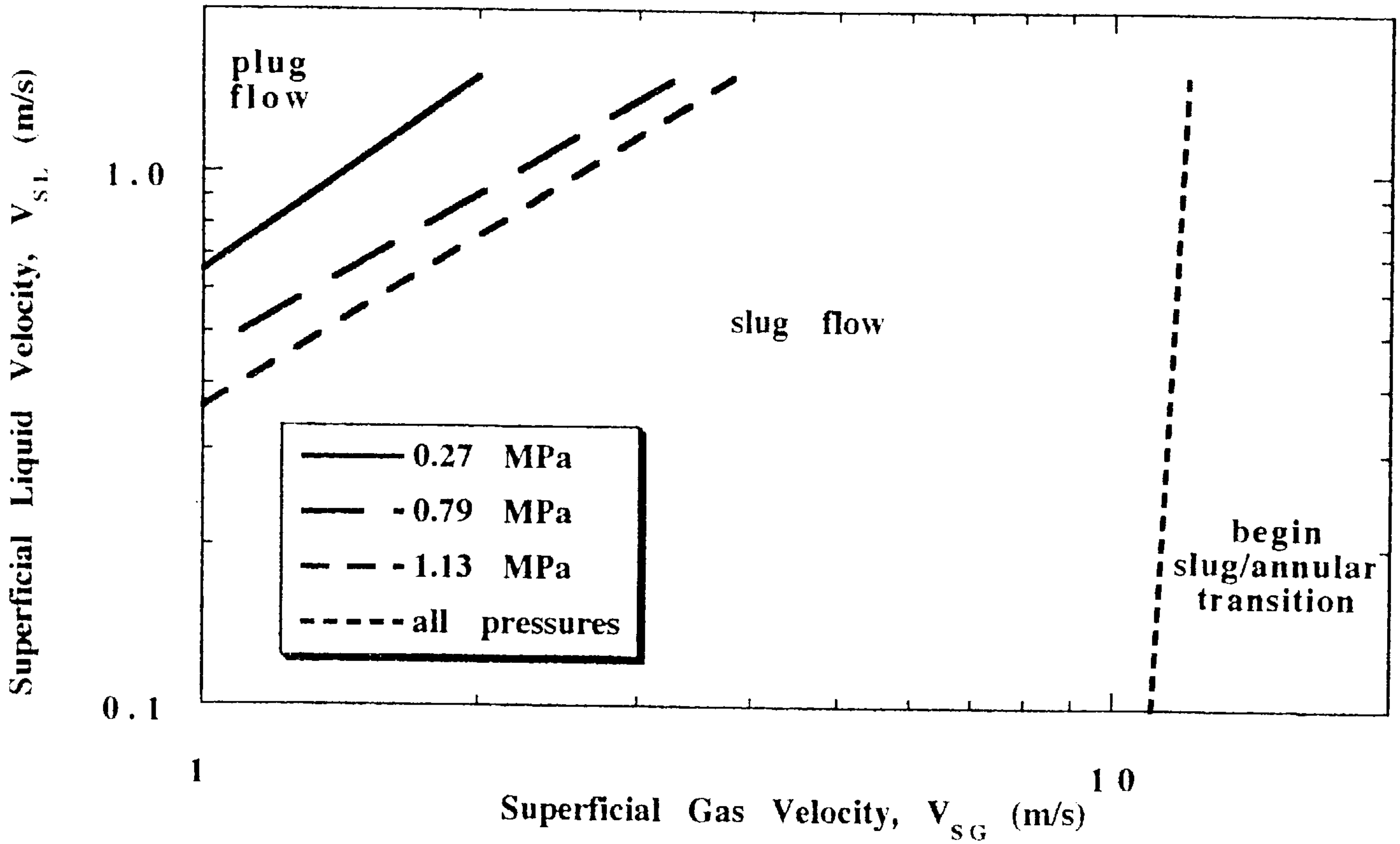

Figure 4. Flow Regime Transition Map for 20% LVT200 - 80% ASTM Seawater
60 °C, 5 ° Inclination

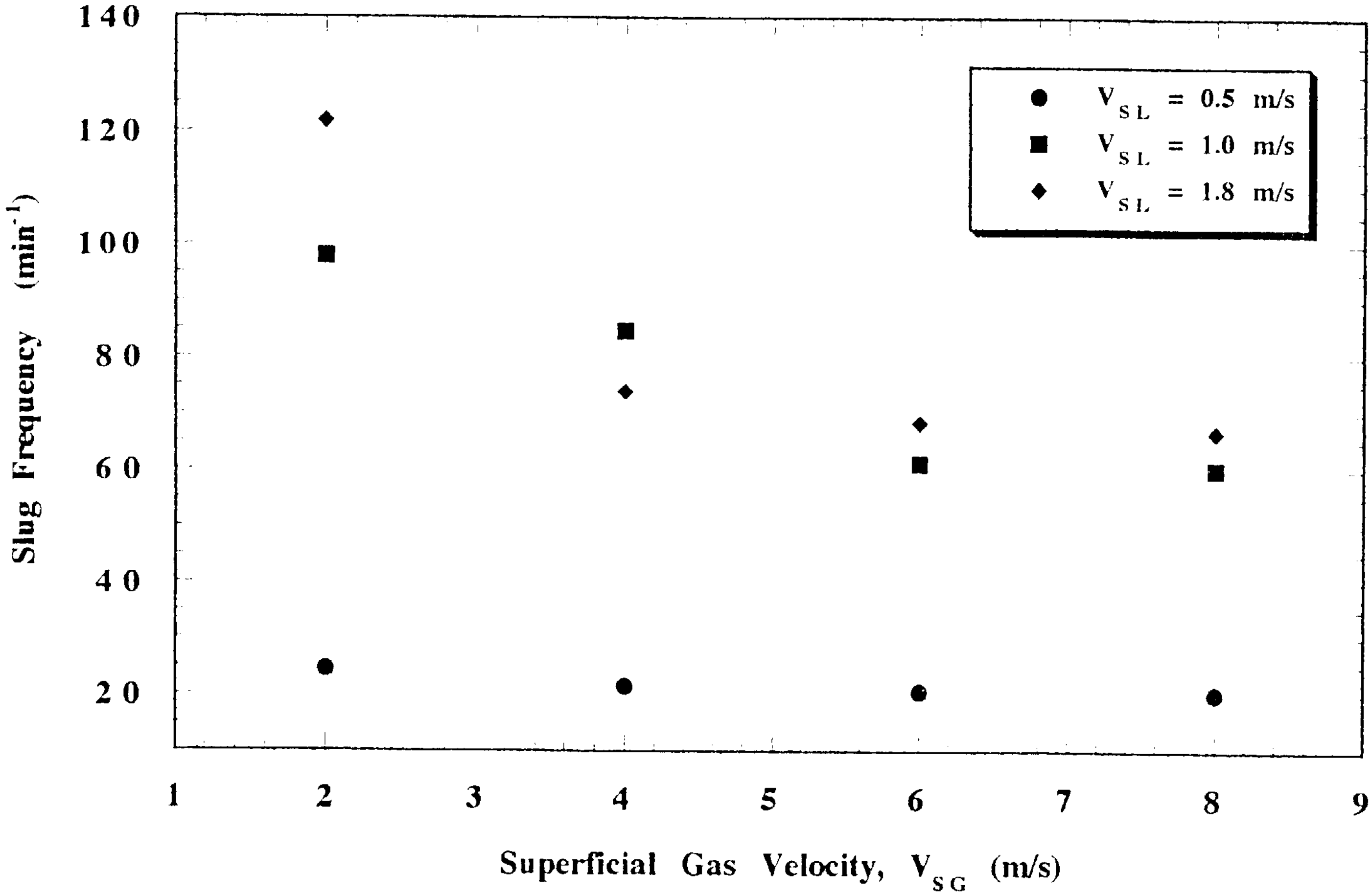

Figure 5. Slug Freqency for Horizontal Flow 100% Salt Water

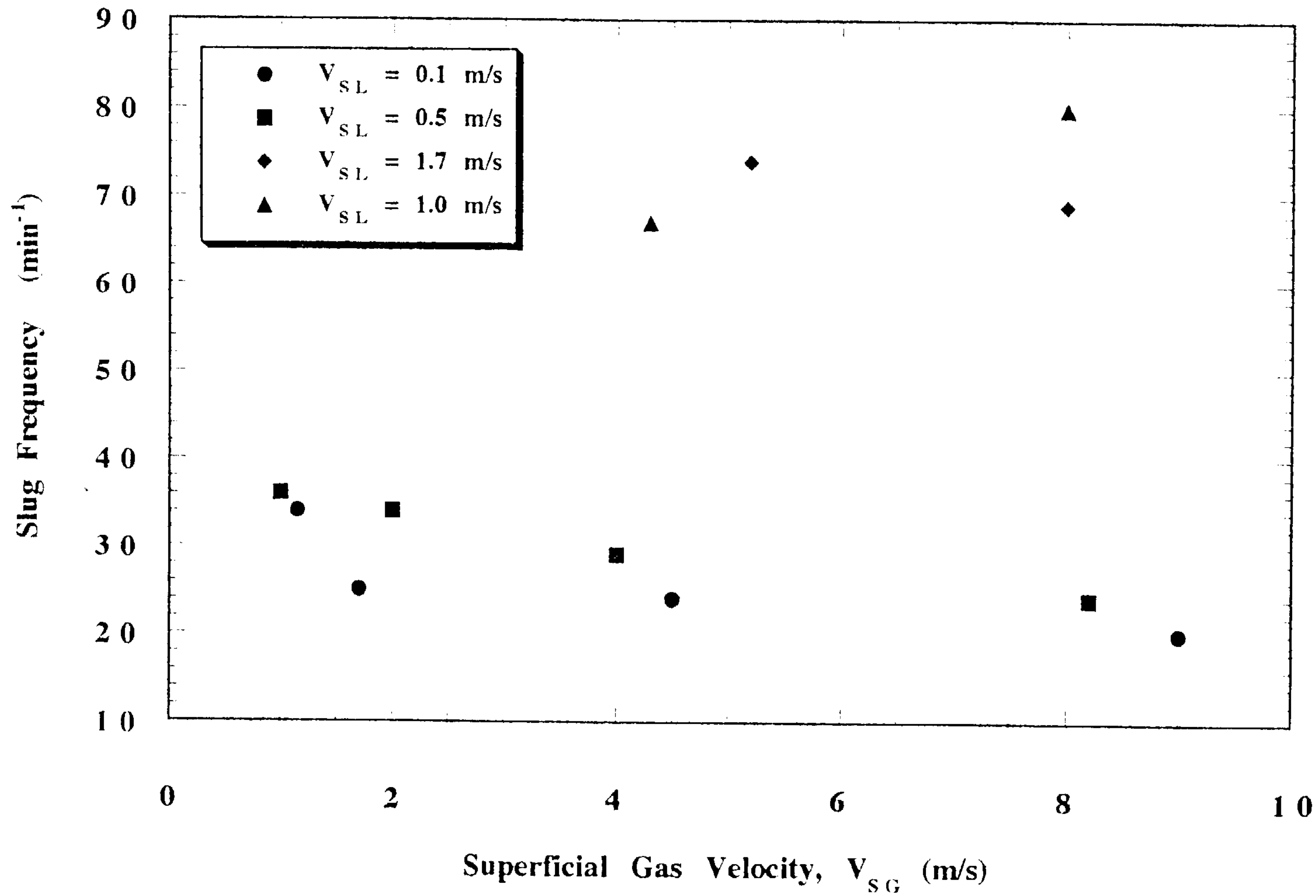

Figure 6. Slug Frequency Vs. Gas Velocity in upper section of the pipe

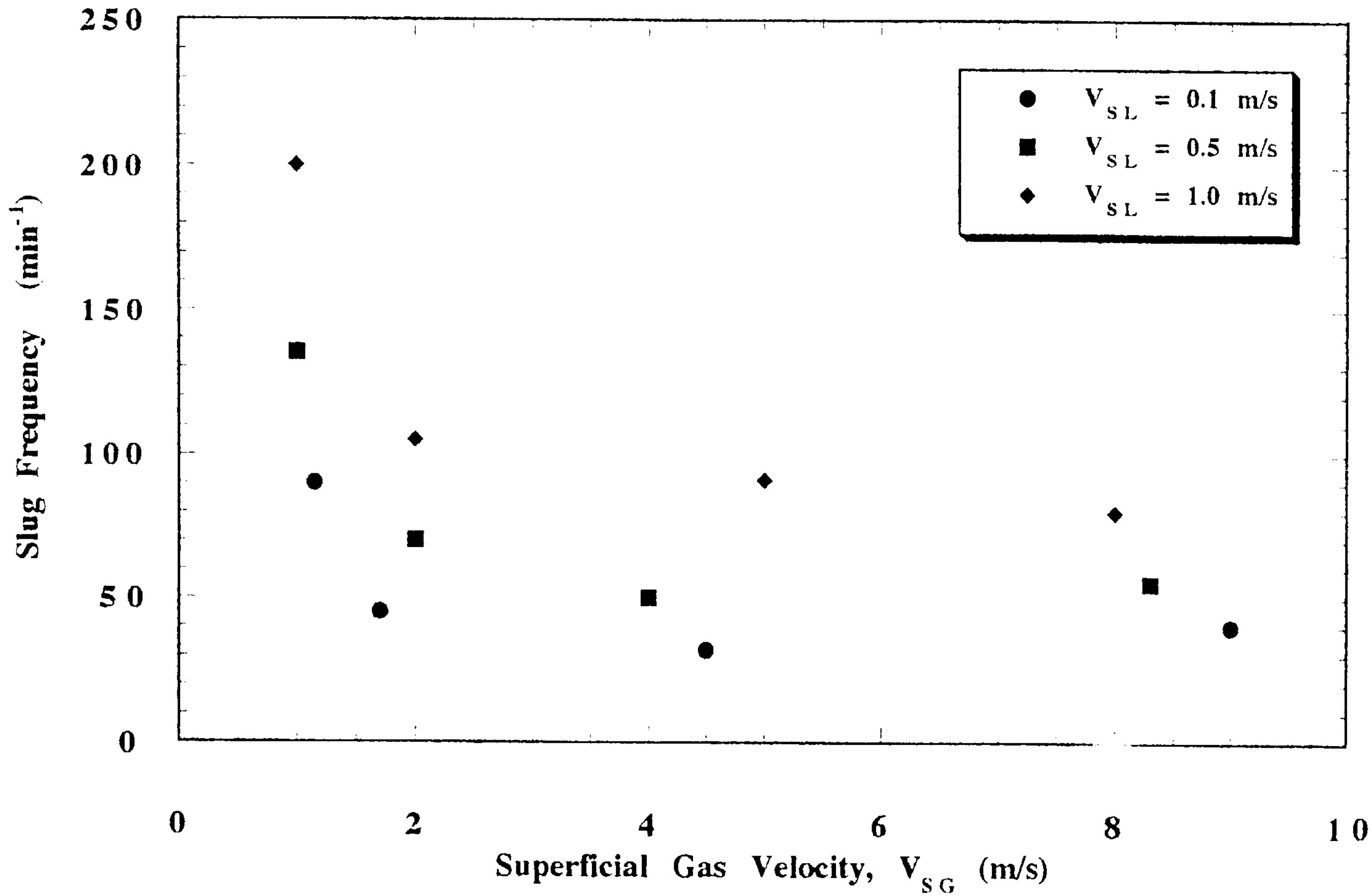

Figure 7. Slug Frequency Vs. Gas Velocity 2 m from inlet (for 60% water cut)

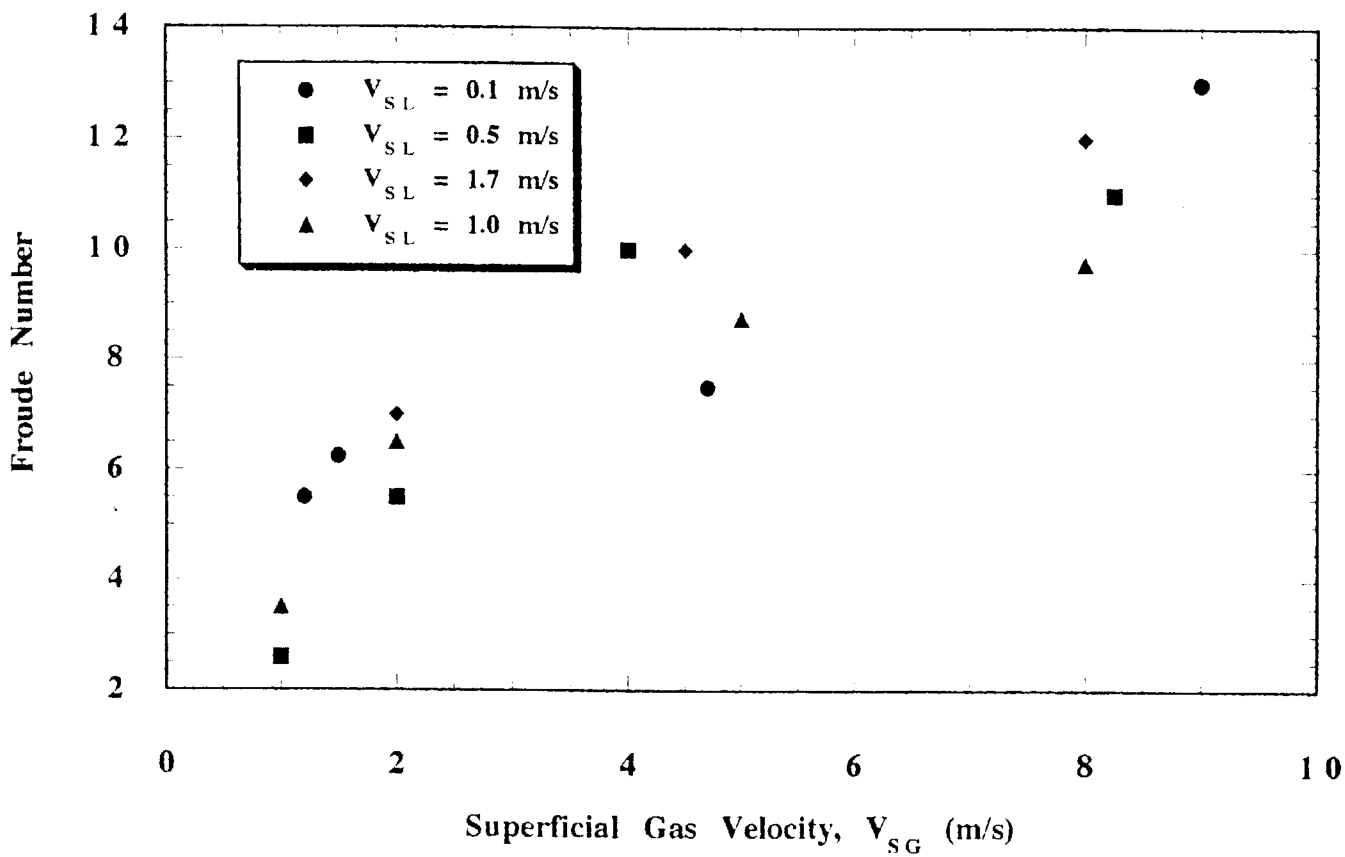

Figure 8. Froude Number Vs. Gas Velocity 2 m from inlet

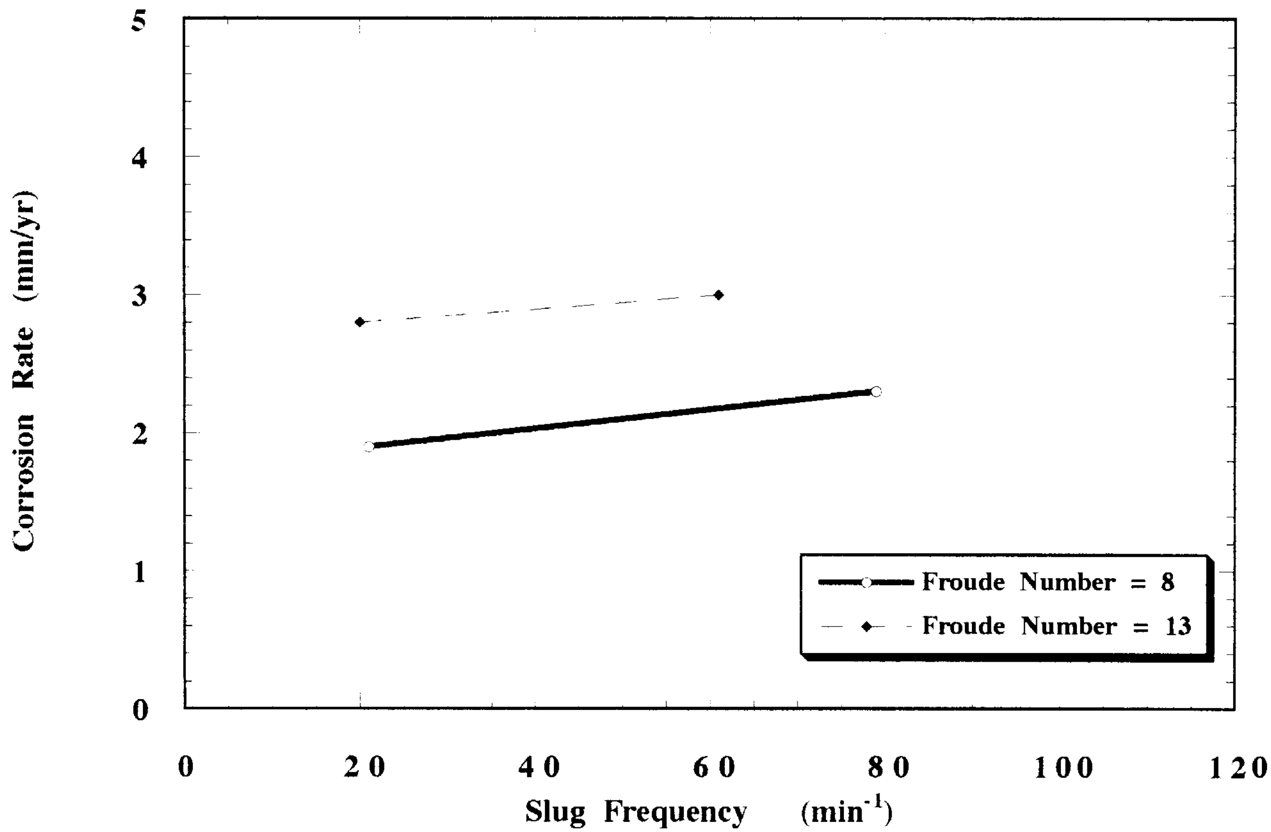

Figure 9 Corrosion Rate vs. Slug Frequency for 100% Salt Water - Carbon Dioxide Gas in Horizontal Pipes

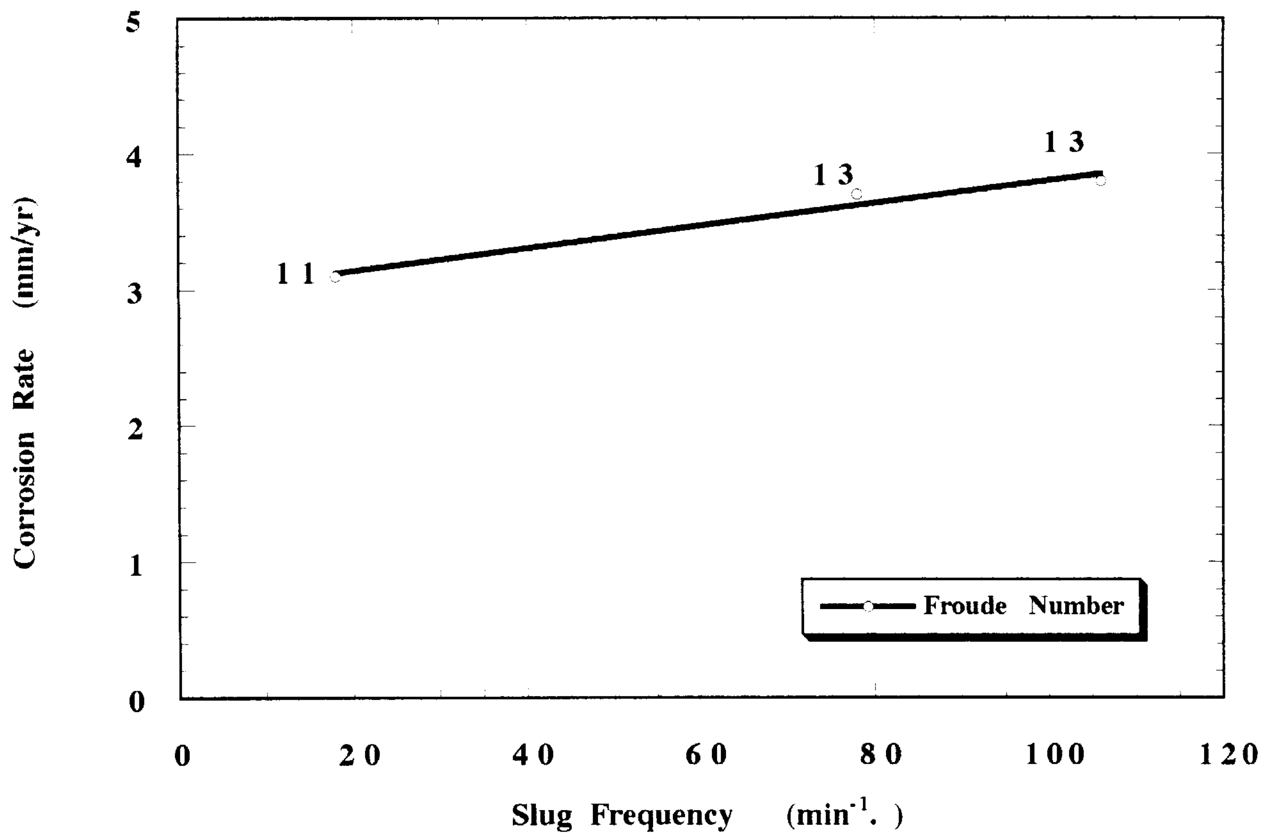

Figure 10 Corrosion Rate vs. Slug Frequency in 20% LVT Oil-80% Salt Water-Carbon Dioxide Gas in Horizontal Pipes